A review of flooding and erosion in Canadian rivers: a precursor to guidance for nature-based solutions

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A Review of Flooding and Erosion in Canadian Rivers: A Precursor to Guidance for Nature-based Solutions

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Executive Summary

Nature-based solutions (NbS), and their ability to manage flood and erosion risks, are receiving increasing attention internationally but have been less widely implemented in Canada. There are a number of knowledge gaps and research needs that are preventing broader uptake of NbS in Canadian river systems, including a need for practical guidance to support design and implementation of NbS. The Ocean, Coastal and River Engineering Research Centre of the National Research Council of Canada (NRC-OCRE) is leading a multi-year project that aims to address key technical knowledge gaps that currently prevent broader uptake and implementation of NbS for riverine flood and erosion risk management in Canada. This report provides foundational information pertaining to river flooding and erosion risk in Canadian river systems as a step towards guidance for design and implementation of riverine NbS.

NbS depend on, or mimic, natural system processes to manage flood and erosion risk. Therefore, a fundamental understanding of natural flood and erosion generating processes, as well as anthropogenic factors that influence these processes, is an essential precursor for design and implementation. This report provides a review of existing literature, resources, and examples to shed light on regional aspects of river flooding and erosion across Canada's diverse and varied landscape. Regional factors pertaining to hydrology, climate, physiography, and other relevant factors are presented for seven regions in Canada based on reviewed literature, and implications for potential riverine NbS are highlighted. Where possible, historical examples of river flooding and erosion are presented as well as a discussion of long-term trends and potential, future conditions. The report also provides a brief summary of flood and erosion risk management programs and funding in Canada. Findings from the literature review are synthesized to formulate concluding remarks pertaining to regional differences and commonalities, riverine NbS, watershed-scale approaches, and considerations for climate trends.

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1 Introduction

1.1 Project Overview

River flooding has caused some of the costliest natural disasters in Canada (Andrews, 1993; Reuters, 2021). In many regions, the frequency and severity of coastal and riverine flooding are projected to increase in the future as the impacts of climate change on temperatures, weather patterns, precipitation extremes, spring runoff, and sea levels evolve over time. Therefore, effective and environmentally friendly methods of reducing the escalating risks of flooding and erosion on many Canadian communities are needed.

The riparian environment is highly dynamic and subject to continual change in response to a variety of driving factors including seasonal variations in temperature, precipitation, runoff, streamflow and river stage; changes in land use and urbanization; as well as climate change. Many conventional engineering approaches to flood and erosion risk management involve constructing “hard” structural measures (e.g. dams, dikes, and channelization) that disrupt the natural evolution of the river system. Most conventional engineering approaches have a limited capacity to adapt to long-term changes in the river system (therefore escalating risk), and are associated with a loss of valuable and bio-diverse riparian habitats that are crucial to the survival of many species. In response to these challenges and concerns, more natural solutions for flood and erosion risk management are receiving increasing attention and interest.

Nature-based solutions (NbS), and their ability to address riverine flood and erosion risk, are receiving increasing attention internationally, but have been less widely implemented in Canada. Factors limiting the wider adoption of NbS for flood and erosion risk reduction and climate adaptation in Canada include uncertainty surrounding performance during floods and extreme weather events, and an absence of authoritative design guidance backed up by research and case studies. Evidence-based guidance for design and implementation would help address uncertainties, assist practitioners, and encourage decision-makers to consider and accept design concepts that include nature-based features.

NRC’s Ocean, Coastal and River Engineering Research Centre (OCRE) is leading a multi-year project that aims to address key technical knowledge gaps that currently prevent broader uptake and implementation of NbS for riverine flood and erosion risk management in Canada. The project aims to assess and demonstrate the performance of riverine NbS through case-study-based research focused on pilot-sites across Canada where NbS have been implemented or are being considered. Lessons-learned through case-study research will be integrated into new guidelines for design and implementation of NbS for flood and erosion risk management in Canadian river systems.

1.2 Background and Scope

In a recent report completed for CSA Group, Vouk et al. (2021) completed a literature review and engaged with relevant stakeholder groups 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”. The report also summarized needs for practical guidance and standards to inform selection and application of NbS.

Vouk et al. (2021) presented a list of eight overarching challenges related to effective implementation of NbS in Canada as well as opportunities to address these challenges. The first item on the list highlighted challenges associated with Canada’s distinct and varied environmental conditions. Because riverine NbS rely on emulating or mimicking natural system processes, they must be selected and designed with regional system compatibility in mind, in accordance with site-specific (local and watershed-scale) conditions pertaining to ecology, hydrology, climate, geomorphology, and other relevant factors (ICF, 2018; Vouk et al., 2021). These factors vary widely across Canada’s diverse landscape (Buttle et al., 2016) and there is a paucity of guidance and supporting research linking feasibility and functionality of specific NbS to different regions in Canada. Vouk et al. (2021) indicated that these research gaps must be addressed to enable the development of Canadian guides and standards for NbS.

A fundamental understanding of natural flood and erosion generating processes, as well as anthropogenic factors that influence these processes, is an essential precursor for design and implementation of riverine NbS. This report provides a review of existing literature, resources, and case study examples to shed light on regional aspects of river flooding and erosion across Canada. The report summarizes mechanisms that cause, contribute to, or affect river flooding and erosion in different regional settings and also highlights, where possible, linkages to damage and consequences. Findings from the literature review are synthesized to formulate concluding remarks pertaining to regional differences and commonalities, riverine NbS, watershed-scale approaches, and considerations for climate trends.

2 Programs and Funding for Riverine Flood and Erosion Risk Management in Canada

This section presents a broad overview of programs and funding for riverine flood and erosion risk management in Canada, largely based on information available from past review documents (Khaliq & Ferguson, 2016; Shrubsole et al., 2003) and relevant government resources (Indigenous Services Canada, 2022a; Infrastructure Canada, 2021a; Public Safety Canada, 2021a).

Flood hazard mapping guidelines in Canada were introduced in 1975 through the Flood Damage Reduction Program (FDRP). The program supported bilateral arrangements between federal and provincial/territorial governments to support flood risk management and risk reduction through floodplain mapping, floodplain regulation, and flood forecasting (Bruce, 1976; Khaliq & Ferguson, 2016; Shrubsole et al., 2003). As described by Khaliq & Ferguson (2016), the FDMP was terminated in 1999 and flood mapping responsibilities were delegated to provincial and territorial governments. Khaliq & Ferguson (2016) provide a concise summary of flood hazard assessment and mapping activities in each province and territory, including a summary of provincial and territorial administration as well as hydraulic and hydrologic procedures. However, readers are referred directly to provincial and territorial resources and websites for the most current and up-to-date information.

Since the termination of the FDRP, other federal programs and initiatives have been introduced to support disaster mitigation across Canada. The National Disaster Mitigation Program (NDMP), administered jointly by Public Safety Canada and Natural Resources Canada (NRCan), was introduced in 2014. The NDMP was created, in part, to “reduce the impacts of natural disasters on Canadians by focusing investments on significant, recurring flood risks and costs” (Public Safety Canada, 2021a). Provincial and territorial governments were eligible to apply for funding through the NDMP to support cost-shared (federally-provincially/territorially funded) projects focused on flood mitigation. The NDMP supported successful applicants through four funding streams focused on: risk assessment, flood mapping, mitigation planning, and investments in non-structural and small-scale mitigation projects. After the conclusion of the NDMP, provinces and territories were also eligible to access funding through the Flood Hazard Identification and Mapping Program (FHIMP), administered by NRCan, to support flood hazard assessment and mapping projects (Natural Resources Canada, 2022). Similar to the NDMP, flood hazard assessment initiatives supported by the FHIMP are also cost-shared between federal government and provincial/territorial government.

In addition to the NDMP and FHIMP, the Disaster Mitigation and Adaptation Fund (DMAF), administered by Infrastructure Canada, was introduced in 2018 to support "public infrastructure projects designed to mitigate current and future climate-related risks and disasters triggered by climate change, such as floods, wildland fires, droughts and seismic events" (Infrastructure Canada, 2021a). Subject to specific program criteria, eligible applicants for DMAF funding include: provincial, territorial, municipal, or regional government groups; public sector bodies; Canadian public or not-for-profit institutions; private sector bodies including for-profit and not-for-profit organizations; Indigenous governing bodies; Indigenous Development Corporations; and not-for-profit organizations whose central mandate is to improve Indigenous outcomes (Infrastructure Canada, 2021a). Funding is also available through the Emergency Management Assistance Program (EMAP), administered by Indigenous Services Canada, to support emergency management initiatives in First Nations communities related to emergency mitigation, preparedness, response, and recovery (Indigenous Services Canada, 2022a).

Projects funded through the NDMP or DMAF program are selected through a competitive, merit-based process (Infrastructure Canada, 2021a; Public Safety Canada, 2021a). Detailed evaluation criteria are available from relevant federal and provincial/territorial resources (Government of New Brunswick, 2022; Government of Ontario, 2021; Infrastructure Canada, 2021a; Public Safety Canada, 2021b). In general, strong applications should demonstrate expected benefits to risk reduction and protection of people and/or property, as well as good value for money and return on investment. Similarly, EMAP mitigation and preparedness applications are reviewed on an ongoing basis, under a finite amount of funding, and applicants are expected to outline expected results and deliverables of the proposed project (Indigenous Services Canada, 2022b).

Vouk et al. (2021) identified challenges to NbS pertaining to traditional project funding models, which tend to emphasize capital spending and, consequently, disincentivize risk management strategies that require maintenance and adaptive management (which are inherent to NbS). However, owing to recent and growing interest in NbS, funding programs are beginning to incorporate methods that incentivize nature-based strategies for flood mitigation. For example, DMAF evaluation criteria encourage funding applicants to consider innovative solutions, including natural infrastructure (Infrastructure Canada, 2021a). Vouk et al. (2021) also highlight challenges associated with the perceived uncertainty or risk associated with NbS owing, in part, to their process-based and adaptive nature (compared to conventional engineering structures which are more static in nature). Vouk et al. (2021) also discuss the paucity of real-life examples of NbS performance in Canada compared to the relatively larger body of case studies demonstrating performance of conventional engineering structures. Current funding programs favour applicants that can demonstrate expected benefits to risk reduction and return on investment. Additional research focused on NbS, including demonstration (and documentation) of performance, would support improvement of NbS, enable evidence-based decision-making, and increase investor confidence. Likewise, funding mechanisms that embrace adaptive management practices would encourage uptake and implementation.

3 Nature-Based Solutions Specific to Riverine Flooding and Erosion

Vouk et al. (2021) present a summary of NbS and nature-based features that can be employed to support flood and erosion risk management in riverine environments. Six broad categories of riverine NbS are presented and a detailed summary of flood and erosion risk management benefits, as well as factors affecting performance, are presented for each category. Table 1, taken from Vouk et al. (2021), summarizes key findings of the study.

Table 1. Examples of NbS for riverine flood and erosion risk management, from Vouk et al. (2021)

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

4 Riverine Flooding and Erosion in Canada

Canada's watersheds are dispersed across a highly-diverse landscape comprised of high mountains, forests, arctic tundra, wetlands, and agricultural lowlands. Similarly, climate varies greatly across Canada, which spans temperate and arctic zones. Consequently, factors influencing river flows and geomorphology such as precipitation, runoff, sediment transport, bank composition, and vegetation vary across the nation (Andrews, 1993; Buttle et al., 2016; Lawford et al., 1995; Power & Power, 1995; Satchithanantham et al., 2019; Shrubsole et al., 2003).

A non-exhaustive review of river flooding and erosion processes across Canada was conducted, highlighting historical damages and consequences as well as factors potentially affecting the viability and implementation of NbS in different geographic regions. The review builds on previous works that summarize flood processes across the country (e.g. Andrews, 1993; Buttle et al., 2016), adding details pertinent to NbS, where necessary. Roughly following the geographic classification proposed by Buttle et al. (2016), the country was divided into seven regions to guide the review. However, it is acknowledged that there is substantial variability within each region. Figure 1, adapted from Vouk et al. (2022), presents an approximate visual representation of the regions proposed by Buttle et al. (2016). Figure 1 was developed using a variety of geospatial data resources pertaining to physiography, permafrost, ecozones, forest areas, political boundaries, and major drainage areas (Agriculture and Agri-Food Canada, 2013; Brandt, 2009; Elections Ontario, 2022; Natural Resources Canada, 2019, 2021b, 2021a; Statistics Canada, 2016, 2017). The following Sections 4.1 through 4.7 describe flood and erosion processes relevant to each region. Sections 4.2, 4.6, and 4.7 are largely adapted from Vouk et al. (2022).

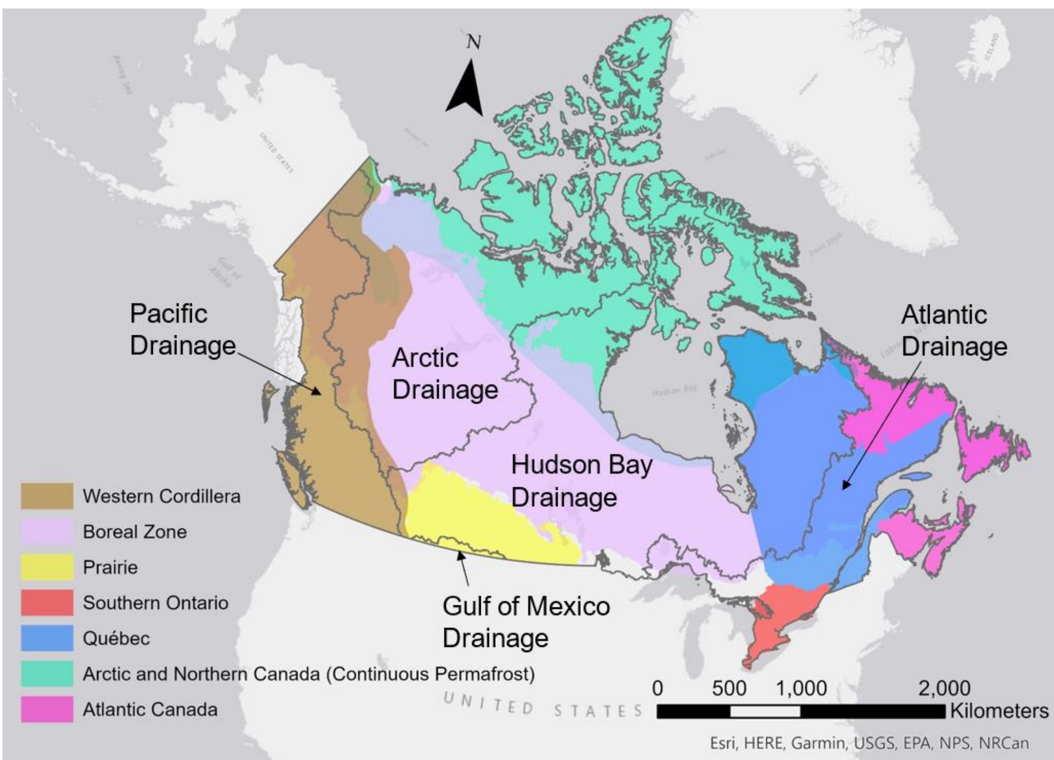

Figure 1. Regional grouping of river flooding and erosion processes across Canada from Vouk et al. (2022). Major drainage areas are also shown. Considerable overlap amongst regions is apparent.

4.1 Boreal Zone

The Boreal Zone spans a large portion of the Canadian landscape. It overlaps many of the other regions discussed in this report, including large portions of the Western Cordillera, Ontario, Québec, the southern fringe of Arctic and Northern Canada, and Atlantic Canada (Figure 2). The Boreal Zone spans a number of distinct ecozones (Figure 2) that can be generally categorized into "shield" (e.g. Boreal and Taiga Shield) and "plain" (e.g. Boreal and Taiga Plain) landscapes. The Boreal Zone also covers the northern portion of the Western Cordillera region; however, regional considerations for those areas are not discussed in this section and readers are, instead, directed to Section 4.7. For simplicity, the area covered by the Boreal and Taiga Shield ecozones (as shown in Figure 2) is hereafter referred to as "Boreal Shield", and the area covered by the Boreal and Taiga Plain ecozones is hereafter referred to as "Boreal Plain". Readers are directed to documentation from the National Ecological Framework for Canada for additional details regarding specific ecozones (Ecological Stratification Working Group, 1995).

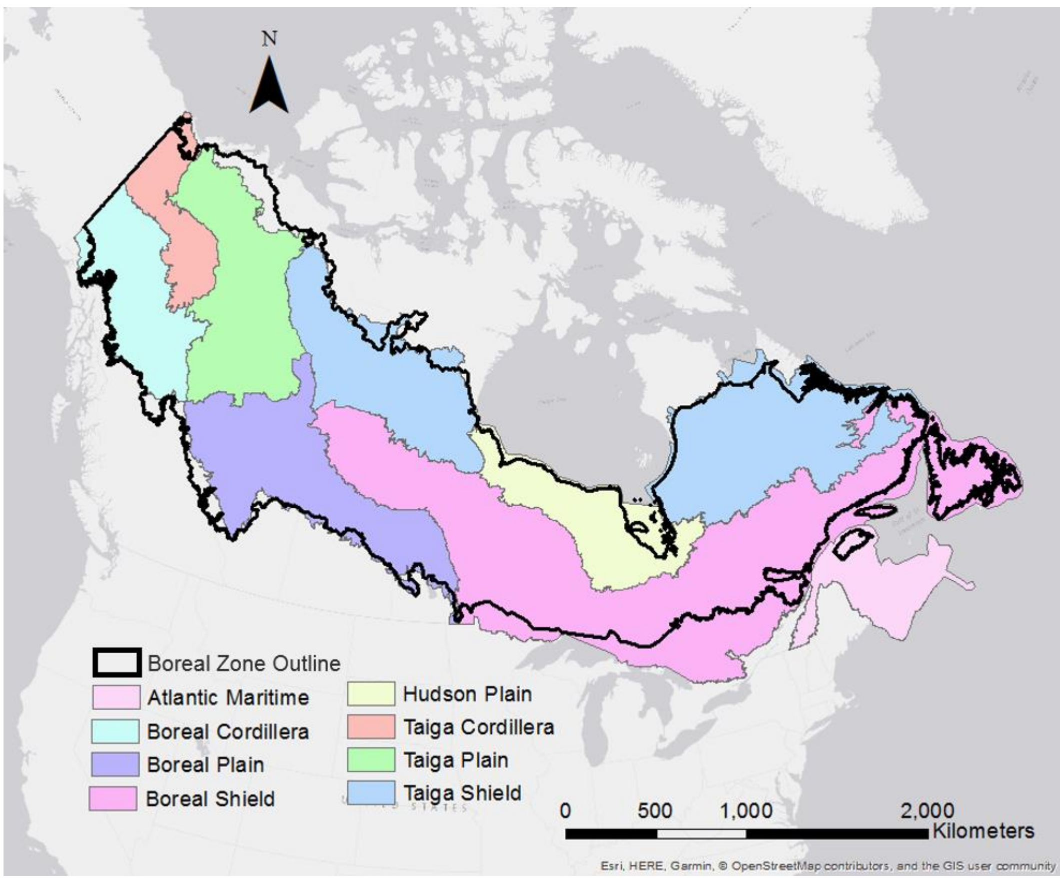

Figure 2. Canada's Boreal Zone and coinciding ecozones (Agriculture and Agri-Food Canada, 2013; Brandt, 2009).

Canada's Boreal Zone covers approximately 627 million hectares and contains extensive forests, wetlands, and lakes (Brandt, 2009). The Boreal Shield landscape is characterized by rolling topography comprised of bedrock outcrops, interspersed by generally thin soil deposits, and numerous lakes and wetlands (Buttle et al., 2016; Ecological Stratification Working Group, 1995). The Boreal Shield, alone, contains approximately 22% of Canada's surface freshwater area (Urquizo et al., 2000). By comparison, the Boreal Plain landscape is characterized by level-to-gently rolling topography with generally deep surficial soil deposits, and comparatively fewer lakes than the boreal shield (Buttle et al., 2016; Ecological Stratification Working Group, 1995). Collectively, the Boreal Zone contains approximately 800,000 km^2 of surface freshwater, 35% of the world's wetlands, 90% of Canada's remaining large intact forest, and 25% of the world's remaining large intact forest (Anielski & Wilson, 2005; Wells et al., 2010).

High river flows and flooding events in the Boreal Zone are largely controlled by the seasonal accumulation of snow and subsequent spring snowmelt (Aygün et al., 2020; Buttle et al., 2016). The timing and volume of snowmelt runoff and associated river flows are influenced by spring temperatures, winter snow accumulation, and antecedent soil conditions (i.e. soil moisture content and frozen ground conditions) (Aygün et al., 2020; Buttle et al., 2016; Nolin et al., 2022). High flows coinciding with snowmelt can be further compounded by spring rainfalls as evidenced by flooding in northwestern Ontario in 2022 (Levesque, 2022a, 2022b), and by river ice dynamics as evidenced by flooding in Fort McMurray, Alberta in 2020 (Heidenreich, 2021). Summer rainfall events can also cause severe river flooding as evidenced by the Timmins, Ontario flood of 1961, which has regulatory significance for flood hazard delineation in Northern Ontario (McNeil, 2019; Ontario Ministry of Natural Resources, 2002). Recent research has highlighted observed, and projected, changes in regional hydrological processes owing to climate change and increased temperatures including earlier snowmelt runoff generation, increased ratio of rainfall to total precipitation, and a shift from snowmelt-driven to rainfall-driven high river flows (Aygün et al., 2020; Gaur et al., 2018; Nolin et al., 2022; Teufel & Sushama, 2021). Zhang et al. (2019) describe observed and projected changes in temperature and precipitation for Canada.

Citing several resources (Elliott et al., 1998; Granger & Pomeroy, 1997; Pomeroy et al., 1998, 2002; Pomeroy & Granger, 1997), Buttle et al. (2016) describe linkages between boreal forest vegetation and hydrology, including impacts of natural and anthropogenic disturbances such as forest fires and forestry operations. Key points from Buttle et al. (2016) are summarized here. The Boreal Zone contains expansive coniferous forests that play a fundamental role in regulating regional hydrology. The dense, evergreen canopy of the coniferous forest vegetation reduces overwinter accumulation of snow on the forest floor by intercepting snowfall, which is then lost through sublimation. Likewise, the coniferous forest canopy regulates the melt rate of the underlying snowpack during spring by providing shade cover. Conversely, areas with deciduous forest vegetation (because they lose their leaves in winter), or forest stands that have been cleared by forest fire or forestry operations produce comparatively larger volumes of, and more intense, snowmelt runoff. Furthermore, forest clearcutting leads to higher soil moisture content, resulting in reduced infiltration capacity and greater runoff during snowmelt and rainfall events. Forestry and replanting operations can also alter the physical characteristics of the soil (e.g. soil compaction) and, ultimately, hydrological processes affecting runoff (Elliott et al., 1998; Huang et al., 1996).

Forestry operations can also impact river sediments and geomorphology. Root systems provide subsurface biomass that enhance hillslope stability against landslides and debris flows (Lehmann et al., 2019; Sakals et al., 2006). Consequently, deforestation can influence the sediment supply of river systems. Root systems also provide reinforcement against bank erosion and, consequently, influence channel migration (Horton et al., 2017; Reid, 1993; Sakals et al., 2006). In addition, forestry operations can influence the availability of woody debris; in-stream woody debris influences channel roughness, energy dissipation, flow patterns, and channel morphology (Reid, 1993; Sakals et al., 2006).

Wells et al. (2010) and Anielski and Wilson (2005) provide insight to the Boreal Zone landscape and associated natural system functions. Introducing the significance of Boreal Zone water resources, Wells et al. (2010) present the following:

> Many of the waterways and wetlands of the boreal forest are among the most pristine in Canada, as well as globally, with low or undetectable levels of human-caused pollutants, little human-made nitrogen and phosphorous inputs, and few invasive plant and animal species. [...] Canada's boreal forest contains the world's highest concentrations of large wetlands, lakes and undammed rivers. Its waterways and wetlands make vast and critical contributions to the global environment—stabilizing climate and feeding the productivity of the world's oceans, ultimately supporting the health and welfare of people across the Earth.

Anielski and Wilson (2005) estimated the total value of ecosystem services provided by the boreal forest to be equal to $93.2 billion per year; flood control and water filtering provided by boreal forest peatland had the highest value of all ecosystem services evaluated, equal to $77.0 billion per year. Wells et al. (2010) further explain that "Canada's boreal forest region provides one of the last global opportunities to conserve large-scale, pristine aquatic ecosystems, the biodiversity they sustain, and the ecosystem services they provide". Therefore, it is reasonable to conclude that NbS for the Boreal Zone may focus primarily on conservation and preservation of existing natural features, with relatively less emphasis on physical intervention or construction of new features to mimic natural system functions. However, natural system functions have been impacted in certain areas by human activities, particularly those focused on exploitation of natural resources such as forestry, hydropower, and oil/gas extraction (Wells et al., 2010). In addition to a direct loss of habitat, construction of access roads to support natural resource exploitation can inhibit migration of fish and other aquatic organisms, and interfere with surface water drainage and flows (Wells et al., 2010). As discussed above, forestry operations and use of machinery can also impact soil properties affecting hydrological processes (Elliott et al., 1998; Huang et al., 1996). Furthermore, the Boreal Zone is home to some of the largest hydropower operations in the world which often include significant alteration of natural drainage systems such as damming and water diversion (Wells et al., 2010). These challenges present an opportunity for advancement of NbS tailored to address the impacts of the natural resources industry, which may include research to improve reforestation strategies and access road design. However, NbS should prioritize conservation and preservation of existing natural features over interventions intended to replicate natural system functions.

4.2 Arctic and Northern Canada

Arctic and northern Canada is comprised of the northern Territories of Nunavut and Northwest Territories as well as portions of Yukon, Manitoba, Ontario, Québec, and Newfoundland and Labrador (Buttle et al., 2016). The region is characterized by tundra vegetation (i.e. small shrubs, herbs, and graminoid vegetation, and relatively free from trees), peatlands, and barren landscapes underlain by permafrost (Buttle et al., 2016; Nilsson et al., 2015; Power & Power, 1995).

The region has long, cold winters and most open water flow is limited to the brief, cool summer season; small headwater streams may even freeze solid during the winter months (Buttle et al., 2016; Nilsson et al., 2015; Power & Power, 1995). The majority of the annual precipitation falls as snow, which accumulates over the long winter season (Power & Power, 1995). High river flows are associated with snowmelt during the spring or summer, and a large proportion of the annual discharge is concentrated within this short period, but high flows can also be produced by summer or autumnal rainfall events (Buttle et al., 2016;

Power & Power, 1995; Stern & Gaden, 2015). Regional hydrology is characterized by the presence of frozen ground conditions and permafrost. Infiltration, groundwater storage, and subsurface flow are limited to the active layer, above the permafrost, which is seasonally thawed during the summer (Kane et al., 2003; Stern & Gaden, 2015). Consequently, frozen ground and permafrost conditions hinder or preclude flood attenuation mechanisms provided by infiltration and ground water storage/recharge, and the fraction of runoff generated by snowmelt or rainfall events is often relatively high compared to that in more southern regions of Canada (Buttle et al., 2016; J. B. Jones & Rinehart, 2010; Kane et al., 2003; Power & Power, 1995; Stern & Gaden, 2015). In particular, runoff generated from snowmelt, while the active layer is still frozen, can be quite substantial (Woo & Young, 2006). These mechanisms that contribute to rapid runoff can produce flashy and intense flow hydrographs (J. B. Jones & Rinehart, 2010; Power & Power, 1995). Although not exclusive to the Arctic, river flooding (and associated impacts) can be exacerbated by ice jam processes (Andrews, 1993; Turcotte, 2021).

Channel erosion and geomorphic processes that are influenced by flow, sediment characteristics, and channel pattern are further compounded by the presence of permafrost and freezing and thawing within the channel banks (Power & Power, 1995; Scott, 1978). In general, permafrost and frozen bank material contributes to greater bank stability, and less erosion and lateral channel migration, but the body of research on the subject is somewhat contradictory, with some studies indicating that permafrost contributes to channel instability (Scott, 1978). Scott (1978) highlighted the complexity of permafrost impacts on erosion and channel migration, concluding that the role of permafrost varies depending on other factors such as river size (i.e. upstream drainage area), flow intensity, and temporal aspects of high discharge events. Based on a study of Arctic Alaskan rivers, Scott (1978) suggested that small streams and larger rivers respond differently to high-discharge events associated with ice breakup. Rapid high-discharge events in small streams produce minimal erosion owing to the stability offered by frozen bed and bank materials, whereas drawn-out high-discharge events in larger rivers can produce a large amount of erosion as the stability afforded by frozen bed and bank material diminishes over the duration of the event (Scott, 1978). There is a similar contradiction regarding the timing and seasonality of channel forming processes. In some streams, the dominant erosion and channel forming events may be associated with high discharges associated with ice breakup, and in others, ice breakup events have relatively minor control on channel form (Scott, 1978). Streamside vegetation also impacts bank stability and channel erosion, although riparian vegetation north of the sub-arctic is absent or poorly developed (Power & Power, 1995). During the summer, streamside vegetation insulates the ground, maintaining permafrost and enhancing bank stability (Power & Power, 1995). Streamside vegetation also provides ground insulation during the winter by accumulating snow (Power & Power, 1995). Removal of streamside vegetation (e.g. via fire, animal grazing, or human activities) can contribute to bank instability and erosion (Power & Power, 1995).

Turcotte (2021) summarizes flooding processes at 11 locations in Northwestern Canada, focusing on high water levels associated with, or exacerbated by, ice processes such as ice breakup and ice jam. Turcotte (2021) draws attention to some specific events, including the recent and destructive flood event that occurred in Fort Simpson, NT in spring of 2021. During this event, the community of Fort Simpson, situated at the confluence of the Liard and Mackenzie River, was subject to record high water levels (Turcotte, 2021). The extreme water levels, associated with ice breakup and ice jamming processes, reportedly led to the displacement or evacuation of over 700 residents and caused damage to homes and structures in the community (Lamberink, 2021; Paulson, 2021). Extreme rainfall events have also caused occasional flooding in arctic and northern regions as evidenced by the June 2008 flood event in Pangnirtung, NU and the July 2016 flood event in Iqaluit, NU (CBC News, 2008, 2009; Zerehi, 2016). The June 2008 flood event in Pangnirtung, for example, caused two bridges over the Duvall River to collapse, resulting in damages exceeding 5 million dollars (CBC News, 2009).

As described by Vouk et al. (2022), NbS in Arctic and Northern Canada may need to consider the role of permafrost and seasonally-frozen surface soils in regulating erosion, channel migration, and groundwater storage capacity. NbS that rely on groundwater storage will be largely ineffective in the Arctic region where permafrost inhibits infiltration. In addition, evolving trends in precipitation, temperature, and permafrost conditions, in response to climate warming, will add uncertainty to future flooding and erosion processes (J. B. Jones & Rinehart, 2010; Nilsson et al., 2015) and introduce further complexity to the design of NbS.

4.3 Atlantic Provinces

This section provides a short review of primary flooding mechanisms in Atlantic provinces of Canada, which include Newfoundland and Labrador (NL) and the Maritimes – New Brunswick (NB), Nova Scotia (NS) and Prince Edward Island (PEI).

Buttle et al. (2016) provide an in-depth overview of the region's physiography, which is briefly summarized here. Igneous and metamorphic rock formations make up the highlands of NB and Cape Breton (NS), while sedimentary rocks constitute PEI and NS lowlands from Annapolis Valley to the town of Sydney; Labrador consists of metamorphic rock, while Newfoundland is composed of sedimentary, metamorphic, and igneous rock formations. Much (but not all) of NL and the northern Maritimes are covered by boreal forest and, as such, those regions were characterized in Section 4.1. The majority of the Maritimes are covered by mixed-wood forests, while the southern regions are dominated by the Acadian Forest (Vasseur & Catto, 2008). Northern Labrador is dominated by tundra; mixed coniferous and deciduous forests are the norm in southwestern Newfoundland, whereas the lowlands, including interior plateaus and coastal areas, are dominated by broad peatlands (Buttle et al., 2016).

The climate of Atlantic Canada is generally wet and cool, with mean winter temperatures ranging from -8 to -2 °C though summer temperatures can exceed 30 °C (Buttle et al., 2016; Vasseur & Catto, 2008). Mean annual precipitation in the Maritimes ranges between 800 to 1500 mm with southern and coastal areas receiving the higher end of the overall precipitation amounts while the greater amount of snow is observed inland and in northern regions. Annual precipitation in Labrador ranges between 750 and 900 mm with 50% as snow. Newfoundland can see annual precipitation amounts anywhere between 1000 and 2000 mm with snowfall amounts more predominant in the western mountains and along the east coast.

Heavy rainfall with snowmelt and ice-jamming are the main flooding mechanisms in NL (Buttle et al., 2016). In Labrador, flooding is most prominent between the months of April and July, whereas in Newfoundland flooding is possible throughout the year with the greatest flows occurring in the east and southwest regions of the island (Buttle et al., 2016). For a number of Nova Scotia's rivers the most common contributors to inland flooding are heavy rainfalls and sudden thawing events (Burrell, 2011; Webster et al., 2012). Spring floods tend to occur earlier (March) on the NS mainland while floods in Cape Breton are more common in mid-May (Buttle et al., 2016). The majority of the reported flooding events in PEI have been caused by heavy rainfalls resulting from remnants of hurricanes (Bhatti et al., 2022; Burrell, 2011; Vasseur et al., 2017). However, information on riverine specific flooding is lacking. In NB, data have shown that historically damaging floods were driven by rainfall, rain-on-snow events, ice-jamming, or a combination thereof (Burrell, 2011). Regions that experienced some of the most severe flooding in the province reside along the lower Saint John River and its tributaries from Fredericton to Saint John, though flooding is possible on many rivers throughout the province (Burrell, 2011; Olthof, 2017). For example, the Nashwaak River flooded with adverse effects 42 times over a time span of 180 years (Prowse et al., 1989). Peak flows in the province usually occur between the months of March and May, but are most notable in northern NB (Buttle et al., 2016). Examining 13 different hydrometric stations in the province, Anderson (2008) compared changes to flood dynamics over the historical record, finding that spring floods were occurring earlier in the year and the frequency of mid-winter ice-breakup was increasing which destabilized ice regimes leading to more uncertainty in ice-jamming predictions. Hare et al. (1997) theorized that the increase of high intensity rainfalls could exacerbate the spring freshet, which was witnessed in 2008, and even more recently in 2018 and 2019.

Dietz and Arnold (2021) suggested that streamflow in Atlantic Canada will increase with the changing climate. Using regional climate modelling and an ensemble of climate change scenarios, Teufel and Sushama (2021) predicted that a +2 °C global warming scenario will not significantly change flood generating mechanisms in Atlantic Canada. However, using a high emissions scenario (RCP8.5) the authors projected that portions of Atlantic Canada will become rainfall dominated and will see as much as a 30% increase in annual maximum streamflow in NS and eastern Newfoundland.

A number of NbS initiatives in Atlantic Canada address coastal erosion and flooding such as (but not limited to) protection of coastal salt marshes through managed dyke realignment, beach and dune resiliency via intertidal reefs, and coastal preservation by restoring living shorelines (Bowron et al., 2020; Davies & Thompson, 2019; Dietz & Arnold, 2021; van Proosdij et al., 2021; van Proosdij & Page, 2012). NbS initiatives addressing riverine flooding and erosion in Atlantic Canada seem fewer in number, but do exist. In the Nashwaak River watershed, efforts are being made to restore Campbell Creek and mitigate erosion through natural revegetation (Nashwaak Watershed Association, 2023).

4.4 Québec

The majority of the province of Québec is covered by the Boreal Zone, which is discussed in Section 4.1, except for the southern portion of the province along the St. Lawrence River. The upper watershed of the St. Lawrence River is dominated by the St. Lawrence lowlands composed of fertile plains "covered by surficial deposits" and dominated by urban and agricultural land use (Natural Resources Canada, 2006; Saint-Laurent et al., 2009). East of the lowlands are the Appalachian Mountains extending to Gaspésie and into the Maritimes (Buttle et al., 2016; Natural Resources Canada, 2006; Saint-Laurent et al., 2009). The climate in Québec is primarily made up of long, cold winters and cool to mild summers (Alberti-Dufort et al., 2022).

Many of the headwaters of St. Lawrence River's south shore tributaries are located south of the Canadian border in the US (e.g. Saint-Francois River, Richelieu River) in mountainous areas dominated by forest and scattered with valleys and hills (ILCRRSB, 2019; N. K. Jones, 1999, n.d.; Saint-Laurent et al., 2009). The mechanisms of flooding are similar in nature. For example, through extensive studies of the Saint-Francois River and its tributary the Massawippi River, Saint-Laurent et al. (2009) and N. K. Jones (1999, n.d.), respectively, observed similarity in flooding regimes. The authors found that the majority of high/flood flows in the watersheds occurred in March and early April during spring freshet as a result of heavy rain over a large snowpack, leading to road closures, damages to properties, and inundation of low-lying agricultural fields. In addition, ice jamming along major river confluences and constrictions, where ice and water build-up during ice cover break-up, can exacerbate flood hazards and cause bridge collapses and road closures (N. K. Jones, n.d.). Spring rain-on-snow events in the Lake Champlain watershed and upstream tributaries of the Richelieu River have contributed to flood hazards in the lower part of the Richelieu River basin (ILCRRSB, 2019). In fact, the largest flood recorded in the basin occurred in the spring of 2011 lasting for 69 days as a result of heavy snowpack, unusually warm temperatures, and unprecedented amounts of spring precipitation. Additionally, wind setup on Lake Champlain caused by intense winds during this time period increased the Richelieu River's water levels (ILCRRSB, 2019). The spring season is not the only time of year when flood hazards have been observed in this area. Sudden temperature increases during the winter (i.e. December to February) have melted the snow cover and, in combination with heavy rainfall events, have instigated flooding (N. K. Jones, n.d.). In the summer, flash floods in response to long-duration heavy rainfalls and tropical storms have caused flooding in the region (Gagnon et al., 1970; ILCRRSB, 2019). These events have also resulted in erosion of unstable hillside barren lands and debris flow. Flooding has also been observed in the fall where remnants of hurricanes with intense rainfall can cause flash floods. Studies have shown that climatic conditions are not the only cause of high flows in the area. Anthropogenic changes to the land cover, including deforestation, increased imperviousness in floodplains, draining wetlands for agriculture, and development along river banks, all lead to flashier flows (ILCRRSB, 2019; Saint-Laurent et al., 2009).

Similar to the south shore watersheds other tributaries to the St. Lawrence River have experienced devastating flood effects (Lapointe et al., 1998). Recently, in May of 2023, severe flooding of the Rivière du Gouffre in the region of Charelvoix washed away roads and forced several communities to declare emergencies (CBC News, 2023).

Some modelling studies predict an increase in lengthy dry events across Québec in the future, but “interspersed with more intense flooding events in summer and fall across Southern Quebec” (Alberti-Dufort et al., 2022). In addition, increased mean winter flows and earlier spring freshet are projected as a result of climate change. Teufel and Sushama (2021) predicted a more wet southern Québec in a +2 °C global warming scenario.

There are a number of NbS initiatives and examples in Québec. For example, in 2021, Infrastructure Canada and the City of Montreal announced investments to protect the Island of Montreal’s shorelines from erosion (Infrastructure Canada, 2021b). As the news article states: “The project aims to rehabilitate and secure some 10 km of shoreline using bioengineering-inspired techniques, such as planting shrubs and vegetation, which will help better manage the impacts of erosion and protect shoreline ecosystems and communities.” In 2014, a research team from Québec provided guidance to enhance river resilience through sustainable management approaches that embrace “Freedom Space” for river systems (Biron et al., 2014). Demonstrating their approach in three rivers in Southern Québec and Gaspésie, Biron et al. (2014) proposed three levels of freedom space based on expected flood severity and channel mobility. The different levels of freedom space reflect the space required for various fluvial process to occur, providing context for river corridor management.

4.5 Southern Ontario

Southern Ontario is situated within the Great Lakes and Ottawa River drainage basins and is comprised of diverse landscapes with generally modest relief that are dominated by forest, agriculture, and water bodies (Buttle et al., 2016; Sangal & Kallio, 1977; Zahmatkesh et al., 2019). The region contains a number of distinct physiographic features including: the Oak Ridges Moraine, a significant feature within Ontario’s Greenbelt, which is made up of sand and gravel; the Algonquin highlands, a high relief area within the Canadian Shield, which is dominated by rock outcrops; the eastern regions belonging to the St. Lawrence-

Ottawa lowlands which are low lying; and the Niagara Escarpment which is comprised of bluffs and cliffs on the scale of 100 to 300 m in size (Ministry of Municipal Affairs, 2017; Sangal & Kallio, 1977). In regions outside of the Canadian Shield the soils are quite productive and agricultural fields dominate much of the area, which is highly populated and becoming more urbanized (Sangal & Kallio, 1977; Zahmatkesh et al., 2019).

The climate in Southern Ontario is strongly influenced by the Great Lakes (Buttle et al., 2016). The summers tend to be warm to hot and humid with total precipitation between 400 and 600 mm and average temperatures between 16 and 22 °C, with higher temperatures in the southwestern portions of the region (Colombo et al., 2007; Zahmatkesh et al., 2019). Winter precipitation ranges between 300 and 600 mm depending on geographic location, with the greatest amounts exhibited along the shores of Lake Huron. The warmest mean winter temperatures are just below 0 °C in the Toronto to Sarnia corridors along Lake Ontario and Lake Erie, while the Algonquin highlands exhibit the coldest mean winter temperatures between -10 and -15 °C (Colombo et al., 2007). Average winter temperatures elsewhere in Southern Ontario vary between -5 and -10 °C. At times, the winter temperatures can drop to severely cold levels, such as recently reported temperatures below -40 °C in Algonquin Park (ECCC Weather Ontario, 2023). Mean annual snowfall ranges from less than 100 cm to more than 300 cm, with the amount of precipitation from snow ranging from less than 20% in the south to more than 30% in the north (Ontario Ministry of Natural Resources, 1984) via (Buttle et al., 2016).

The main causes of flooding in Ontario are snowmelt, heavy rainfalls, ice jams, and high lake levels and storm surges (Emergency Management Ontario, 2023). For example, flooding along the Grand River has been described as a result of any of the following: sudden snowmelt, rain-on-snow events, localized ice-jams, extreme localized rain storms, rain falling on frozen or saturated ground, and storm surge from Lake Erie (McNeil, 2019). Snowmelt in Ontario typically starts in March, though bouts of snowmelt in January and February are common occurrences (Zahmatkesh et al., 2019). Studying 547 historical flood events between the years of 1680 and 1989, Shrubsole et al. (1993) found that 66% of Ontario floods occurred between the months of February and May and were caused by a combination of snowmelt, rainfall, and in some cases ice-jamming. Summer and fall floods are also possible in Southern Ontario. They are generally caused by hurricane remnants and heavy rainfalls (Shrubsole et al., 1993). In the City of Toronto, Canada's most populated city, the most significant floods take place in the summer. They are caused by intense short-duration rainfalls, or long-lasting high-volume rainfalls (Nirupama et al., 2014). In fact, one of the largest flooding events in the region occurred in 1954 when *Hurricane Hazel* deposited a record rainfall of up to 285 mm in 48 hours in some regions, resulting in 81 casualties and sweeping away bridges and a number of homes (Cumming Cockburn Limited, 2000; Nirupama et al., 2014; Ontario Ministry of Natural Resources, 2001). The occurrence of such events incited the identification of flood hazard zones in Ontario and the policies that now guide the province (Ontario Ministry of Natural Resources, 2001). Spatially narrow, localized storms have also caused challenges in the region. In August of 2018, a localized storm deposited over 100 mm of rain in less than two hours, causing a Toronto stream (Black Creek) to rise over two meters in less than two hours (McNeil, 2019). The storm, circumventing detection by local gauges, was not forecasted; yet was large enough to cause flooding of nearby properties.

In the spring of 2019, widespread flooding occurred in Southern Ontario. McNeil (2019) embarked on a comprehensive review of flooding mechanisms and resulting flood damages which are further summarized in the following text (floods in 2017 and 2018 were also reported but have been omitted in this report). In April of 2019, the Ottawa River water levels surpassed its banks in Ontario and Québec, flooding towns and adjacent communities. At the time, the majority of the watershed was heavily weighed by an excessive snowpack (more than 200 mm excess of snow water equivalent (SWE), and upwards of 188% SWE of normal values). Precipitation exceeded average amounts for that time of the year (between 125% and 175% of normal for the months of April and May). This massive flood event was generated by a large rainfall event accompanying a peak snowmelt event. During the same time period a heavy rain-on-snow event along the Muskoka River led to the highest flows on record. The nearby Magnetawan River surpassed bank flows flooding the village of Katrine, caused by a heavy snowpack (recorded SWE amounts were 260% of normal) and subsequent snow-melt. A rain-on-snow event in mid-March caused an ice-jam in the town of Caledon, flooding a number of homes and leading to home evacuations. The same year saw record precipitation along the Great Lakes with above average water levels. For perspective, the total inflow into Lake Ontario in May 2019 was “the second highest inflow of any month of the year dating back to 1900” (McNeil, 2019). Lake Erie also experienced high water levels during the summer of 2019, which eroded large blocks of peat from marshlands in Rondeau Bay and the town of Leamington. The Lake Erie shoreline in this area is primarily made up of clay soils that erode naturally from wave action. However, the erosion of the shore can be exacerbated by high water levels. Shoreline hardening has disrupted the sediment balance of the lake causing barrier beaches, such as those within Rondeau Bay, to erode from lack of soil deposition. It is important to note that high water levels and subsequent wave action not only affect shorelines of lakes, but also river banks of discharging tributaries.

Emergency Management Ontario (2023) decreed that “floods are the costliest natural hazard in terms of property damage in Ontario”. In 2017, a precipitation event in Essex Region and the Lower Thames Valley, exceeding the region’s local pumping scheme and dyke design standards, causing over $300 M in insurable losses (McNeil, 2019). Many areas along Lake Erie that are at risk of flooding are also at great risk of erosion, as evidenced by road closures and bluff failures near existing and new developments. Flood events in Toronto have caused erosion of streams, creeks, and ravines resulting in failures to infrastructure, such as bridges and roads (Nirupama et al., 2014). In 2013, a precipitation event during rush hour caused flooding of the Don River, stranding thousands of commuters and over 1400 passengers on the GO Train resulting in approximately $1B in insurable losses (McNeil, 2019).

In 2001, the Ontario Ministry of Natural Resources with Trent University’s Watershed Science Centre (Ontario Ministry of Natural Resources & Watershed Science Centre, 2001) developed a comprehensive guide for stream restoration and naturalization through adaptive management. The document was written with Southern Ontario in mind, but was meant to be transferrable to other jurisdictions. There are many examples of stream restoration projects in Southern Ontario including, for example, the Wilket Creek Rehabilitation Project in Toronto, Ontario. During extreme flow events, this highly urbanized stream experienced significant erosion issues engendering risk to nearby infrastructure and public safety, which prompted its rehabilitation to a more natural state (Papangelakis & MacVicar, 2020; Toronto and Region Conservation Authority, 2023).

4.6 Prairies

The prairie region spans the southern portions of the Canadian interior provinces of Alberta, Saskatchewan, and Manitoba. The region has a general west-to-east slope (Buttle et al., 2016). Major river systems include the eastward-draining North and South Saskatchewan Rivers, and the northward-draining Red River. The North and South Saskatchewan River (including major tributaries such as the Bow, Oldman, and Red Deer Rivers) headwaters originate in the Western Cordillera region, along the eastern slopes of the Rocky Mountains (Andrews, 1993). Conversely, the Red River (including major tributaries such as the Qu’Appelle, Souris, and Assiniboine Rivers) headwaters originate in the prairie landscape.

The prairie region is characterized by flat or gently rolling landscapes, dominated by grassland vegetation, although the landscape has been heavily modified by agricultural practices (Buttle et al., 2016; Pattison-Williams et al., 2018). Surface water drainage systems are poorly developed owing to the low-relief topography; many surface water bodies and wetlands are internally drained and do not contribute to river flows except during extreme surface water accumulation and flood events (Andrews, 1993; Buttle et al., 2016; Pattison-Williams et al., 2018). These internally-drained surface water bodies and wetlands, such as pothole lakes, play an important role in the regional hydrology by controlling river flows through off-channel storage (Pattison-Williams et al., 2018). The region is susceptible to flooding during extreme runoff events, driven by convective storms, owing to the low topographical relief (Pattison-Williams et al., 2018).

Most historical river flooding events were associated with spring snowmelt runoff over frozen soils as well as spring and early summer rainfall events (Andrews, 1993; Buttle et al., 2016). Spring runoff volumes are also influenced by antecedent soil moisture conditions which are linked to precipitation volumes in the preceding fall and winter prior to freeze up (Manitoba Water Stewardship, 2009). Past research indicates decreasing trends in spring snowmelt runoff volume and peak flows, linked to a combination of reduced snowfall and warmer winter temperatures (Akinremi et al., 1999; Burn et al., 2008).

A number of impactful river flooding events that occurred in the prairie region are well documented in media resources and literature. In particular, flooding events in the Red River catchment are common and there are a number of historic events that have caused substantial damages, including those occurring in 1950, 1997, 2009, and 2011 (Burn, 1999; Province of Manitoba, n.d.b). This susceptibility to flooding has inspired major flood mitigation measures such as the Red River Floodway and community ring dikes (Province of Manitoba, n.d.a). Extreme flood events in the prairie region can cause a variety of immediate and long-term consequences, including damage to infrastructure in both urban and rural areas. In rural areas, specifically, extreme flood events can also damage agricultural equipment, drown livestock, and delay spring planting (Andrews, 1993).

Riverine erosion hazards and consequences in the prairie region have also been documented in literature. These erosion hazards are largely linked to bank instability and slope failure (i.e. landslide) events along river banks and valley walls (Baracos & Graham, 1981; Clifton et al., 1981; Ruban, 1983). Clifton et al. (1981) and Baracos & Graham (1981) described a number of damaging landslide events in the Saskatoon and Winnipeg area, respectively. A recent article from CTV News (2021) described a slope failure event along the Red River in 2020 that consumed a large portion of the backyard of a residential property. These slope failure events are influenced by groundwater conditions, local geology, anthropogenic factors (e.g. anthropogenic impacts on groundwater), and flow-induced erosion of river banks (Baracos & Graham, 1981; Clifton et al., 1981; Kimiaghalam et al., 2015; Ruban, 1983). Erosion hazards in this region are exacerbated by increased pressure for development near river banks and inadequate development setbacks associated, in part, with historical development that predated comprehensive understanding of the risks (Baracos & Graham, 1981; Clifton et al., 1981).

NbS in the prairie region may need to consider the limited capacity for groundwater storage during the spring season and the importance of wetland surface water storage (Pattison-Williams et al., 2018). For example, the Pelley's Lake Wetland Restoration Project in south-central Manitoba provides flood mitigation services by storing surface water runoff during the spring, while offering a variety of co-benefits including nutrient retention, carbon sequestration, and enhanced wildlife habitat (Berry et al., 2017; Vouk et al., 2021). The restored wetland also supports cattail growth, which can be harvested for bio-fuel, providing economic benefits to the landowners (Berry et al., 2017).

4.7 Western Cordillera

Canada's Western Cordillera region spans the majority of British Columbia and Yukon, as well as the western portions of Alberta and Northwest Territories (Buttle et al., 2016). The region is comprised of three main mountain systems including the Rocky Mountains (in the eastern portion of the region), the interior mountains and plains, and the Coast Mountains (in the western portion of the region) (Buttle et al., 2016; Monger & Price, 2002). The region can be further subdivided into 10 subregional areas as shown in Figure 3 (Natural Resources Canada, 2019). There is large variability in local climates and vegetation throughout the region owing to the rugged terrain and variability in elevation (Buttle et al., 2016). The mountains of the Western Cordillera create a "rain-shadow" effect, where most precipitation falls on windward slopes, leaving lee-ward slopes relatively arid (Buttle et al., 2016; Demarchi, 2011). Coniferous forests are widespread within the region, although other vegetation types thrive in specific, subregional and local areas (Demarchi, 2011). For example, steppe vegetation dominates in valleys and river basins of the southern interior and muskeg and black spruce dominate in low-lying, poorly-drained areas of the north (Demarchi, 2011). Alpine areas above the treeline are characterized by tundra vegetation (Buttle et al., 2016). A detailed summary of ecoregions and vegetation in British Columbia is available in Demarchi (2011).

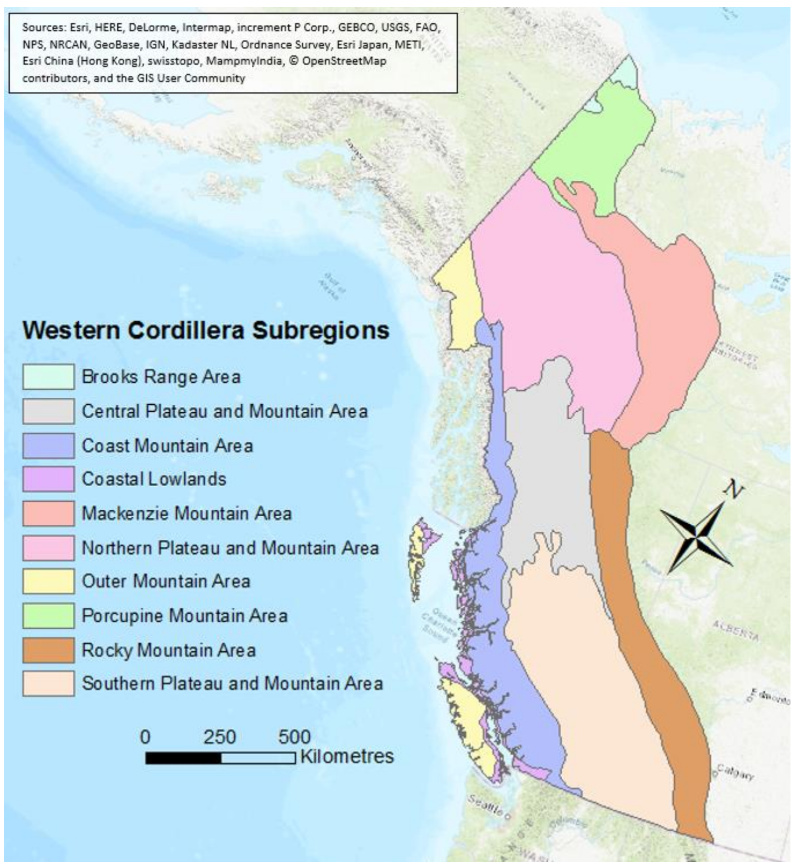

Figure 3. Subregions of Canada's Western Cordillera. GIS data for this figure were sourced from Natural Resources Canada (2019).

There are a number of processes and mechanisms that influence river flows in the Western Cordillera region. Snowmelt, rainfall, and rain-on-snow events can all contribute to high flows (Buttle et al., 2016; Curry et al., 2019; Neiman et al., 2011; Pomeroy et al., 2016; Teufel et al., 2017; Woo & Liu, 1994). However, the relative contribution of each of these flow-generating processes varies depending on the geographic location within the region as well as the characteristics of the watershed (Waylen & Woo, 1983; Woo & Liu, 1994). In general, there is an eastward transition from rainfall-dominated floods to snowmelt-dominated floods (Waylen & Woo, 1983). Buttle et al. (2016) describe other types of floods as well including ice jam floods, debris floods, avalanche and landslide generated floods, and glacial outburst floods.

Atmospheric river events (commonly referred to as “Pineapple Express” in this region) deliver large quantities of moisture to the Western Cordillera (Curry et al., 2019; Neiman et al., 2011; NOAA, 2021). Moisture delivered via atmospheric rivers may fall as rain, contributing directly to runoff, or as high-elevation snow, contributing to snowpack accumulation (Curry et al., 2019; NOAA, 2021). Presently, most peak river flows in the Fraser River basin are generated by snowmelt during the spring freshet with relatively fewer peak flows generated by direct rainfall events (Curry et al., 2019). However, future climate trends suggest an increase in landfalling atmospheric rivers in the Western Cordillera and an increasing fraction of precipitation that will fall as rain (Curry et al., 2019). This future trend may result in a shift towards more rainfall generated peak flows, less snowpack accumulation, relatively fewer snowmelt-driven peak flows, and more potential for peak flows to occur outside of the freshet season (Curry et al., 2019).

Some historical floods in the Western Cordillera region were responsible for some of the costliest and most destructive natural disasters in Canada. Based on insured losses, the June 2013 Alberta flood is the second-costliest natural disaster in Canadian history to date (1.7 billion dollars in insured losses); the costliest natural disaster in Canadian history is the May 2016 Fort McMurray, Alberta wildfires (Reuters, 2021). The June 2013 Alberta flood caused damages and undesirable consequences in the Western Cordillera region (e.g. Canmore, Alberta) as well as in the neighbouring prairie/interior plains (e.g. Calgary and High River, Alberta). However, high river flows were mostly driven by hydrologic processes in the Rocky Mountain subregion of the Western Cordillera, where a combination of precipitation, snowmelt, rain-on-snow, and frozen soil conditions led to high surface runoff (Teufel et al., 2017). This flood event has been studied in detail and hydrologic and climatological processes associated with the event are well-documented in scientific literature (Fang & Pomeroy, 2016; Liu et al., 2016; Pomeroy et al., 2016; Teufel et al., 2017). More recently, extensive and destructive flooding and extreme river flows occurred in several locations across British Columbia in November 2021 owing to a series of atmospheric river events (Charlebois, 2021). This flood event has not yet been well-investigated and documented in the scientific literature. However, there are an abundance of news articles and online resources that describe the event and associated consequences, including loss of life (University of Victoria, 2022). The event produced widespread flooding in lowland areas (e.g. the Sumas Prairie area) as well as channel erosion and migration, causing extensive damage to major transportation infrastructure (e.g. the Coquihalla Highway and Highway 8) (CBC News, 2021; Charlebois, 2021; Judd, 2021; University of Victoria, 2022).

Landslide and glacial outburst mechanisms can also cause flooding in the Western Cordillera region. In November 2020 a massive flood event in Elliot Creek, located in the traditional territory of the Homalco First Nation in the southern Coast Mountains of British Columbia, was triggered by a glacial outburst event (Geertsema et al., 2022). The glacial outburst was triggered by a landslide which deposited 18 million cubic-metres of rock debris into the upstream glacial lake, creating a wave that overtopped the lake outlet (Geertsema et al., 2022). Owing to the remoteness of the area, there was no damage to built infrastructure, nor were there any reported fatalities. However, the event caused extreme channel scour and destruction of forest and salmon habitat (Geertsema et al., 2022). Despite having potential to generate intense river flows and scour, Carrivick & Tweed (2016) indicated that many glacial outburst floods in British Columbia occur far away from people and built infrastructure and, therefore, the reported economic impacts are often low.

Vouk et al. (2022) describe some recent and ongoing initiatives to integrate NbS into river flooding and erosion risk management in the Western Cordillera region including the Peach Creek and Hooge Wetland Restoration Project and the Nicomekl Riverfront Park Project (City of Surrey, 2020; Fraser Valley Watersheds Coalition, n.d.). Both projects are situated in south-western British Columbia in the Fraser Valley lowland. The projects include channel and floodplain restoration works that enhance accommodation of floodwater within the project sites, essentially promoting connectivity between the main channel and floodplain features (e.g. side-channels, wetlands, and park spaces). In addition to providing flood mitigation services, both projects also enhance off-channel aquatic habitat.

5 Discussion

Nature-based solutions mimic natural system processes to manage flood and erosion risk. Therefore, a fundamental understanding of flood and erosion generating processes, as well as anthropogenic factors that influence these processes, is an essential precursor for design and implementation of NbS. The information presented in Section 4 provides an overview of river flooding and erosion processes across Canada's diverse landscape, and highlights some implications for NbS. This section synthesizes some general findings and observations based on the summaries presented in Section 4.

Land uses and development vary widely across Canada. For example, some areas are comprised of natural landscapes that are largely unaffected by direct human intervention and development, whereas other areas are heavily modified by agriculture or urban development. Although some landscapes may not be impacted by direct anthropogenic development, it should be noted that they may be impacted by global anthropogenic drivers that influence the climate. Landscapes that are not directly impacted, or are minimally impacted, by anthropogenic development present an opportunity for preservation. Decision-makers are encouraged to consider the value of natural system processes, and their ability to alleviate flood and erosion risks, when making development and land use decisions. For example, it may be more valuable to preserve the natural flood and erosion management functions provided by the natural features than it would be to develop the land and potentially face future costs to mitigate damage to infrastructure or support disaster relief. Inadequate valuation of NbS and natural system services has been highlighted as a barrier to broader uptake of natural and nature-based strategies (Eyquem, 2023; Vouk et al., 2021). Eyquem (2023) presents several tools that are available to support appraisal and valuation of NbS. Valuation case studies such as Anielski & Wilson (2005) also provide valuable reference material for practitioners and decision-makers. If development is necessary in natural areas, it is best done in a manner that minimizes negative impacts to natural system functions, and promotes proactive hazard avoidance (e.g. establishing setbacks that accommodate natural flood and erosion processes) as opposed to reactive mitigation (e.g. construction of barriers that mitigate flood or erosion hazards). This ideology is aligned with recent, international guidance from the U.S. Army Corps of Engineers (Haring et al., 2021):

> Floods in natural rivers (defined here as rivers unaffected or almost unaffected by humans) are not considered to be major events or even catastrophes. A disaster starts when the river floods areas where there is human occupation or economic activity.

Some regional flood and erosion processes are quite unique and location-specific. For example, glacial outburst floods are unique to the Western Cordillera, permafrost impacts on infiltration and runoff are unique to Arctic and northern Canada, and post-tropical cyclones (i.e. the remnants of hurricane events) are unique to the eastern part of the country. However, there are some common themes that are applicable to all regions. Many spring flood and erosion events across Canada are caused by various combinations of snowmelt, rainfall, and rain-on-snow events that contribute to large volumes of runoff over frozen or moisture-laden ground with limited capacity for infiltration. However, large flood and erosion events are not exclusive to the spring season (e.g. Hurricane Hazel in Ontario). In many parts of the country, spring floods can also be exacerbated by ice jam events. Practitioners and decision-makers should be mindful of seasonal nuances when selecting and designing NbS. For example, NbS that aim to attenuate peak river flows by promoting subsurface infiltration may have limited capacity to impact spring runoff until the ground is sufficiently thawed. Likewise, NbS that employ vegetation to manage flooding and erosion risks should consider seasonal variation of the vegetation itself.

Historical flood and erosion observations and scientific research provide valuable reference material for nature-based design. Practitioners and decision-makers should be mindful of how potential changes within the watershed may influence their study site and, likewise, how interventions at their study site may influence other areas within the watershed. Recent guidance from CSA Group stresses the importance of adopting a whole-system, watershed-scale approach to manage flood and erosion risk in Canadian river systems (Eyquem, 2023). Practitioners and decision-makers should also be mindful of potential changes to Canadian climates and associated impacts on flooding and erosion and viability of NbS. For example, many sources have highlighted long-term trends and potential changes in temperature, snowmelt, precipitation, and permafrost as well as potential impacts on hydrologic, hydraulic, and geomorphic processes in various regions of Canada (Akinremi et al., 1999; Aygün et al., 2020; Burn et al., 2008; Curry et al., 2019; Gaur et al., 2018; J. B. Jones & Rinehart, 2010; Nilsson et al., 2015; Nolin et al., 2022; Teufel & Sushama, 2021; Zhang et al., 2019). Projected changes in various climatological parameters across Canada are presented in *Canada's Changing Climate Report*, including projections for temperature, precipitation, snow, ice, and permafrost (Bush & Lemmen, 2019).

6 Conclusions

A review of existing literature, reports, and examples was completed to improve understanding of riverine flooding and erosion across Canada's diverse and varied landscape, as well associated hazards and risks. The report summarizes mechanisms that cause, contribute to, or affect river flooding and erosion, including a discussion of regional climates, physiography, hydrology, and other relevant factors. Findings were synthesized to highlight implications for NbS in different geographic regions. A brief overview of relevant programs and funding mechanisms available in Canada was also presented. This report provides foundational information towards development of future guidelines for design and implementation of NbS for flood and erosion risk management in Canadian river systems.

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8 References

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