Advancing the Climate Resilience of Canadian Infrastructure:

A review of literature to inform the way forward

IISD REPORT

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July 2021

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This project has been made possible by the Government of Canada.

Canada

Foreword

This report was prepared by the International Institute for Sustainable Development (IISD) for Infrastructure Canada. It reviews the current literature on climate change hazards, impacts, and adaptation options for six types of built infrastructure across Canada and looks at the complementary role of natural infrastructure solutions in building climate resiliency. The report examines existing policies, guides, standards, codes, and financing programs at the federal level in Canada that inform and incentivize climate-resilient infrastructure, both built and natural. International examples of policies, principles, and tools that can inform Canada's efforts are highlighted. The paper concludes by drawing attention to the need for greater action in areas such as increasing the availability of assessment and planning tools, deepening knowledge of resilience-building approaches, enhancing monitoring and maintenance of infrastructure, diversifying sources of finance, and facilitating the integration of built and natural infrastructure solutions.

Acknowledgements

IISD and the authors would like to thank Infrastructure Canada for its financial support and the technical input provided by Chad Nelson, Daniella Echeverría, Catherine Bulman, and Claire O'Manique which enabled the preparation of this report. We also thank representatives from Environment and Climate Change Canada, Infrastructure Canada, the National Research Council, Natural Resources Canada, Parks Canada, Public Services and Procurement Canada, the Standards Council of Canada, Transport Canada, and the Treasury Board for the informal review of this report; Jo-Ellen Parry (IISD) for her input on its content; Savannah Sarosiak-Larter for her background research; Catherine Burge (IISD) for her support on the development of the report's accompanying infographics; and Elise Epp (IISD) for her design work on this report and its infographics.

Executive Summary

Relying on past climate parameters when making decisions related to maintaining existing infrastructure and building anew is no longer an option. Canada's climate has changed and will continue to do so—driving associated shifts in precipitation levels, sea levels, sea ice coverage, glacial retreat, wind speed, and permafrost stability (Bush & Lemmen, 2019). Our country has already seen an increase in the frequency and intensity of extreme weather events such as floods, forest fires, and snowstorms, all of which have had costly impacts on human lives, economies, and ecosystems. These changes have clear implications for Canada's built and natural infrastructure.

This report is intended to inform and create awareness of an integrated, whole-of-society approach to making infrastructure across Canada resilient to a changing climate. Written for infrastructure owners, designers, builders, operators, investors, policy-makers, and stakeholders, it provides a snapshot of the substantial progress of efforts to increase the climate resilience of Canadian infrastructure since the International Institute for Sustainable Development published its 2013 report, *Climate Change Adaptation and Canadian Infrastructure* (Boyle et al., 2013). The report compiles available information on the impacts and risks of climate change for Canada's infrastructure from a regional perspective and for six types of built infrastructure. Illustrative examples of current technical solutions to addressing these risks are also presented. In addition, it summarizes the range of natural infrastructure solutions that are available to enhance the resilience of communities to climate change. To better understand actions being taken to improve the climate resilience of Canadian infrastructure, the report synthesizes a range of current policies, guidelines, and financing being implemented federally and internationally to inform and incentivize climate-resilient infrastructure. A comprehensive review of the vast array of policies, guidelines, and financing delivered by provinces, territories, municipalities, and Indigenous communities was not possible within the scope of this report.

The review identified a range of climate hazards and impacts that present risks for different types of Canadian infrastructure. These are described in detail in Section 3.2 with examples illustrated in Table ES1, including:

- **Land transportation infrastructure**: Softening and rutting of roads due to more frequent heatwaves and a shorter winter ice road season due to warming.
- **Buildings**: Threats to the integrity of building foundations as seasonal temperature increases degrade permafrost, leading to subsidence and buckling.
- **Water supply infrastructure**: Reduced sources of potable water due to greater frequency of drought.
- **Wastewater and stormwater infrastructure**: Overwhelmed drainage and stormwater infrastructure as changing precipitation patterns increase the intensity of heavy downpours and flooding.

- **Marine infrastructure**: Damage to ports and coastal infrastructure as sea levels rise and storm surges increase erosion.
- **Energy and information and communications technology (ICT) infrastructure**: More frequent power outages as winter storms and high winds compromise utility lines and potential overheating of data centres due to increased temperatures and heatwaves.

Such events may occur individually but can also lead to cascading infrastructure failures due to the interconnectedness of many systems and their associated climate risks (Council of Canadian Academies, 2019).

Sector experts recommend three categories of options for improving the climate resiliency of infrastructure—planning and assessment, monitoring and maintenance, and structure changes. An essential first ingredient observed in the literature is climate change-informed planning and assessment. Associated actions include performing climate risk assessments using accepted methodologies, along with siting and designing infrastructure based on climate change projections. Enhanced monitoring and maintenance is another key aspect for climate-resilient infrastructure, such as in relation to snow and ice accumulation and foundation movements due to permafrost melting. The critical third ingredient involves structure changes that can increase the resilience of infrastructure components. Examples of structure changes that promote climate resiliency include:

- **Land transportation infrastructure**: For example, the use of geotextiles for resilience to permafrost, increasing culvert capacities to manage increased precipitation and snowmelt, and using tree hedgerows for protecting roadways from snow accumulation and wind gusts.
- **Buildings**: For example, green roofs for managing increased temperatures and heatwaves and installation of backwater valves and sump pumps to reduce flooding due to increased precipitation.
- **Water supply infrastructure**: For example, increased surface and groundwater storage and retention for drought management, including constructed wetlands, rain gardens, and bioretention systems.
- **Wastewater and stormwater infrastructure**: For example, increased drainage capacity, culvert debris clearing, and use of permeable pavement in urban areas to better manage more intense storms.
- **Marine infrastructure**: For example, raised infrastructure, floating buildings, dunes, salt marshes, and marine forests to protect against storm surges and sea level rise.
- **Energy and ICT infrastructure**: For example, fortifying against flooding by elevating electrical substations and electrical components, burying distribution lines and using microgrids for protection and redundancy against summer and winter storms, and increasing the cooling capacity of data centres to cope with higher temperatures.

Natural infrastructure is also becoming a mainstream option for enhancing the resilience of built infrastructure and communities. In Canada, a diverse range of natural infrastructure solutions have been used to address climate change hazards, including salt marshes and maritime forests to address coastal flooding; wetlands and riparian buffers to address riverine flooding; permeable pavement and retention ponds to improve urban and rural stormwater management; and green roofs and trees to increase resilience to extreme heat in cities. These nature-based solutions also generate a range of co-benefits, such as biodiversity habitat, carbon sequestration, recreation, water purification, and mental well-being. Studies show that natural infrastructure is cost effective and is often a more efficient use of funds compared to relying solely on built infrastructure to adapt to climate change and increase resilience. Natural infrastructure, though, also can be affected by various climate hazards, and its own resilience should therefore be ensured through planning and assessment, structural changes, and ongoing monitoring and maintenance.

A diverse range of strategies, policies, guides, standards, codes, and financing programs have emerged at the federal level in Canada to help inform adaptation efforts for infrastructure. Many of these initiatives have been led by Infrastructure Canada. For instance, it has created a climate resilience assessment guidance for infrastructure that is a requirement for certain federal funding mechanisms. To develop new future climate design data, guidelines, standards, and codes, Infrastructure Canada funded the National Research Council-led Climate-Resilient Buildings and Core Public Infrastructure Initiative (2016–2021) and collaborated with the Standards Council of Canada. Infrastructure Canada also supports climate-resilient public infrastructure projects under the Green Stream of the Investing in Canada Infrastructure Program and the Disaster Mitigation and Adaptation Fund, as well as capacity building through the Municipalities for Climate Innovation and Asset Management programs implemented by the Federation of Canadian Municipalities.

While a number of steps have been taken to increase the climate resiliency of infrastructure, **greater effort and investment are needed if Canada's ageing infrastructure is to keep up with accelerating climate change and close the infrastructure gap**. The estimated infrastructure deficit in Canada is believed to range anywhere from CAD 150 billion to CAD 1 trillion, and critically, the gap in First Nations infrastructure alone is estimated at between CAD 25 billion and CAD 30 billion (Advisory Council on Economic Growth, 2016). Such statistics are particularly urgent in light of the results of the 2019 Canadian Infrastructure Report Card, which concluded that "a concerning amount of municipal infrastructure in Canada is in poor or very poor condition" (BluePlan Engineering, 2019, p. 9). Because infrastructure assets have long lifespans, it is important that decisions made while closing this gap look to the future, recognizing that climate-resilient infrastructure builds community resilience over the long term. To achieve this objective, greater effort is needed in areas such as increased use of climate risk assessments and climate projections for infrastructure design, and the development and use of updated building codes and natural infrastructure solutions. To finance these changes, there is a need to move beyond federal–provincial–territorial funding mechanisms to leverage the full potential of sustainable finance and risk-informed investment in the public, private and cooperative/mutual business sectors. In the context of the current pandemic, when public spending is strained, ensuring maximum value from infrastructure investments is essential, a sentiment reflected by extensive calls for a "green recovery" by such groups as the Task Force for a Resilient Recovery (2020) and the Canadian Construction Association (2021).

The benefits of acting now are significant. The Council of Canadian Academies, in addition to ranking damage to physical infrastructure as Canada's most consequential climate risk, highlighted that infrastructure is the top sector for climate resilience potential in Canada, as measured by the proportion of damages that can be avoided through adaptation policy and programs. There is abundant evidence for this ranking. For instance, the benefit-cost ratio for Canada's National Guidelines for the Flood Resistance of Buildings is estimated at 11:1 (Institute for Catastrophic Loss Reduction, 2020). Crucially, closing the infrastructure gap in Canada also brings with it a multiplier effect for the economy of 1.7 (Globe Capital, 2017).

A whole-of-society, integrated approach is essential to building the resilience of Canada's interconnected infrastructure systems. Learning from international experiences and—given the complexity of joint responsibility for infrastructure in Canada—planning and investing in resilient infrastructure will necessarily require an integrated and whole-of-society approach, leveraging the creativity and agency of interdisciplinary professional practices, Indigenous Knowledge Systems, and federal–provincial–territorial and public–private partnerships. Because infrastructure in Canada is owned, operated, and relied on by individuals, businesses, and governments at all levels, it is vital for all of these stakeholders to be engaged in building climate-resilient infrastructure for a sustainable and prosperous Canada.

Table ES1. Climate hazards, impacts, and resilience options for Canada's built infrastructure

Infrastructure type	Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Land transportation	Heat	• Pavement softening, rutting, and bleeding • Thermal rail expansion (buckling due to heat)	• Use heat-tolerant pavement mixtures • Use low-solar absorption rail coatings
	Changing precipitation patterns	• Increased risk of critical events (e.g., washouts) • Increased ice accretion on cable-stayed bridges	• Increase culvert capacities • Use of cable coverings to shed accreted ice
	Seasonal temperatures changes	• Shortened winter ice road season • Soil and slope instability plus ground movement/settlement	• Transform ice roads into all-season roads • Install geotextiles
	Storm surges	• Causeways, bridges, and low-lying roads inundated or damaged	• Build riprap and dikes
	High winds	• Blocked roads, bridges, and railways due to debris or snow	• Update vegetation management-related standards (e.g., plant different trees species along roads)

Infrastructure type	Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Buildings	Heat	• Increased indoor air temperature and reliance on cooling systems • Accelerated ageing of building materials	• Upgrade ventilation systems and install window shades • Install thermally reflective material for the roof and facades of buildings
	Changing precipitation patterns	• Increased risk of flooded structures • Roof collapse from heavier snow loads on roofs	• Install backwater valves, sump pumps; redesignate no-build areas in high-risk flood zones • Retrofit at-risk structures to a higher standard and monitor/remove snow accumulation
	Seasonal temperature changes	• Foundation and building damage from changes in freeze/thaw patterns and drying of soils	• Select concrete mixture aggregates that perform better in freeze–thaw cycles
	Permafrost degradation	• Subsidence and buckling can damage foundations • Loss of strength in building	• Improve ventilation and adjustable structural posts • Best design practices for foundations
	Storm surges	• Erosion compromises the integrity of foundations • Increased corrosion of metals	• Protective structures/dikes/seawalls • Metal product components with enhanced resistance to corrosion
	High winds	• Loss of roof sheathing • Windborne debris can shatter windows and damage exteriors and facades	• Reinforce roofs/hurricane straps and additional fasteners • Install impact-resistant glass
Water supply infrastructure	Changing precipitation patterns	• Power outages due to electrical storms affecting pumping stations • Reduced structural integrity and/or accelerated deterioration of dams	• Enhanced and redundant backup power supplies • Adopt structural adaptations to dams, weirs, and drainage canals
	Permafrost degradation	• Rupture of water lines and storage tanks	• Use of polystyrene insulation beneath roads
	Storm surges and sea level rise	• Flooding of treatment plant infrastructure	• Seawalls, dikes, floodwalls, levees, local surge barriers, etc.
	Drought	• Reduced source of potable water • Cracking of earthen dams, increasing flood risk	• Demand management and use of natural infrastructure such as bioswales, constructed wetlands, rain gardens, and bioretention systems • Structural adaptations to dams, weirs, and drainage canals

Infrastructure type	Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Wastewater and stormwater infrastructure	Heat	• Higher temperature streams and decreased streamflow lead to more concentrated influent flows that are harder to disinfect	• Apply natural infrastructure solutions (green roofs, urban forests) to increase assimilative capacity of receiving streams
	Changing precipitation patterns	• Exceeding stormwater/drainage systems	• Increased capacity of stormwater and drainage collection systems • Reduce or green up impervious surfaces (e.g., roofs, parking areas)
	Seasonal temperature changes	• Increased frequency, duration, and severity of thermal cracking and rutting	• Use phase-change materials to reduce the number of freeze/thaw cycles
	Storm surges	• Damaged or flooded structures that reduce treatment efficiency	• Hybrid built and natural infrastructure solutions (e.g., terraced berms, drainage improvements, bulkheads, beach nourishment, reinforced dunes, offshore breakwaters, living shorelines)
Marine infrastructure	Seasonal temperature changes	• Soil and slope instability and ground movement/settlement due to permafrost melt and increased freeze/thaw cycles	• Thicken embankments and new infrastructure design suited to permafrost environments
	Storm surges	• Inundation of ports and other coastal infrastructure • Increased wave damage to docks and other mooring structures	• Build flooding considerations into building and infrastructure design • Actively restore shoreline habitat (i.e., dunes, salt marshes, vegetation)
	Sea ice changes	• Increased shipping traffic in Arctic waters due to less sea ice creating new and additional demand for Northern ports	• Demand forecasting and planning for Arctic shipping and port facilities
	Fluctuations in inland water levels	• Lower water levels leading to reduced vessel capacity	• Shift freight to road or rail, change navigation procedures, invest in flow augmentation technologies, and increase dredging of channels

Infrastructure type	Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Energy and ICTs	Heat	• Overheating in ICT data centres, exchanges, and base stations • Water level fluctuations and drier soils can increase internal erosion of embankment dams	• Increase cooling system capacity • Enhanced dam safety monitoring and management
	Seasonal temperature increases resulting in permafrost degradation and changing freeze-thaw cycles	• Displaced transmission tower foundations and damage to underground vaults and cable chambers	• Modify structural designs to permit adjustment of towers when displacement due to permafrost thaw occurs
	Changes in precipitation patterns	• Flooding of energy generation plants and substations and dam spillway gate performance issues • Damage to the supporting infrastructure of ICT systems such as copper and fibre-optic cables	• Elevate substations and electrical infrastructure components and enhance dam safety monitoring and management • Bury transmission and distribution lines to fortify against flooding
	Winter/ice/ windstorms	• Snapped power lines, broken or fallen utility poles, ice buildup on wind turbine blades	• Bury distribution lines • Install microgrids to enable communities to separate from failed central grids and run on secondary sources
	Wildfires	• Damage and/or destruction of lines and transmission poles • Annealed or damaged conductors	• Bury electrical grid to avoid infrastructure damage from extreme heat and fire • Keep fire-prone areas clear of brush

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Acronym List

ACEG	Advisory Council on Economic Growth
BRACE	Building Regional Adaptation Capacity and Expertise
CCA	Council of Canadian Academies
CCME	Canadian Council of Ministers of the Environment
CDRI	Coalition for Disaster Resilient Infrastructure
CEA	Canadian Electricity Association
CIB	Canada Infrastructure Bank
CICC	Canadian Institute for Climate Choices
CIRC	Canadian Infrastructure Report Card
CRBCPI	Climate-Resilient Buildings and Core Public Infrastructure Initiative
CRI	Climate Risk Institute
CSA	Canadian Standards Association
DMAF	Disaster Mitigation and Adaptation Fund
EC	European Commission
ECCC	Environment and Climate Change Canada
EPA	Environmental Protection Agency
FCM	Federation of Canadian Municipalities
FSDS	Federal Sustainable Development Strategy
G20	Group of Twenty
GCA	Global Commission on Adaptation
IBC	Insurance Bureau of Canada
ICIP	Investing in Canada Infrastructure Program
ICLR	Institute for Catastrophic Loss Reduction
ICT	information and communication technology
IPCC	Intergovernmental Panel on Climate Change

ISI	Institute for Sustainable Infrastructure
ISO	International Organization for Standardization
ISC	International Science Council
NIC	National Infrastructure Commission
NRC	National Research Council of Canada
OECD	Organisation for Economic Co-operation and Development
PCF	Pan-Canadian Framework on Clean Growth and Climate Change
PIEVC	Public Infrastructure Engineering Vulnerability Committee
RCC	Resilience Rating System
SCC	Standards Council of Canada
SDG	Sustainable Development Goal
SuRe	Standard for Sustainable and Resilient Infrastructure
TCFD	Task Force on Climate-Related Financial Disclosures
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers

1.0

Introduction

Photo: Ivan Bandura / Unsplash

Canadians have witnessed and experienced a growing number of climate-related events in the past decade—from the floods in southern Alberta (in 2013) and southern Ontario and Quebec (in 2018), to the devastating forest fires in Fort McMurray (in 2016) and southern British Columbia (in 2017), and the tornados in the Ottawa-Gatineau region (in 2019). These events have displaced people from their homes, impacted local and regional economies, and caused billions of dollars in damage to public and private property. These events are part of a trend that has seen the damage cost of weather-related disasters like floods, storms, and wildfires rise over the past 50 years "from tens of millions of dollars to billions of dollars annually," with insured losses from catastrophic weather events totalling over CAD 18 billion between 2010 and 2019 (Canadian Institute for Climate Choices [CICC], 2020, p. 8).

The growing frequency and cost of weather-related disasters demonstrate the vulnerability of Canada's infrastructure and offer insight into the potential near- and long-term consequences of continued climate change. Canada warmed by an average of 1.7°C between 1948 and 2016—a rate double that of the rest of the world (Bush & Lemmen, 2019). The pace of warming is even greater in Northern Canada and the Prairies (Bush & Lemmen, 2019). Ongoing changes in temperature, precipitation patterns, sea levels, wind speeds, and the frequency and intensity of extreme weather events have clear implications for Canada's built and natural infrastructure. Examples include heavy downpours and floods disrupting transportation networks, rapid melting of snowpack impacting flood protection and stormwater infrastructure, degrading permafrost threatening the integrity of building systems, and sea level rise and storm surges damaging ports and coastal infrastructure. Individually, these events can cause significant damage, but they also can lead to cascading infrastructure failures (Council of Canadian Academies [CCA], 2019).

Given these observed impacts of climate change, it is perhaps not surprising that **the Expert Panel on Climate Change Risks and Adaptation Potential recently ranked Canada's physical infrastructure as the country's most consequential risk area** based on a review of a dozen different major climate risk areas (CCA, 2019). An assessment by the *Canadian Infrastructure Report Card* similarly concluded that much of Canada's core public infrastructure is "at risk" (BluePlan Engineering, 2019). The nature of this risk varies significantly across Canada, reflecting the diversity of our climate, geography, and types of infrastructure.

Socio-economic differences within and between communities also influence their level of risk. The "design, materials, size and maintenance of infrastructure systems" can be influenced by a community's level of wealth, ability to access technology, skill set, and response capacity, helping to make some communities more vulnerable to climate change compared to others (Boyle et al., 2013, p. 6). Such interrelated social factors are important considerations for climate-resilient infrastructure, particularly for Northern Indigenous communities, which are "at a greater risk from the combination of drastic Northern climate change and socio-economic vulnerability that is the legacy of racist colonial policies" (CICC, 2020, p. 6).

Within this context, Canada invested CAD 81.6 billion in infrastructure assets in 2020, on par with the level of investment made in the previous four years (Statistics Canada, 2021). These investments are critical to addressing the country's infrastructure gap, the estimate of which ranges from CAD 150 billion to as high as CAD 1 trillion (Advisory Council on Economic Growth [ACEG], 2016). Importantly, ACEG notes that the infrastructure gap in First Nations alone is estimated to be CAD 25 billion to CAD 30 billion (ACEG, 2016). While significant annual and gap investment is required to meet Canada's existing and growing infrastructure needs, every 1% increase in infrastructure spending is estimated to have a multiplier effect for the economy of 1.7, "increasing productive capacity, creating jobs and enabling new economic opportunities" (Globe Capital, 2017).

If Canada is to minimize the adverse consequences of climate change, these investments in new and updated infrastructure must account for current and projected climate change impacts. In other words, they will need to be "designed, built and operated in a way that anticipates, prepares for, and adapts to . . . changing climate conditions" (Organisation for Economic Co-operation and Development [OECD], 2018b, p. 4). As observed by the OECD, "climate-resilient infrastructure has the potential to improve the reliability of service provision, increase asset life and protect asset returns" (OECD, 2018b, p. 6). While protecting lives and livelihoods, investments in climate-resilient infrastructure can also generate positive benefit-cost ratios. For example, a recent study has demonstrated that implementation of Canada's National Guidelines for the Flood Resistance of Buildings could have a benefit-cost ratio of 11:1 (Institute for Catastrophic Loss Reduction [ICLR], 2020).[1] Planned climate adaptation will ensure that investments made today are robust and resilient over the long term and do not increase the vulnerability of Canadians to future climate risks.

In 2013, IISD released a report entitled *Climate Change Adaptation and Canadian Infrastructure* to stimulate discussion around the need to ensure the viability of Canada's built infrastructure in the face of climate change (Boyle et al., 2013). Since its release, a range of new policies, programs, codes, standards, and financing programs have been introduced to enhance the climate resilience of infrastructure in Canada. At the federal level, for example, this includes implementation of commitments made under the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) to "building climate resilience through infrastructure" (Government of Canada, 2016, p. 28). Actions stemming from this commitment include Infrastructure Canada's Climate Lens General Guidance to support the incorporation of climate resilience into the design of new infrastructure investments; the establishment of the Disaster Mitigation and Adaptation Fund (DMAF) to finance efforts to make public infrastructure more climate resilient; and the creation of science-based decision-support tools, codes, standards, and guidelines as part of the National Research Council of Canada's Climate-Resilient Buildings and Core Public Infrastructure Initiative.

Building on the PCF, the 2020 federal plan *A Healthy Environment and a Healthy Economy* describes updated climate commitments and initiatives to make Canada more resilient to climate change,

[1] This study of the federal government's Climate-Resilient Buildings and Core Public Infrastructure Initiative by the Institute for Catastrophic Loss Reduction also found that implementation of the National Wildland Urban Interface (Wildfire) Guideline and Standard and the Canadian Highway Bridge Design Code could have benefit to cost ratios of 6:1 and 9:1, respectively (ICLR, 2020). Similarly, a 2017 study by the National Institute of Building Sciences found that the United States could save USD 6 in future disaster costs for every USD 1 spent on hazard mitigation (Multihazard Mitigation Council, 2017).

including creating a National Adaptation Strategy together with provincial, territorial, and municipal governments (Environment and Climate Change Canada [ECCC], 2020). The federal government has also recently committed to undertaking a National Infrastructure Assessment to identify Canada's long-term infrastructure needs and priorities (Infrastructure Canada, 2021a).

Canada is also actively involved in international efforts to advance climate-resilient infrastructure, including the G20 Action Agenda on Adaptation and Resilient Infrastructure (G20, 2019), implementation of the United Nations Sendai Framework for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction [UNDRR], 2015), and the UN's global Sustainable Development Goals (SDGs) (UN, 2015). As well, Canada recently co-led the Action Track of the Global Commission on Adaptation (GCA) focused on nature-based solutions, which highlighted the potential of natural infrastructure in climate adaptation efforts (GCA, 2019).

This report is intended to provide a snapshot of the current understanding of the impacts and risks of climate change for Canada's built and natural infrastructure, from both a regional perspective and by types of infrastructure. **It also seeks to synthesize the range of actions being taken at the federal level and internationally to increase the sector's climate resiliency**. Its content is based on a review of published literature, reports, and policy documents. The report is intended to create awareness and stimulate further discussion around the need to ensure that existing and new infrastructure is climate resilient in order for it to support our communities, businesses, and economies.

The remainder of this report is structured as follows:

- Section 2 discusses key issues that frame the content of the report, namely concepts related to climate risk reduction and resilience, the role of interdisciplinary professional practice and Indigenous Knowledge in advancing resilient infrastructure, and the complementary role of both built and natural infrastructure for building resilient communities.
- Section 3 focuses on how climate hazards could affect infrastructure in different regions of Canada before examining hazards, impacts, and resilience-building measures for six different infrastructure types: land transportation, buildings, water supply, marine infrastructure, wastewater and stormwater, and energy and information and communication technology (ICT). The section concludes with a summary of the different types of natural infrastructure that can be used to address climate hazards, either on their own or integrated with built infrastructure.
- Section 4 examines policies, guidelines, practices, standards, codes, and financing mechanisms from a federal perspective and points to illustrative international examples that can and are informing Canadian efforts. While the authors acknowledge that provincial, territorial, municipal, and Indigenous governments throughout Canada are taking action to improve the climate resiliency of infrastructure, the sheer volume of initiatives precluded examination within the scope of the literature review.
- Section 5 concludes the paper by providing a summary of key insights from the review.

2.0

Framing the Discussion

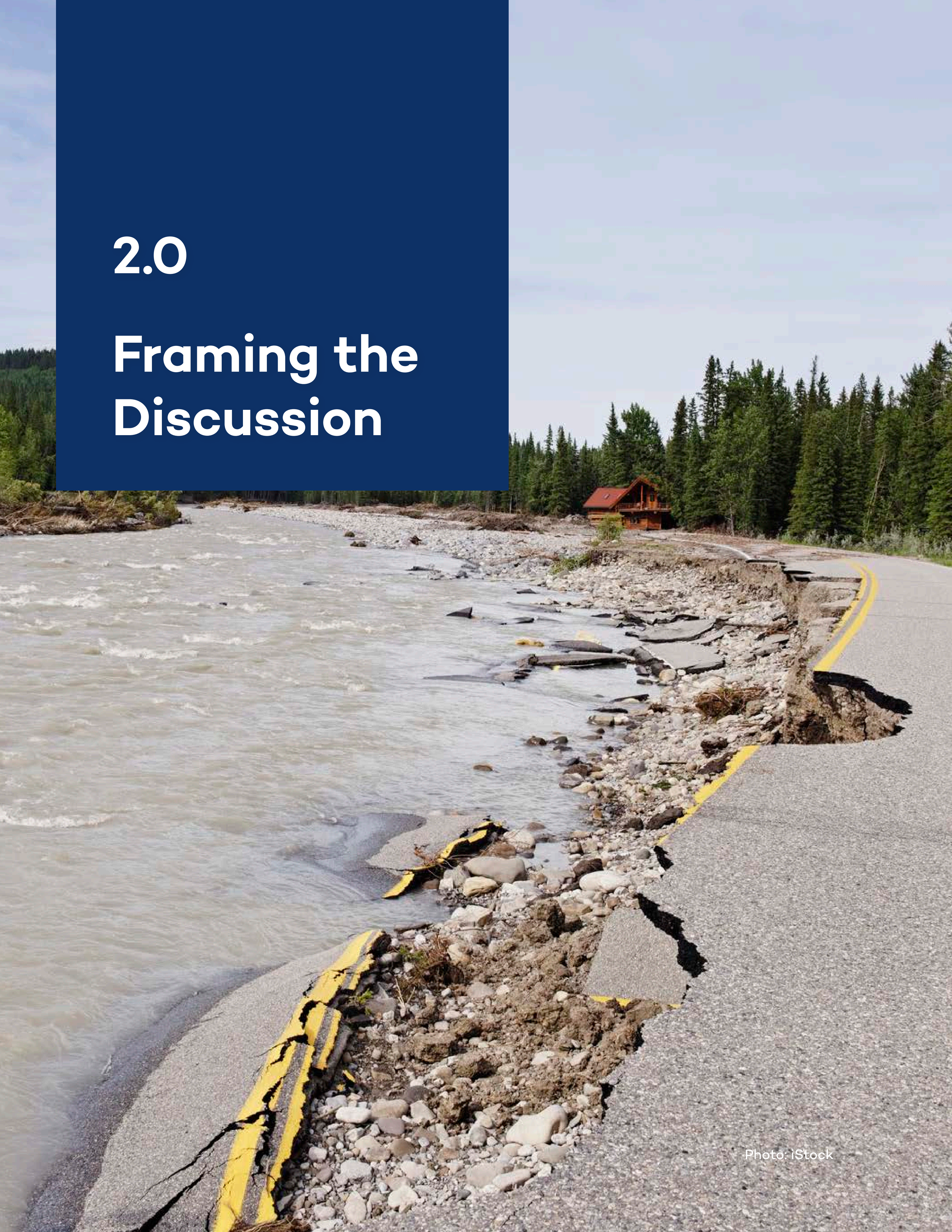


Photo: iStock

A variety of concepts, types of knowledge, and approaches inform efforts to strengthen the climate resiliency of infrastructure. This section explores some of this complexity by introducing the concepts that underlie efforts to build climate resilience, the need for diverse sources of knowledge to inform decisions, and the growing recognition of the role of nature in delivering some of the services traditionally provided by built infrastructure.

2.1 Conceptual Understanding of Climate Resilience

Understanding the risk that climate change poses for Canada's infrastructure—and the actions that can be taken to address these risks—is rooted in an understanding of key concepts such as climate-related hazards, risk, and resilience, and the interactions between them. As elaborated in Figure 1, a hazard is defined by the Intergovernmental Panel on Climate Change (IPCC) as "the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources" (IPCC, 2014a, p. 1766). Climate-related losses and damage can include those associated with long-term, incremental processes referred to as slow-onset events (such as droughts) or due to extreme hazard events (such as floods) (International Science Council [ISC] & UNDRR, 2020, p. 21). All of these different types of climate-related hazards have implications for the safety and reliability of Canadian infrastructure.

Within the context of climate change, **risk** is understood to result "from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems" as illustrated in Figure 1 (IPCC, 2014b, p. 3). As such, the drivers of risk stem both from the changes taking place in our climate globally and locally, and the changes taking place in our socio-economic systems (e.g., population growth, changes in trade patterns, etc.). The OECD's policy paper on climate-resilient infrastructure notes, for example, that requirements for water storage are influenced by changes in precipitation patterns and by changes in consumption patterns (OECD, 2018a).

The concept of **resilience** has been defined in a number of ways by different actors. In comparison to the IPCC's definition outlined in Figure 1, for instance, resilience has been defined from a disaster risk reduction perspective as (UNDRR, 2016, p. 22):

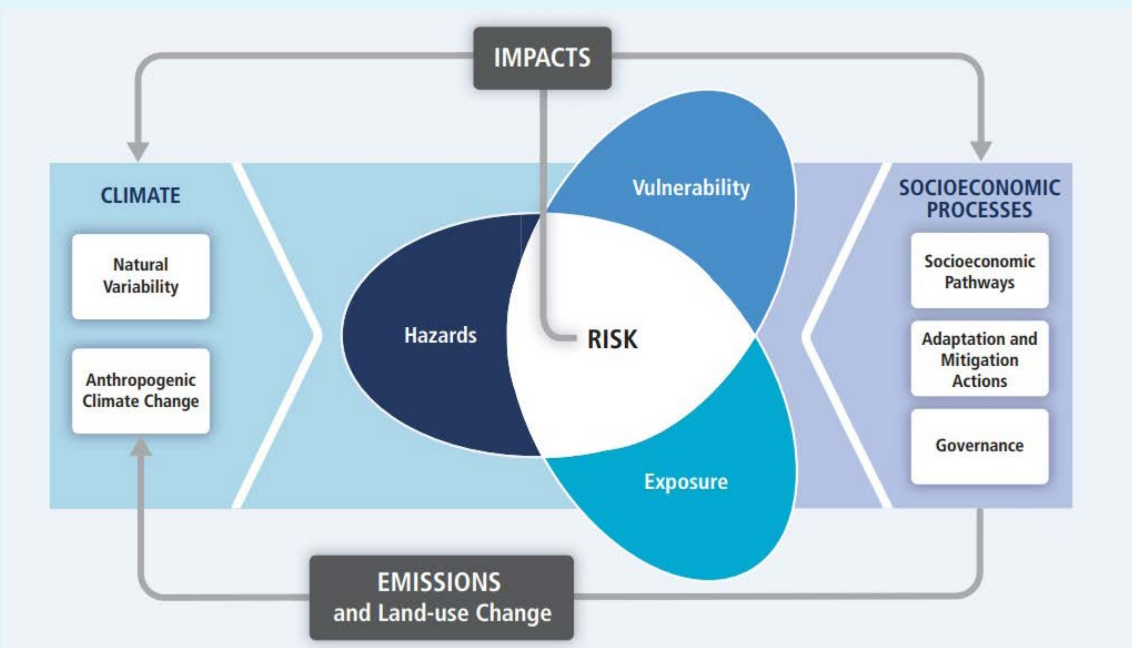
> the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.

Purely from a risk management perspective, the OECD defines resilience to mean that "risks have been considered and managed to achieve an acceptable level of performance given the available information, and that capacities to withstand and recover from shocks are in place" (OECD, 2014a, as cited in OECD, 2018a, p. 13).

Climate-resilient infrastructure can therefore be understood as (built or natural) infrastructure that is sited, designed, built, and operated with projected changes in climate conditions and risk in mind, to ensure that it is able to continue to maintain its form and function. Increasing the climate resilience of infrastructure therefore typically involves a combination of responses focusing on (adapted from Boyle et al., 2013, p. 5):

- **Technical aspects** (e.g., modifying the design of infrastructures to make them more resistant to the increased intensity of floods)
- **Policy and legal aspects** (e.g., new building codes)
- **Financial aspects** (e.g., specific funds allocated to support the maintenance of infrastructure)
- **Socio-economic aspects** (e.g., relocation or abandonment of infrastructures, change in habit and behavioural patterns associated with the use of infrastructures)
- **Institutional aspects** (e.g., awareness raising and capacity building of the infrastructures sector on climate adaptation)

Figure 1. Risk framing as described in the Intergovernmental Panel on Climate Change's 5th Assessment Report



Source: IPCC, 2014b

- **Hazard**: The potential occurrence of a natural or human-induced physical event, trend, or impact that may cause loss of life, injury, or other health impacts, as well as damage to or loss of property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.

- **Exposure**: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.
- **Vulnerability**: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
- **Resilience**: The capacity of social, economic, and environmental systems to cope with a hazardous event, trend, or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure while also maintaining the capacity for adaptation, learning, and transformation.

2.2 Knowledge Systems and Professional Practice

The complexity of climate change in combination with the diversity of infrastructure types located in different geographies and social, political, and economic systems means that different sources of knowledge and expertise are required to understand and respond to climate risks. People from different disciplines and with different experiences will need to come together to provide a full understanding of the nature of the challenge and potential solutions.

On the ground, the **implementation of resilient infrastructure will inherently be guided by a mix of professional practices**, both public and private, including professional engineers, architects, landscape architects, planners, climatologists, hydrologists, risk assessors, accounting and finance experts, contractors, and operational staff. Greater capacity to engage in interdisciplinary planning and practice will be required across these professions to increase the resilience of infrastructure to climate change. This will require increased knowledge of climate change vulnerability, impacts, and adaptation options. Efforts in this regard have been initiated in a variety of disciplines. For example, Engineers Canada established the Public Infrastructure Engineering Vulnerability Committee (PIEVC) in 2005, which published its professional practice PIEVC Protocol for climate vulnerability risk assessment of infrastructure in 2008, and initiated the Infrastructure Resilience Professional designation in 2015 (ICLR & Climate Risk Institute [CRI], 2021).

Importantly, **Indigenous Knowledge must play a key role in the design and implementation of resilient infrastructure** across Canada. First Nations, Métis, and Inuit Peoples are at the forefront of climate impacts in Canada, have long adapted to changes in environmental conditions, and have already taken a climate leadership role through mitigation and adaptation initiatives (CICC, 2020; Government of Canada, 2020). Indigenous Knowledge Systems are cumulative, dynamic, and adaptive, intertwined with personal, community, and national/cultural knowledge, a “way of being” that is broader than specific ecological knowledge (Cappell, 2019). Integrating Indigenous Knowledge Systems in risk assessments provides an opportunity to support a more comprehensive understanding of threats from climate change and potential solutions (Cappell, 2019). As noted by the CICC, “Indigenous Knowledge Systems and Western research can provide significant insights into the potential costs of climate change in Canada" (CICC, 2020, p. 2).

The need for interdisciplinarity and incorporation of Indigenous Knowledge Systems reflects a critical take-away message from a policy and practice perspective—namely that **achieving climate-resilient infrastructure objectives necessitates an integrated whole-of-society approach**. Cappell (2019) highlights that most international, national, and subnational resilient infrastructure frameworks recognize and embrace such an integrated approach. For example, the Climate-Safe Infrastructure Working Group to the California State Legislature and the Strategic Growth Council (2018) recognized that "infrastructure planners and designers must confront old paradigms of stationarity[…] and view infrastructure not as individual structures but as whole systems embedded in a more complex and interconnected world." An additional benefit of such an integrated, whole-of-society approach is that it recognizes that the resilience of public infrastructure, both built and natural, can improve resilience in other sectors as well, such as public health (Cappell, 2019). Canada's Federal–Provincial–Territorial Emergency Management Strategy – Towards a Resilient 2030 (Public Safety Canada, 2019) amplifies this whole-of-society approach in many of its priority areas of activity to strengthen overall resilience to an increasingly complex and rapidly evolving risk environment in Canada. Similarly, as part of Canada's climate plan, a whole-of-society approach will be an essential pillar for the development of a National Adaptation Strategy.

2.3 Complementary Roles of Built and Natural Infrastructure

Built infrastructure (also referred to as hard or grey infrastructure) is what Canadians typically think of when the topic of infrastructure comes up. Examples include roads, buildings, water treatment facilities, ports, culverts, transmission lines, and solar energy systems, to name but a few. **In recent years, though, there has been growing awareness and interest in the potential for natural infrastructure such as wetlands, trees, and coastal grasses to provide the benefits derived from built infrastructure**—either on their own or in combination with grey infrastructure. This surge in interest is reflected in actions like the American Society of Civil Engineers (ASCE) including natural and green infrastructure, for the first time, in its *2021 Report Card* on infrastructure. They recognized that advancements in resilience across all infrastructure sectors can be made by including or enhancing natural or green infrastructure (ASCE, 2021).

In a report prepared for the Canadian Council of Ministers of the Environment (CCME), natural infrastructure was defined as (ICF, 2018, p. 1):

> existing, restored, or enhanced combinations of vegetation and associated biology, land and water, and naturally occurring ecological processes that generate infrastructure outcomes such as preventing and mitigating floods, erosion, and landslides; mitigating effects of extreme heat; and purifying groundwater.

The report also stated that natural infrastructure "uses natural ecosystems and materials (such as trees, sand, stone, etc.) to produce ecosystem service outcomes and contribute to climate resilience" and that "these ecosystems and materials can be existing natural features or human-made and constructed" (ICF, 2018, pp. 7–8). While the term "natural infrastructure" is used exclusively throughout the remaining sections of this report, the authors acknowledge that it is used interchangeably with other terms and definitions—including for green infrastructure, nature-based solutions, hybrid solutions, and engineering with nature—that have nuanced differences in terms of their scope and understanding of the relationship between the built and natural environment (see Box 1).

Interest in the use of natural infrastructure stems in part from its potential cost effectiveness and capacity to deliver co-benefits. For example, the OECD has observed that "ecosystem-based approaches, including natural infrastructure . . . can be cheaper than relying solely upon 'grey' infrastructure, as well as yielding co-benefits" (OECD, 2018b, p. 6). Similarly, the Insurance Bureau of Canada (IBC) has stated that natural infrastructure "can be a cost-effective way to mitigate material financial losses that would otherwise result from flooding" and "can offer other valuable environmental and social benefits that are often not attainable through the implementation of traditional, grey-engineered solutions" (Moudrak et al., 2018, pp. 4–5). These co-benefits include protection of biodiversity, carbon sequestration, recreational opportunities, and positive contributions to mental health.

Section 3.3 of this paper reviews in more detail the various types of natural infrastructure solutions that are being deployed in Canada and worldwide to build climate resilience.

Box 1. Other definitions relating to natural infrastructure

The term "natural infrastructure" is used interchangeably with several other related terms, including nature-based solutions, ecosystem-based approaches, engineering with nature, and green infrastructure. Below are a few common definitions:

- **Green Infrastructure** (Municipal Natural Assets Initiative, 2017, p. 3): "Includes designed and engineered elements that have been created to mimic natural functions and processes in the service of human interests." Green infrastructure includes natural assets (i.e., wetlands, forests, parks, lakes/rivers/creeks, fields, soil), enhanced assets (i.e., rain gardens, bioswales, urban trees and parks, biomimicry, stormwater ponds), and engineered assets (i.e., permeable pavements, green roofs, rain barrels, green walls, cisterns).
- **Engineering with nature** (U.S. Army Corps of Engineers [USACE], 2021): "The intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes."
- **Nature-based solutions** (International Union for the Conservation of Nature French Committee, 2019, p. 9): "Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." Societal challenges that nature-based solutions help address include climate change, food security, water security, disaster risk, human health, and economic and social development.
- **Hybrid solutions** (ICF, 2018, p. 8): "A result of nature-based solutions that are combined with grey infrastructure to enhance the resilience of both the infrastructure and the surrounding ecosystem to higher intensity events."

3.0

Climate Change Hazards, Impacts, and Adaptations for Infrastructure in Canada

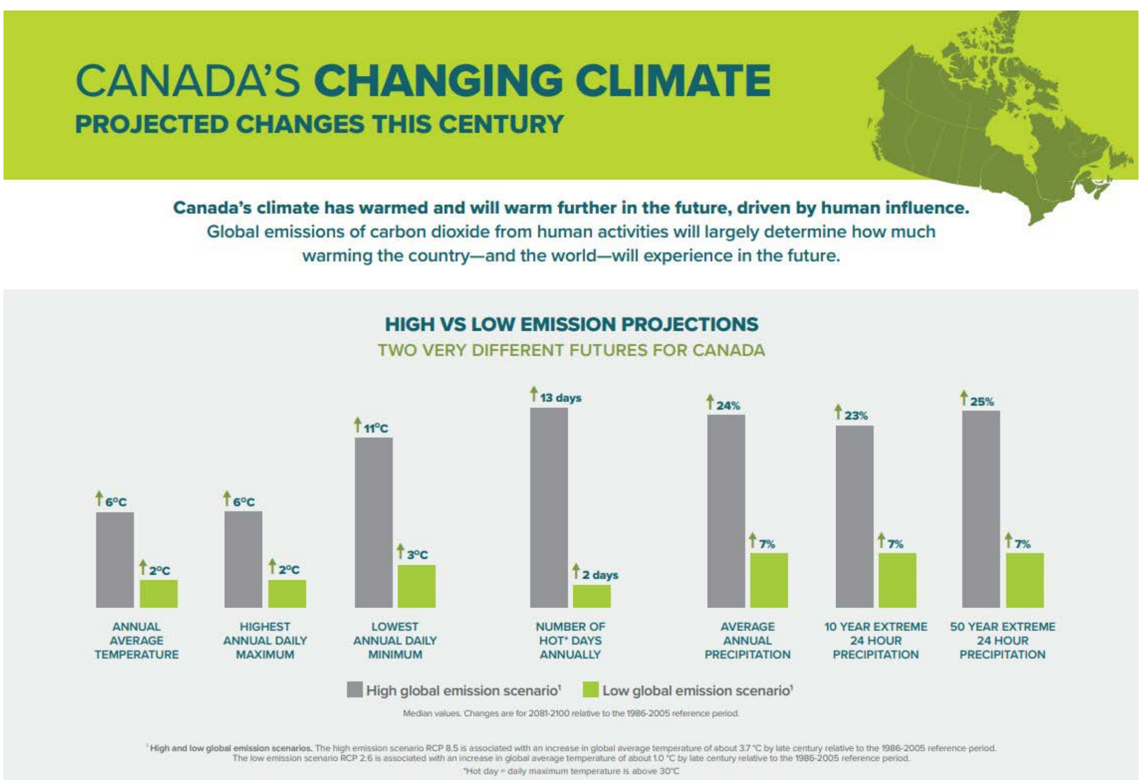
Photo: Marc Bruxelle / Alamy Stock Photo

This section begins with an overview of climate change hazards for—and impacts on—infrastructure in different regions across Canada. This is followed by a detailed review of climate change hazards, impacts, and illustrative adaptation options for six different types of built infrastructure. The section concludes with an examination of the role of natural infrastructure in increasing climate resilience while providing additional co-benefits.

3.1 Climate Change Impacts on Infrastructure Across Canada

The climate in Canada is changing—and will continue to change in the coming decades. As depicted in Figure 2, depending on the success of global efforts to reduce greenhouse gas emissions, annual mean temperatures in Canada could rise by 1.8°C (under a low-emission scenario) to 6.3°C (for a high-emission scenario) by the end of this century (2081–2100) (Bush & Lemmen, 2019). Because of Canada's vast and diverse geography, the current and future rate and magnitude of warming varies between regions and seasons, as do associated changes in precipitation and other variables. The impacts of climate change on infrastructure will also vary across different regions. The paragraphs below examine how the climate is changing across five distinct regions of Canada—Northern and Arctic, Pacific, Prairies, Central, and Atlantic regions—and the implications for local infrastructure.

Figure 2. Canada's changing climate: Projected changes this century



Source: Government of Canada, 2019a.

Northern and Arctic Regions. Average annual temperatures across Northern Canada continue to increase at a rate more than double that of the global average. In turn, this rise in temperature is influencing the occurrence and intensity of extreme events such as droughts, wildfires, and floods, as well as gradual onset changes such as shifts in snow, ice, and permafrost. These changes can significantly affect infrastructure (Government of Northwest Territories, 2018). Rising temperatures and shifting weather patterns negatively affect season length and load capacity of winter ice roads—essential infrastructure for remote communities (CCA, 2019; Pendakur, 2017). Recently, lightning-induced wildfires, a consequence of increased temperatures and precipitation, have become more frequent across the Northwest Territories (Arctic Council, 2019). Similarly, changes in river ice break-up increase the potential for inland flooding and subsequent damages to nearby communities, roads, and water and sanitation systems (Government of Yukon, 2020). Thawing permafrost affects transportation corridors, buildings, pipelines, airstrips, industrial facilities, and water and sanitation infrastructure. For some communities, this can mean losing access to essential services (CCA, 2019). In the Northwest Territories, it is estimated that the cost of permafrost impacts on assets in 33 communities will be approximately CAD 51 million per year (Northwest Territories Association of Communities, 2011).

Arctic marine areas are experiencing longer ice-free periods, increasing the risk of flooding and damage to coastal infrastructure (Ford et al., 2016). Many of these locations are also being impacted by sea level rise, increasing the exposure of the Northern communities' coastal infrastructure to damages due to erosion, flooding, and storm surge (Arctic Council, 2019). The prospect of an ice-free Arctic Ocean this century (Guarino et al., 2020) points to the very real potential for climate change to simultaneously directly affect Northern infrastructure while also bringing about a significant increase in demand for services. Potential opportunities for year-round marine transport and commercial activities in the North by many countries have already been documented at length by several researchers and organizations (for example, Arctic Council, 2019; Maritime Executive, 2021; Polar and Ocean Portal, 2015). This increase in demand could further strain existing infrastructure and create pressure for the construction of new infrastructure.

Pacific Region. Many areas within British Columbia's coast and interior will experience increased risk to infrastructure and communities from droughts, floods, and wildfires (Office of the Auditor General of British Columbia, 2018). Reduced winter precipitation, spring snowpack, and river flows combined with winter and spring warming will increase the probability of seasonal water shortages (BC Ministry of Environment and Climate Change Strategy, 2019; Bush & Lemmen, 2019; Cohen et al., 2019). Inland and coastal flooding caused by intense, short-duration rainfall events, including those associated with atmospheric rivers,[2] as well as by earlier and more rapid snowpack melt, larger storm surges, and sea level rise, are also an increasing

[2] Atmospheric rivers are "long narrow streams of high water vapour concentrations in the atmosphere that move moisture from tropical regions towards the poles across the mid latitudes" (Pacific Climate Impacts Consortium, 2013, p. 2., as cited in Vadeboncoeur, 2016, p.211). These events are responsible for extreme rainfall events on the West Coast, which can lead to landslides and flooding (Vadeboncoeur, 2016).

threat. Flooding across the Pacific region would result in costly damages to airports, ports, ferry terminals, roads, bridges, buildings, and water and sanitation infrastructure (Vadeboncoeur, 2016).

Flooding caused by sea level rise will disproportionately affect the Fraser Lowland, southern Vancouver Island, and the Northern coast. Higher sea levels can lead to more severe coastal storm surges, which, along with strong winds from extreme weather, will further increase the severity of flooding events. These changes put infrastructure and property at risk, especially along the shorelines and areas below sea level, such as Richmond and Delta in Greater Vancouver. Finally, coastal tourism infrastructure and cultural sites may also be threatened by sea level rise, storm surges, and erosion due to extreme weather (CCA, 2019; Lemmen et al., 2016; Vadeboncoeur, 2016).

Prairie Region. The diverse landscapes of Alberta, Saskatchewan, and Manitoba—from the Rocky Mountains and the Great Plains to the northern Canadian Shield and the Hudson Bay coastline—are characterized by a variety of climatic conditions and extreme weather events. During the decade from 2010 to 2020, the Prairie provinces experienced the costliest extreme weather disasters on record, including flooding, drought, and wildfires (Sauchyn et al., 2020). The frequency and intensity of these events will increase in the future, along with changes in average temperatures and precipitation (Sauchyn et al., 2020). Projections for the Prairies include more frequent and intense droughts and soil moisture deficits, heavier rainfall events that increase the risk of flooding, and increased risk of wildfires (Sauchyn et al., 2020).

Such events are expected to continue to disrupt critical infrastructure across the region. Urban transportation infrastructure on the Prairies, including roads, bridges, railways, and runways, are "heavily exposed to climate impacts such as rising temperatures and more frequent and intense rainfall," and particularly so for river cities such as Calgary and Edmonton that receive large amounts of precipitation in short periods of time (Temmer & Venema, 2017, p. 1). Additionally, the Prairie Climate Centre observes that climate change puts stress on electricity grids (by increasing cooling demand requirements and through exposure to climate shocks such as ice storms, droughts, and tornados) and on water supply and sanitation systems, necessitating multiple forms of resilient infrastructure and integration of water conservation and natural infrastructure solutions (Venema & Temmer, 2017a, 2017b). For the Prairie provinces, it is acknowledged that the combined change of more intense extreme weather events and shifts in baseline climate "may ultimately be the most challenging scenario" as "eventually temperature, precipitation and water levels will cross a threshold beyond which impacts will abruptly become more severe, including the permanent loss of water stored as snow and ice [and] rainfall intensity that exceeds the watershed and storage capacity of infrastructure" (Sauchyn et al., 2020, p. 55).

Central Region. Ontario is prone to extreme climate events such as intense rainfall, ice storms, windstorms, and heatwaves—and the resulting climate hazards such as drought, flooding, landslides, coastal erosion, and forest fires. In the coming years, temperatures and precipitation levels in the province are expected to increase (Cohen et al., 2019). The resulting impacts on infrastructure will range from the softening of pavement in severe heat and the cracking of concrete during freeze–thaw cycles, to water mains that overflow in severe rain and ice storm damage to hydro lines (Government of Ontario, 2015). Extreme weather events also damage infrastructure, such as the May 2018 windstorm in southern Ontario (and Quebec), followed by tornados in the National Capital Region in September 2018, that caused close to CAD 1 billion in insured losses (Standards Council of Canada [SCC], 2019). Warmer air temperatures, increased precipitation, and more extreme swings between periods of drought and heavy precipitation in the Great Lakes Region will lead to variability in water levels that will challenge coastal infrastructure, including the potential for overall water levels in the Great Lakes to decline as a result of higher evaporation rates (Cohen et al., 2019; Emerging Issues Working Group of the Great Lakes Water Quality Board, 2017).

In Quebec, increases in temperatures and levels of precipitation also are expected. In the Gulf of St. Lawrence, relative sea level is expected to rise and wave heights and the duration of the wave season are expected to increase (Cohen et al., 2019). Melting permafrost, greater coastal erosion, and more frequent extreme weather events are negatively affecting the built environment in Quebec (Ouranos, 2015). Infrastructure damage associated with flooding is increasing and now occurs in all seasons; whereas flooding in the past tended to occur in the spring and be associated with snow melt and ice break-up (Ouranos, 2015). Declining sea ice cover in the Estuary and Gulf of St. Lawrence exposes the shoreline to storm surges and stimulates coastal erosion, with increasing risks for coastal buildings and infrastructure (Bernatchez et al., 2015). Ensuring the resilience of infrastructure, including through the use of natural infrastructure, is among the four fundamental issues emphasized in Quebec's approach to climate change (Government of Quebec, 2020).

Atlantic Region. Climate change in Atlantic Canada is projected to lead to more frequent and intense storms, rising sea levels, storm surge flooding, reductions in sea ice cover, coastal erosion, coastal and inland flooding, and saltwater intrusion into surface water and groundwater (Savard et al., 2016). Storm damage to coastal communities caused by rising sea levels, heavy precipitation events, and storm surges has been identified as one of the top six areas of climate change risk facing Canada (CCA, 2019). Major financial costs are associated with extreme weather events in the region, including hurricanes and winter storms. Between 2003 and 2011, damage caused by three hurricanes and one major winter storm in the region resulted in insured losses ranging from CAD 51 million to CAD 132 million (Kovacs & Thistlethwaite, 2014). Sea level rise and storm surges could overtop the system of historic dikes that control lowland flooding and protect the transportation and trade corridor between New Brunswick and Nova Scotia, the Chignecto Isthmus or Tantramar Marshlands, through which a trade value of CAD 50 million passes each day (Dietz & Hoyt, 2016). The Atlantic Region has been identified as among the area of Canada most in need of adaptation investment to protect against climate risks (along with the Northern region), including addressing infrastructure priorities of local buildings, dikes, and roads (IBC & Federation of Canadian Municipalities [FCM], 2020).

3.2 Climate Change Impacts and Adaptations for Built Infrastructure

The literature review revealed that all types of built infrastructure in Canada are at risk in the face of a wide range of climate hazards, including: changing precipitation patterns; storm surges; higher tides; changing sea levels and fluctuating inland water levels; high winds and changing wind conditions; driving rain/wind pressure; hurricanes and tornados; overland and coastal flooding; winter storms and ice storms; seasonal temperature increase resulting in permafrost degradation and changing freeze–thaw cycles; extreme heat and heatwaves; drought; and wildfires. Different types of infrastructure may be affected by these climate hazards in different ways, including reduced lifespan, disrupted service due to damage, and/or capacity thresholds being exceeded during extreme climate events or slow-onset change. Practical adaptation options to these various climate hazards do exist for all types of infrastructure, and many are already being implemented across Canada. These adaptation options fall into three main categories: climate-informed planning and assessment at the conceptual stage, structural solutions, and enhanced monitoring and maintenance. The review of literature also highlighted the importance of risk-based approaches in decision making and planning together with flexible, robust, and redundant adaptation pathways and policies (Risk Sciences International & Ontario Centre for Climate Impacts and Adaptation Resources, 2015; Swanson & Bhadwal, 2009; Venema, 2017).

This section presents how different types of built infrastructure are impacted by a range of climate hazards and potential options for mitigating these risks. It focuses on six types of built infrastructure:

1. **Land transportation** (roads and runways, bridges, and railways)
2. **Buildings** (both public and private)
3. **Water supply** (surface and groundwater sources, treatment facilities, dams, reservoirs, and aquifers)
4. **Wastewater and stormwater** (treatment facilities, culverts, sewers, storm drains, and pipes)
5. **Marine** (ports, canals, wharves, piers, and seawalls)
6. **Energy and information and communication technologies (ICTs)** (transmission corridors, renewable energy, oil and gas, Internet, and wireless technologies)

For each infrastructure type, tables are provided in the appendices that describe relevant climate hazards, reported or anticipated infrastructure impacts, and examples of the types of adaptations observed or suggested by experts. These technical solutions and processes are continuing to evolve as knowledge and experience with climate-resilient infrastructure grows.

3.2.1 Land Transportation

ROADS AND RUNWAYS, BRIDGES, AND RAILWAYS

Canada's land transportation infrastructure is essential for connecting Canadians across such a vast landmass and constitutes the gateway for Canada's trade corridor, playing a critical role in the country's economy. In 2018, there were 1,066,180 kilometres of publicly owned roads in Canada (two-lane equivalents), of which 14.7% were deemed to be in poor or very poor physical condition (Statistics Canada, 2020). Canada's National Highway System (the Trans-Canada Highway) covers 38,098 km, 95% of which is owned and operated by provincial and territorial governments (Council of Ministers Responsible for Transportation and Highway Safety, 2019).

Climate hazards have the potential to affect land transportation infrastructure in three ways: (i) critical events; (ii) compromised structural integrity; and (iii) reduced lifespan. Examples of critical events include road washouts; bridge failures; embankment failures; and landslides that destroy roads, bridges, and railways. All of these types of critical events can result in loss of life and service as well as the considerable cost to repair the damage to the infrastructure. Additionally, climate hazards can compromise the infrastructure's structural integrity and require intervention before the diminished integrity results in a critical event. Compromised structural integrity examples include bridge scours; erosion of foundations (roads, runways, and railways); thermal expansion of bridges and railways; and cracking, rutting, and softening of roads and runways (asphalt and/or pavement). Finally, climate change can also affect the lifespan of infrastructure that was designed based on past climate conditions (Transport Canada, 2016). Appendix 1 details the types of climate change hazards and the associated potential impacts of these hazards on Canada's land transportation infrastructure.

Three main categories of adaptation strategies were observed in the literature to reduce and/or eliminate the impacts of climate change on land transportation infrastructure. **The main categories of adaptation strategies are: (i) infrastructure planning and siting, including risk assessment; (ii) structural solutions, including construction techniques and technologies; and (iii) monitoring and maintenance practices**. Examples of infrastructure planning and siting adaptation are conducting risk assessments using International Organization for Standardization (ISO) 31000 and/or PIEVC Protocol; mapping permafrost; and designing structures that account for climate change projections (e.g., what was previously considered a 1-in-100-year event using historical climate data is actually occurring more often under climate change). Examples of construction techniques are thickening embankments and using innovative materials and methods (e.g., geotextiles, highly durable and impermeable concrete mixes, articulated concrete mats, and thermosyphons). Finally, ongoing maintenance and monitoring methods include installing devices to monitor bridge scours; clearing debris from culverts; and rerouting traffic if land transportation infrastructure has temporary structural integrity issues (Melillo et al., 2014; Transport Canada, 2016). Appendix 1 details the types of adaptation strategies that can be undertaken to reduce (or eliminate) the impacts of climate change hazards on Canada's land transportation infrastructure. Examples of these measures are provided in Table 1 below.

Table 1. Illustrative examples of climate hazards, impacts, and resilience options for land transportation systems

Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Heat	• Pavement softening, rutting, and bleeding • Thermal rail expansion (buckling due to heat)	• Use heat-tolerant pavement mixtures • Use low-solar absorption rail coatings
Changing precipitation patterns	• Increased risk of critical events (e.g., washouts) • Increased ice accretion on cable-stayed bridges	• Increase culvert capacities • Use of cable coverings to shed accreted ice
Seasonal temperatures changes	• Shortened winter ice road season • Soil and slope instability plus ground movement/settlement	• Transform ice roads into all-season roads • Install geotextiles
Storm surges	• Causeways, bridges, and low-lying roads inundated or damaged	• Build riprap and dikes
High winds	• Blocked roads, bridges, and railways due to debris or snow	• Update vegetation management-related standards (e.g., plant different trees species along roads)

3.2.2 Buildings

Buildings are a critical component of life in Canada, where residents spend 90% of their time indoors (Parks Canada, 2014, p. 3) and are an important component of the economy. The sector in Canada is comprised of 14.79 million households (based on 2018 data, Natural Resources Canada [NRCan], 2021) and 482,000 commercial or institutional buildings (based on 2014 data, Statistics Canada, 2016). Evidence shows that there is a continued investment in building stock. For example, in 2019, municipalities issued building permits worth CAD 102.4 billion in the residential and non-residential sectors (Statistics Canada, 2020). The construction of new buildings, including housing, is expected to experience positive growth to 2029, driven by continued high levels of immigration and economic recovery (BuildForce Canada, 2020). At present, the design life of most buildings is 50 years, and the average age of municipal building infrastructure is about 37 years (based on 2016 data, Amec Foster Wheeler & Credit Valley Conservation, 2017).

The impacts of climate change can pose significant challenges to buildings, affecting the envelope, structure, and materials, as well as the performance of some mechanical and electrical systems (Ouranos, 2015). Most building design parameters are based on historical weather data, and many existing buildings were not constructed to withstand the projected range of climate conditions and increased frequency of extreme weather events (Amec Foster Wheeler & Credit Valley Conservation 2017). Buildings in Canada's North are becoming unstable, with some having to be destroyed because of shifting foundations caused by the degradation of permafrost (Government of Nunavut, 2013; Lamb, 2017). Increased precipitation has reduced the structural integrity of many buildings, accelerated the deterioration of building facades, caused premature weathering of building materials, increased surface leaching, and in some instances, decreased the integrity of engineered berms as a result of slope instability (Infrastructure Canada, 2006). Increased winter precipitation during a shorter snow accumulation period can increase the potential of roof collapse (Government of Canada, 2019b), as occurred in February 2019 when several roofs collapsed across Quebec following heavy snowfall and freezing rain (Olivier, 2019). Extreme weather events, such as heavy rainfall in a short time period, can lead to flooding that can cause extensive damage to buildings, including basement flooding (IBC & FCM, 2020). The 2016 wildfire in Fort McMurray, Alberta, that destroyed over 2,600 buildings was fuelled by an extremely dry winter coupled with unseasonably hot weather and high winds (Canadian Press, 2017; Di Liberto, 2016). Appendix 2 details the types of climate change hazards and the associated potential impact of these hazards on buildings in Canada.

From an infrastructure perspective, **buildings require the greatest investment in adaptation; and urgent upgrades are needed to address flooding, erosion, and melting permafrost**, which pose the greatest risks to buildings (IBC & FCM, 2020). A recent ECCC report identified that, based on current knowledge of climate variability and change in Canada, future building design should consider projections of temperature increases and the likelihood of extreme precipitation, and account for driving rain wind pressure, an emerging risk for existing buildings (Cannon et al., 2021).

Adaptation measures can include updating and developing new building codes and standards; considering climate impacts and risks in policies, planning, and zoning; engineered solutions such as modifying construction practices and applying new technologies; revising investment and insurance practices; and research, improving data, and sharing information (see Table 2 and Appendix 2). Considerable progress is being made to design and construct buildings that can withstand the impacts of climate change and to have the buildings remain functional during and after disruptions. New and updated codes, standards, and guides have been developed or updated to enhance climate change resilience in regard to wind-resilient design, wildfires, snow loads, flood resilience, and building on permafrost (SCC, 2019). The PIEVC Protocol has developed several models for studying the potential effects of climate change on buildings and identifying adaptation options (ICLR & CRI, 2021). Climate resilience guides have been developed for particular types of buildings, such as health facilities (Energy & Environmental Sustainability and Integral Group, 2020).

Table 2. Illustrative examples of climate hazards, impacts, and resilience options for buildings

Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Heat	• Increased indoor air temperature and reliance on cooling systems • Accelerated ageing of building materials	• Upgrade ventilation systems and install window shades • Install thermally reflective material for the roof and facades of buildings
Changing precipitation patterns	• Increased risk of flooded structures • Roof collapse from heavier snow loads on roofs	• Install backwater valves, sump pumps; redesignate no-build areas in high-risk flood zones • Retrofit at-risk structures to a higher standard and monitor/remove snow accumulation
Seasonal temperature changes	• Foundation and building damage from changes in freeze/thaw patterns and drying of soils	• Select concrete mixture aggregates that perform better in freeze–thaw cycles
Permafrost degradation	• Subsidence and buckling can damage foundations • Loss of strength in building	• Improve ventilation and adjustable structural posts • Best design practices for foundations
Storm surges	• Erosion compromises the integrity of foundations • Increased corrosion of metals	• Protective structures/dikes/seawalls • Metal product components with enhanced resistance to corrosion
High winds	• Loss of roof sheathing • Windborne debris can shatter windows and damage exteriors and facades	• Reinforce roofs/hurricane straps and additional fasteners • Install impact-resistant glass

3.2.3 Water Supply Infrastructure

SURFACE WATER AND GROUNDWATER SOURCES, TREATMENT FACILITIES, DAMS AND RESERVOIRS, DISTRIBUTION SYSTEMS

Canadians are heavily dependent upon infrastructure systems to supply water for drinking, irrigation, recreation, navigation, and waste assimilation. In 2018, there were approximately 15,000 potable water facilities (non-linear assets: treatment, reservoirs, storage tanks, and pump stations) and approximately 214,000 km of potable water distribution systems (linear assets: local pipes and water transmission pipes) in Canada (Statistics Canada, 2020). Approximately 20% of water distribution and transmission pipes were built before 1970 (Statistics Canada, 2020). Dams are sometimes used to supply potable water and water for irrigation, recreation, navigation, thermal power cooling, industry, and waste assimilation. However, large dams used strictly for water supply are not common in Canada due to the general abundance of water resources (Canadian Dam Association, 2019).

Climate hazards have the potential to impact water supply infrastructures in four ways: (i) failed systems; (ii) exceeded capacity; (iii) reduced lifespan; and (iv) mismatched supply and demand. Examples of failed systems include underground pipes rupturing due to freezing or permafrost degradation. Exceeded capacity occurs when intense downpours and/or storm surges flood non-linear assets and/or dams. Reduced lifespan occurs when original design specifications that were developed for a stable climate environment end up deteriorating at an accelerated rate due to climate change (e.g., changes in precipitation, temperature, and humidity). Finally, in periods of drought, water supply infrastructure can be strained due to a mismatch of supply (less surface and groundwater available due to drought or decrease in water quality) and increases in demand (Amec Foster Wheeler & Credit Valley Conservation, 2017). Appendix 3 details the potential impact of different climate change hazards on Canada's water supply infrastructure.

The literature revealed three main categories of adaptation strategies to reduce and/or eliminate the impact of climate change on water infrastructure. These **adaptation strategies are: (i) using assessment and monitoring tools; (ii) incorporating natural infrastructure with built infrastructure and/or decommissioning/replacing built infrastructure; and (iii) building in redundancy (emergency back-up) systems**. The use of risk assessment approaches such as the ISO 31000 Standard on Risk Management or the PIEVC Protocol, along with monitoring tools such as permafrost mapping or water demand management assist in the design or retrofitting of water supply infrastructure under a changing climate. Incorporating natural infrastructure (see Section 3.2.7) such as wetlands, green roofs, and urban forests together with built infrastructure can be effective for water conservation programs (Amec Foster Wheeler & Credit Valley Conservation, 2017). Finally, given the critical nature of water supply infrastructure, building in a failsafe such as emergency electrical backup for a pumping station is a proactive strategy to adapt to a changing climate and ensure that the facility continues to operate. Appendix 3 also details the types of adaptation strategies that can be undertaken to reduce (or eliminate) the impacts of climate change hazards on Canada's water supply infrastructure, examples of which are provided in Table 3.

Table 3. Illustrative examples of climate hazards, impacts, and resilience options for water supply infrastructure

Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Changing precipitation patterns	• Power outages due to electrical storms affecting pumping stations • Reduced structural integrity and/or accelerated deterioration of dams	• Enhanced and redundant backup power supplies • Adopt structural adaptations to dams, weirs, and drainage canals
Permafrost degradation	• Rupture of water lines and storage tanks	• Use of polystyrene insulation beneath roads
Storm surges and sea level rise	• Flooding of treatment plant infrastructure	• Seawalls, dikes, floodwalls, levees, local surge barriers, etc.
Drought	• Reduced source of potable water • Cracking of earthen dams, increasing flood risk	• Demand management and use of natural infrastructure such as bioswales, constructed wetlands, rain gardens, and bioretention systems • Structural adaptations to dams, weirs, and drainage canals

3.2.4 Wastewater and Stormwater Infrastructure

TREATMENT FACILITIES, CULVERTS, SEWERS, STORM DRAINS, PIPES AND LIFT STATIONS

Canadians are heavily dependent upon urban infrastructure systems to treat wastewater and handle stormwater. In 2018, an inventory of Canadian wastewater and stormwater infrastructure listed over 38,000 wastewater and stormwater facilities (non-linear assets: 19,000 wastewater treatment, storage tanks, pump stations and lift stations plus 19,500 stormwater pump stations, ponds/wetlands, and end-of-pipe facilities). Additionally, the distribution system is over 600,000 km (linear assets: 426,000 km of wastewater pipes and forced mains as well as 175,000 km of stormwater culverts, ditches, and pipes). According to the 2018 study, approximately 11% of the linear assets are deemed to be in poor to very poor condition. The study did not provide the percentage of non-linear assets that are considered in poor to very poor condition but instead simply stated that two-thirds were reported as being in good or very good condition (Statistics Canada, 2020).

Wastewater and stormwater infrastructure is impacted by many climate hazards both major and minor. The major issues include: critical events, such as flooded treatment facilities and/or ruptured pipes in the distribution system, and failure of the system, as when culverts and sewers are overwhelmed by precipitation volumes and/or when wastewater treatment is unable to disinfect more concentrated influent flows. A critical event can occur at wastewater treatment plants that are typically built at low elevations to use gravity-fed sewage collection; with the increased chances of flooding these wastewater plants are more vulnerable to disruption and/

or reduced efficiency. Freeze–thaw cycles and degradation of permafrost can cause significant ground shifting (instability) that can cause pipes to rupture. At the same time, more intense precipitation combined with escalating urbanization (i.e., more impermeable surface area) may lead to contaminated overland flow in areas with combined (wastewater/stormwater) sewer systems. Additionally, changing climate conditions are projected to affect wastewater treatment and disposal (e.g., elevated stream temperatures, combined with lower flows, may result in higher influent streams that require increased treatment to meet water quality standards) (Melillo et al., 2014). Appendix 4 identifies climate change hazards and their potential impact on Canada's wastewater and stormwater infrastructure.

Beyond using risk assessment approaches such as ISO 31000 or equivalent in the planning stage, the CSA Standard S900.1-2018 on Climate Change Adaptation for Wastewater Treatment Plants can help ensure greater climate resilience, as can the consideration of natural infrastructure solutions (see Section 3.2.7). The literature also suggests that there are **two main pathways to adapt wastewater and stormwater infrastructure to a changing climate** based on modelling of future precipitation, thaw–freeze, and drought rates. One pathway is adapting traditional water management systems by increasing capacity (e.g., increasing the size of storm sewers and culverts; separating wastewater and stormwater sewers) and building protective infrastructure (e.g., constructing dikes to protect facilities against flooding, relocating pumps and pipes to higher elevations, installing backup emergency systems). A second pathway is using alternative water management approaches, including natural infrastructure (e.g., planting urban forests, green roofs, using water capture and storage for on-site use, redirecting and slowing runoff volume via the use of constructed wetlands and bioswales). Both of these pathways can be used separately or together as part of an asset management program (Mercer Clarke & Clarke, 2018). Table 4 identifies various strategies for reducing the impact of climate change hazards on Canada's wastewater and stormwater infrastructure, which are elaborated on in Appendix 4.

Table 4. Illustrative examples of climate hazards, impacts, and resilience options for wastewater and stormwater infrastructure

Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Heat	• Higher temperature streams and decreased streamflow lead to more concentrated influent flows that are harder to disinfect	• Apply natural infrastructure solutions (green roofs, urban forests) to increase assimilative capacity of receiving streams
Changing precipitation patterns	• Exceeding stormwater/drainage systems	• Increased capacity of stormwater and drainage collection systems • Reduce or green up impervious surfaces (e.g., roofs, parking areas)
Seasonal temperature changes	• Increased frequency, duration, and severity of thermal cracking and rutting	• Use phase-change materials to reduce the number of freeze/thaw cycles
Storm surges	• Damaged or flooded structures that reduce treatment efficiency	• Hybrid built and natural infrastructure solutions (e.g., terraced berms, drainage improvements, bulkheads, beach nourishment, reinforced dunes, offshore breakwaters, living shorelines)

3.2.5 Marine Infrastructure

PORTS, CANALS, WHARVES, PIERS, SEAWALLS

Canada's coastline extends more than 243,000 km, making it the longest in the world. The Atlantic, Pacific, and Arctic coastal regions are characterized by relatively narrow coastal zones containing bays and shallow water (Greenan et al., 2019; Lemmen et al., 2016). Marine infrastructure plays a significant role in Canada's national and regional economies, with 550 port facilities across the country. In 2017, marine shipping accounted for almost CAD 90 billion in international exports and CAD 110 billion in imports (Transport Canada, 2019).

As the climate changes, **marine infrastructure will be impacted by weather events** such as storm surges, strong winds, and high-tide flooding; **gradual landscape changes** from erosion and sea level rise (CCA, 2019); **and by land-based weather events** such as floods that affect port access and the transport of people and goods to and from the coast (Lemmen et al., 2016). As these climate hazards become more frequent and intense, they will result in costly damage and possibly render infrastructure unusable (Ford et al., 2018). As goods amounting to approximately CAD 400 billion are shipped on a yearly basis through Canada's ports, inoperable infrastructure can cause significant economic impacts across the country (Lemmen et al., 2016).

Similar to other types of infrastructure, marine infrastructure is affected by climate-related critical events, compromised structural integrity, and reduced lifespan. In the North, extended ice-free seasons will bring more opportunities for resource exploration and transport through

Arctic waters (Arctic Council, 2019). However, new and existing marine infrastructure will be particularly affected by increased permafrost melt, movement of sea ice cover, changing freeze–thaw cycles, high-intensity rain, and storms—and will thus need to adapt to new conditions (Lemmen et al., 2016). The Great Lakes inland shore region is also an area of particular concern given it is home to the most populous region in Canada. As the region experiences more extreme swings between drought and heavy rains (Emerging Issues Working Group of the Great Lakes Water Quality Board, 2017), there will be greater likelihood of low water levels similar to what occurred in 2014, causing navigation and vessel capacity issues (Lemmen et al., 2016), while above-average precipitation across Ontario can result in higher-than-average water levels for Lakes Superior, Michigan-Huron, St. Clair, and Erie (Zuzek, 2020b). Reduced lake ice cover caused by rising temperatures could result in greater storm-related flooding and erosion impacts on shore infrastructure and communities, as ice plays a critical role in protecting shoreline infrastructure from wave impacts (Zuzek, 2020a).

The literature review showed that **there are five types of adaptation strategies to consider when safeguarding marine infrastructure against climate hazards: procedural, avoidance, accommodation, protection, and retreat**. These strategies use land-use planning and engineering tools that integrate planning frameworks, capacity development, regulation, land-use change, and design tools to manage erosion and flooding, localized sea level regression, permafrost melt, and changing freeze–thaw cycles.

Procedural approaches include capacity-building programs that educate the public about climate change, climate data collection and organization to support decision making, planning frameworks, regulations and land-use change, and site design tools. These approaches can support engineering adaptation tools by placing them within a broader adaptation strategy (Arctic Monitoring and Assessment Programme, 2017; van Proosdij et al., 2016). Engineering tools such as the PIEVC Protocol can help identify critical points of vulnerability and potential risks for new and existing marine infrastructure (CCA, 2019).

Avoidance strategies encompass mapping coastal areas to avoid increased development in highly vulnerable areas. These strategies are most appropriate when considering new infrastructure (Palko & Lemmen, 2017; van Proosdij et al., 2016).

Accommodation strategies include managing physical infrastructure to accommodate climate hazard impacts and alterations to manage erosion on the landscape. These strategies can be supported through the use of natural infrastructure, such as artificial reefs, perched beaches, living shorelines, wetlands, drainage ditches, detainment ponds, and rain gardens. Physical structures can incorporate design elements to reduce erosion and prevent flooding, using flexible and more impact-resistant design to accommodate a gradual increase in protection from storm surges and sea level rise.[3] Seawalls, wharves, and retaining walls are most vulnerable to overtopping

[3] Examples of flexible design strategies include adding rocks, raising structures, retrofitting pile and space frame foundations, and floating buildings.

and erosion damage and may require remediation by way of raising the crest of the structure or building a flatter slope (Ford et al., 2017; Leys & Bryce, 2016).

Protection strategies generally focus on landscape alterations aimed at reducing climate impacts on infrastructure and the environment, including the use of hybrid infrastructure. Physical adaptations to reduce erosion include perpendicular and nearshore breakwaters, retaining walls, nearshore artificial reefs, groynes, and engineered revetments or gabions. Flood protection can be provided by dikes, constructed wetlands, and tide barriers (Leys & Bryce, 2016). Building designs to protect against erosion and flooding impacts include scour protection and riprap armouring. The use of these measures, however, should undergo robust review to reduce unintended impacts to natural coastal processes and ecosystems (CCME, 2018). Coastlines can also be protected using barriers such as sandbags, rocks, and even sunken vessels to reduce the impacts of waves. However, when these strategies are insufficient, it may be necessary to employ the final strategy—retreat—and relocate vulnerable infrastructure to prevent damage (Palko & Lemmen, 2017).

Table 5 provides an overview of the adaptation strategies that can be used to address climate hazard impacts on marine infrastructure. A more detailed examination of the climate risks facing Canada's marine infrastructure, as well as potential risk reduction strategies, is provided in Appendix 5.

Table 5. Illustrative examples of climate hazards, impacts, and resilience options for marine infrastructure

Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Seasonal temperature changes	• Soil and slope instability and ground movement/settlement due to permafrost melt and increased freeze/thaw cycles	• Thicken embankments and new infrastructure design suited to permafrost environments
Storm surges	• Inundation of ports and other coastal infrastructure • Increased wave damage to docks and other mooring structures	• Build flooding considerations into building and infrastructure design • Actively restore shoreline habitat (i.e., dunes, salt marshes, vegetation)
Sea ice changes	• Increased shipping traffic in Arctic waters due to less sea ice creating new and additional demand for Northern ports	• Demand forecasting and planning for Arctic shipping and port facilities
Fluctuations in inland water levels	• Lower water levels leading to reduced vessel capacity	• Shift freight to road or rail, change navigation procedures, invest in flow augmentation technologies, and increase dredging of channels

3.2.6 Energy and ICT Infrastructure

TRANSMISSION, HYDRO, WIND, SOLAR, OIL & GAS, DATA & INTERNET, WIRELESS

Energy and ICT infrastructure are critical to the health and safety of Canadian communities and provide a foundation for Canada's economy. In 2021, electricity infrastructure projects alone comprised six of the top 10 largest infrastructure projects in Canada, totalling an estimated CAD 64.4 billion in costs (ReNew Canada, 2021). Crucially, Canada is facing a national Internet connectivity gap for rural and remote communities, a service that is essential for personal and business communications, public safety, and—as the COVID-19 pandemic has proven—for remote learning. In response, *Canada's Connectivity Strategy* was issued in 2019 by the federal government with an envelope of CAD 1.7 billion in new funding to enhance access for 900 communities, including 190 Indigenous communities (Innovation, Science and Economic Development Canada, 2019).

Similar to water supply infrastructure, **climate change can affect energy infrastructure both through physical impacts on the infrastructure components and through impacts to the sources of and demand for energy**. The array of relevant climate change hazards, impacts, and adaptation options for energy and ICT infrastructure is presented in Appendix 6 and discussed below.

Electricity. In 2016, the Canadian Electricity Association (CEA) issued *Adapting to Climate Change: State of Play and Recommendations for the Electricity Sector in Canada*. This report warned that climate change is likely to result in increased costs along the value chain as a result of damaged infrastructure, higher insurance costs, water scarcity, legal liabilities, and evolving regulatory standards (CEA, 2016). Similarly, the CSA reported that events such as high winds, flooding, excessive ice buildup, hail, and extreme heat and cold are already impacting the integrity and reliability of electricity grids, with such risks expected to increase with climate change (CSA Group, 2019f). While implementing adaptation measures may be costly, it was highlighted that upfront costs will be lower than inaction. In addition, much of Canada's electricity infrastructure is ageing, with most non-hydro infrastructure in need of renewal or replacement by 2050 (CEA, 2016).

Climate change impacts to electricity infrastructure are described by the CEA as occurring via three categories: (i) demand, (ii) generation, and (iii) electricity transmission and distribution infrastructure (CEA, 2016). With regard to demand, the report points out that changes in average and extreme temperature can increase summer demand for cooling purposes, including peak demand, but can also decrease winter heating demand. In terms of generation, climate change can affect resource availability and operating efficiencies. There are several risks to transmission, distribution, and supporting infrastructure due to increased temperatures, ice storm damages, changes in precipitation, permafrost melt, and higher winds.

Some climate change impacts are unique to various types of electricity infrastructure, for instance:

- **Hydroelectric dams**: With Canada being the second largest generator of hydroelectric energy in the world, dam safety is an important consideration. There are over 15,000 dams in Canada, of which 1,157 are defined as "large," and the majority were developed as components of hydroelectric projects (Canadian Dam Association, 2019). Climate change can increase the probability of dam failure. For instance, temperature fluctuations may induce additional mechanical stresses in concrete dams, and drier soils and water level fluctuations can increase processes such as internal erosion of embankment dams (Fluixa-Sanmartin et al., 2018).
- **Thermal and nuclear power generation**: As air and water temperatures increase, thermal and nuclear plants may need more water for cooling, but they may also be more constrained by regulations in how they can use and discharge water, potentially leading to plant deratings and shutdowns (CEA, 2016).
- **Wind power**: Ice on wind turbine blades can affect performance and durability. The design of the turbine will be affected by expected turbulence intensity, wind shear, and transient wind conditions such as wind speed or directional changes (Solaun & Cerdá, 2019).
- **Solar power**: Changes in solar irradiation and cloudiness would affect solar power output, while hail can damage photovoltaic panels. An increase in dirt, dust, snow, and atmospheric particles would decrease energy output (Solaun & Cerdá, 2019).

Oil and Gas. Climate change has the potential to affect oil and gas infrastructure in a variety of ways, including in the areas of exploration (i.e., increased ocean wave loading), production (i.e., site access delays in Northern areas due to permafrost melting and ice road deterioration), transport and terminals (i.e., ice-load variation, damage to coastal facilities), pipelines (i.e., thaw subsidence and frost jacking, wildfires), and refining and processing (i.e., loss of access to water, flooding, loss of peak cooling capacity) (International Petroleum Industry Environmental Conservation Association, 2013).

ICTs. While infrastructure related to ICTs will experience climate change impacts similar to electricity transmission and distribution infrastructure (CEA, 2016), some of the impacts will be unique to the sector. For example, increases in daily maximum temperature can cause overheating in data centres, exchanges, and base stations if the capacity of cooling systems is exceeded (Horrocks et al., 2010). Additionally, increases in average daily temperatures can cause the location/density of wireless masts to become sub-optimal since wireless transmission is dependent on temperature and can affect radio-frequency propagation if the density of foliage increases (Horrocks et al., 2010).

Adaptations. The review of literature supports that adaptations for energy and ICT infrastructure can be realized through planning and assessment, structural changes to infrastructure, and through ongoing monitoring and maintenance (see Appendix 6, as well as the illustrative examples in Table 6). For planning and assessment, examples include applying the ISO 31000 on risk management (or similar) to help engineers determine what infrastructure components are the highest risk and require adaptation solutions (CEA, 2016) and applying guidance for integrating climate data in energy valuation modelling (Fournier et al., 2020). Additionally, installing microgrids can enable communities to separate from failed central grids and run on secondary sources (Hendel-Blackford et al., 2017). Structural changes to increase the resilience of energy and ICT infrastructure include such actions as fortifying all flood-prone infrastructure and burying transmission and distribution lines to the degree possible. Ongoing monitoring and maintenance actions include efforts such as installing visual monitors to detect ice loading, boosting current prior to ice loading to melt ice, use of smart grid technology to have a precise location of failed infrastructure, and planned snow removal for solar panels.

Table 6. Illustrative examples of climate hazards, impacts, and resilience options for energy and ICT infrastructure

Climate hazard	Examples of infrastructure impacts	Examples of resilience options
Heat	• Overheating in ICT data centres, exchanges, and base stations • Water level fluctuations and drier soils can increase internal erosion of embankment dams	• Increase cooling system capacity • Enhanced dam safety monitoring and management
Seasonal temperature increases resulting in permafrost degradation and changing freeze-thaw cycles	• Displaced transmission tower foundations and damage to underground vaults and cable chambers	• Modify structural designs to permit adjustment of towers when displacement due to permafrost thaw occurs
Changes in precipitation patterns	• Flooding of energy generation plants and substations and dam spillway gate performance issues • Damage to the supporting infrastructure of ICT systems such as copper and fibre-optic cables	• Elevate substations and electrical infrastructure components and enhance dam safety monitoring and management • Bury transmission and distribution lines to fortify against flooding
Winter/ice/windstorms	• Snapped power lines, broken or fallen utility poles, ice buildup on wind turbine blades	• Bury distribution lines • Install microgrids to enable communities to separate from failed central grids and run on secondary sources
Wildfires	• Damage and/or destruction of lines and transmission poles • Annealed or damaged conductors	• Bury electrical grid to avoid infrastructure damage from extreme heat and fire • Keep fire-prone areas clear of brush

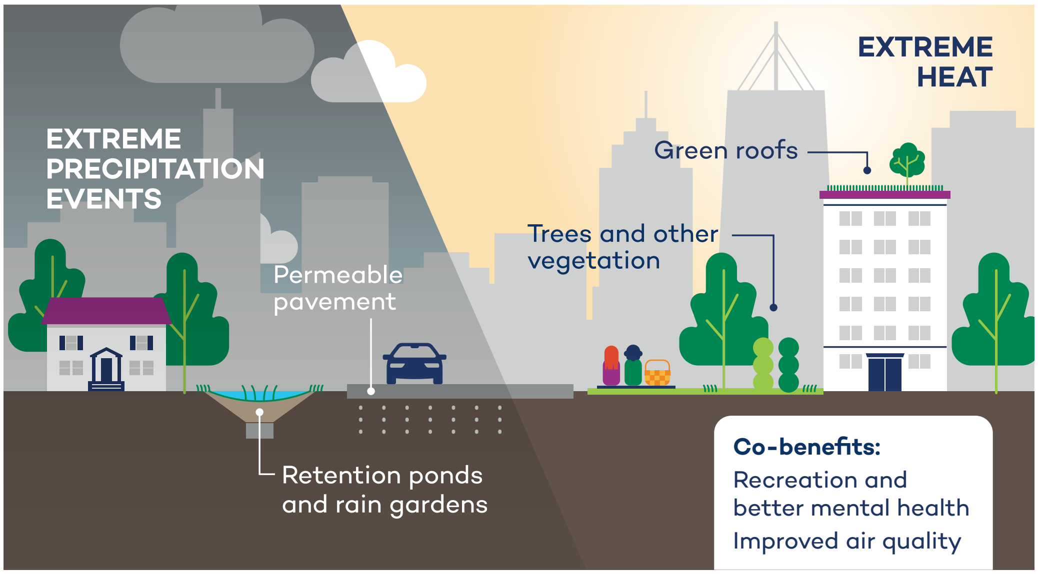
3.3 Natural Infrastructure Solutions

As highlighted in Section 2.3, **natural infrastructure solutions are increasingly being recommended for enhancing the resilience of communities and complementing built infrastructure**. At the international level, the GCA outlines in its flagship report that nature-based solutions work for both climate adaptation and mitigation, calling on governments to "raise understanding of the value of nature for climate adaptation; embed nature-based solutions into adaptation policy and planning; and increase investment in nature-based solutions" (GCA, 2019).[4] In Canada, nature-based solutions are an integral part of the federal government's strengthened climate plan released in 2020, which emphasizes embracing the power of nature to support healthier families and more resilient communities (Government of Canada, 2020).

A variety of natural infrastructure types can be used to reduce risks and enhance resilience relating to a range of climate hazards, as illustrated in Table 7. For example, in the context of coastal storms and flooding, an expert report prepared for the CCME listed such natural infrastructure types as salt marshes, maritime forests, reefs, beaches, dunes and hybrid solutions combining natural and grey infrastructure as ways to enhance resilience (ICF, 2018). Coastal wetland ecosystems can also adapt to sea level rise by migrating landward, assuming there is enough space along the shoreline to allow their movement (Horizon Advisors, 2019). The U.S. Army Corp of Engineers (2015) recommended a similar set of natural and nature-based features for reducing coastal risks and increasing community resilience. Likewise, inland wetland conservation has also been demonstrated to be effective at reducing flood damage in both rural and urban environments. A study at two pilot sites in southern Ontario found naturally occurring wetlands could reduce flood damage costs to buildings by CAD 3.5M (29%) at a rural site and CAD 51.1M (38%) at an urban site (Moudrak et al., 2017). In the context of urban stormwater management, the literature converges on a common set of natural infrastructure solutions for reducing risk and enhancing resilience, including rain gardens, bioswales, porous/permeable pavement, trees, green roofs, and bioretention ponds (see Figure 3).

[4] Canada played a leadership role within the GCA as a convening country and co-led the GCA's Action Track on nature-based solutions with the government of Mexico. The Action Track "engaged with representatives of Indigenous Peoples throughout the Year of Action to ensure that Indigenous knowledge, rights, and leadership are foundational in efforts to scale up NBS" (Climate Adaptation Summit, 2021, p. 2). In its final communique, the Action Track called on governments to "adopt concrete commitments to partner with Indigenous peoples to develop NBS-related policies and programs" (Climate Adaptation Summit, 2021, p. 4).

Figure 3. Natural infrastructure and hybrid solutions for increasing climate resilience in urban areas



Beyond these climate resilience benefits, **natural infrastructure provides a number of environmental and social co-benefits** such as improved air quality, an increase in recreational spaces, and other ecosystem services such as water filtration (ICF, 2018). These benefits are reflected in the conclusions of a 2019 report commissioned by Environment and Climate Change Canada (Horizon Advisors, 2019, p. 3):

> In some applications [natural infrastructure] elements can protect existing built infrastructure; elsewhere, they can help to offset some of the more damaging environmental impacts of grey infrastructure. Overall, what distinguishes [natural infrastructure] is its ability to provide targeted infrastructure outcomes, supported by additional benefits including biodiversity improvements, habitat protection, climate adaptation, carbon sequestration and ecosystems services supporting the health of human communities and functioning ecosystems.

The potential benefits of natural infrastructure also include green growth and job creation. For example, an economic impact assessment of the green infrastructure sector in Ontario found that in 2018, the sector generated CAD 8.6 billion in gross output (revenues), CAD 4.64 billion in direct gross domestic product, and directly employed approximately 84,400 people (Green Infrastructure Ontario Coalition, 2020). The green infrastructure assets and services included landscape horticulture and open spaces, natural heritage, parks, urban forests, green stormwater management, and green roofs and walls, as well as the cross-sectoral support services that play essential roles across these sub-sectors.

Benefit-cost ratios for various forms of natural infrastructure demonstrate their cost efficiency in delivering ecosystem and social co-benefits. For example, in Manitoba, analyses conducted at Pelly's Lake revealed a benefit-cost ratio for its hybrid solutions of 3.6 (Bassi et al., 2019) and for various water storage options including regraded ditches, filter field and ponds, and back-flooded dams, where benefit-cost ratios were approximately 1.9, 1.3, and 3.7, respectively (Dion & McCandless, 2013). Additionally, studies conducted in British Columbia revealed that the types of investments made in transportation infrastructure, parks, and land-use actions can significantly reduce health care costs related to hypertension and heart disease, for instance, 47% and 31% less, respectively for walkable versus car dependent areas (UBC Health & Community Design Lab, 2019).

It is important to also note that natural infrastructure solutions can themselves be affected by various climate hazards. Therefore, resilience options relating to planning and assessment, structural changes, and ongoing monitoring and maintenance may need to be considered in much the same manner as described for built infrastructure in Section 3.2. With the frequency and intensity of climate hazards such as drought, flooding, storms, and wildfires increasing under climate change, impacts can recur before a natural infrastructure component has had a chance to recover, especially when exacerbated by land use, pollution, and other socio-economic stressors (Seddon et al., 2020). From a planning perspective, ecological models and scenario analysis can be used to project the impacts on natural infrastructure components under different climate change scenarios (Chausson et al., 2020) and design modifications incorporated as needed (i.e., more drought-, flood-, or cold-resistant species). In addition, the sensitivity of natural infrastructure can be minimized by reducing the socio-economic stressors on the system, including pollution, invasive species, habitat loss and fragmentation, and over-exploitation (Seddon et al., 2020). Structural resilience options can be implemented to increase ecosystem diversity, such as multi-species tree crops for wind and snow shelterbelts, or by allowing degraded areas to regenerate naturally (Seddon et al., 2020). As with built infrastructure, regular monitoring and maintenance can increase the resilience of natural infrastructure solutions, especially active management to promote ecosystem regeneration following climate stress (Seddon et al., 2020).

Table 7. Natural infrastructure solutions for reducing exposure and vulnerability to climate change hazards

Climate hazard	Natural infrastructure solutions
Sea level rise, coastal storms and flooding, loss of ice cover[1,2,3,4,5,6]	• Artificial reefs • Oyster and coral reefs • Living shorelines • Salt marshes • Wetlands • Submerged aquatic vegetation • Maritime forests and shrub communities • Beaches and dunes • Barrier islands • Plant stabilization • Beach nourishment • Perched beach (enabled by a submerged sill)
Riverine flooding[4,5,6]	• Floodplain restoration • Wetland restoration/conservation/ construction • Flood setbacks • Two-stage channels • Relief channels • In-stream structures • Bank vegetation and seeding • Re/afforestation and forest conservation • Riparian buffers • Reconnecting rivers to floodplains • Establishing flood bypasses
Increased stormwater (urban and rural) from extreme precipitation events[4,5,6]	• Green roofs • Bioswales • Bioretention ponds • Rain gardens • Water harvesting • Urban trees • Vegetative swales • Green spaces (bioretention and infiltration) • Permeable pavements • Wetland restoration/conservation/ construction
Extreme heat[4,6]	• Trees and other vegetation • Green roofs • Hybrid green and cool/reflective roofs

Climate hazard	Natural infrastructure solutions
Drought[5,13,14,15,16,17]	• Re/afforestation and forest conservation • Reconnecting rivers to floodplains • Wetland restoration/conservation/ construction • Water harvesting • Green spaces (bioretention and infiltration) • Permeable pavements • Riparian buffers • Restore water table depth (infilling ditches, channels) • Promote drought-resilient native species
Windstorms and wind erosion[4,7,8,17,18,19]	• Tree walls/shelterbelts/windbreaks • Agroforestry and agro woodlots, including alley cropping • Increase tree species diversity • Manage for unevenly aged stands
Wildfires[9,10,11,12,17,20,21,22,23]	• Green firebreaks • Fuel-break systems and buffer zones • Open spaces and greenbelt areas • Prescribed fire to reduce future burn intensity • Promote fire-resistant native species, where appropriate
Water erosion[5]	• Re/afforestation and forest conservation • Riparian buffers • Reconnecting rivers to floodplains

Sources: [1]USACE, 2015; [2]USACE, 2013; [3]Leys & Bryce, 2016; [4]ICF, 2018; [5]United Nations Environment Programme (UNEP), 2014; [6]Environmental and Energy Study Institute, 2019; [7]Agriculture and Agri-Food Canada, 2010; [8]Bellet, 2013; [9]Cui et al., 2019; [10]Food and Agriculture Organization, 2002; [11]USDA, 2011; [12]FireSmart Canada, 2003; [13]Parks Canada, 2021; [14]Chimner et al., 2019; [15]Schimelpfenig et al., 2014; [16]Howie et al., 2009; [17]Canadian Council of Forest Ministers, 2009; [18]Messier et al., 2019; [19]Lafond et al., 2014; [20]Halofsky et al., 2020; [21]Gillson et al., 2019; [22]Enright et al., 2014; [23]Guiterman et al., 2018.

4.0

Policies, Practices, and Financing to Support Climate-Resilient Infrastructure

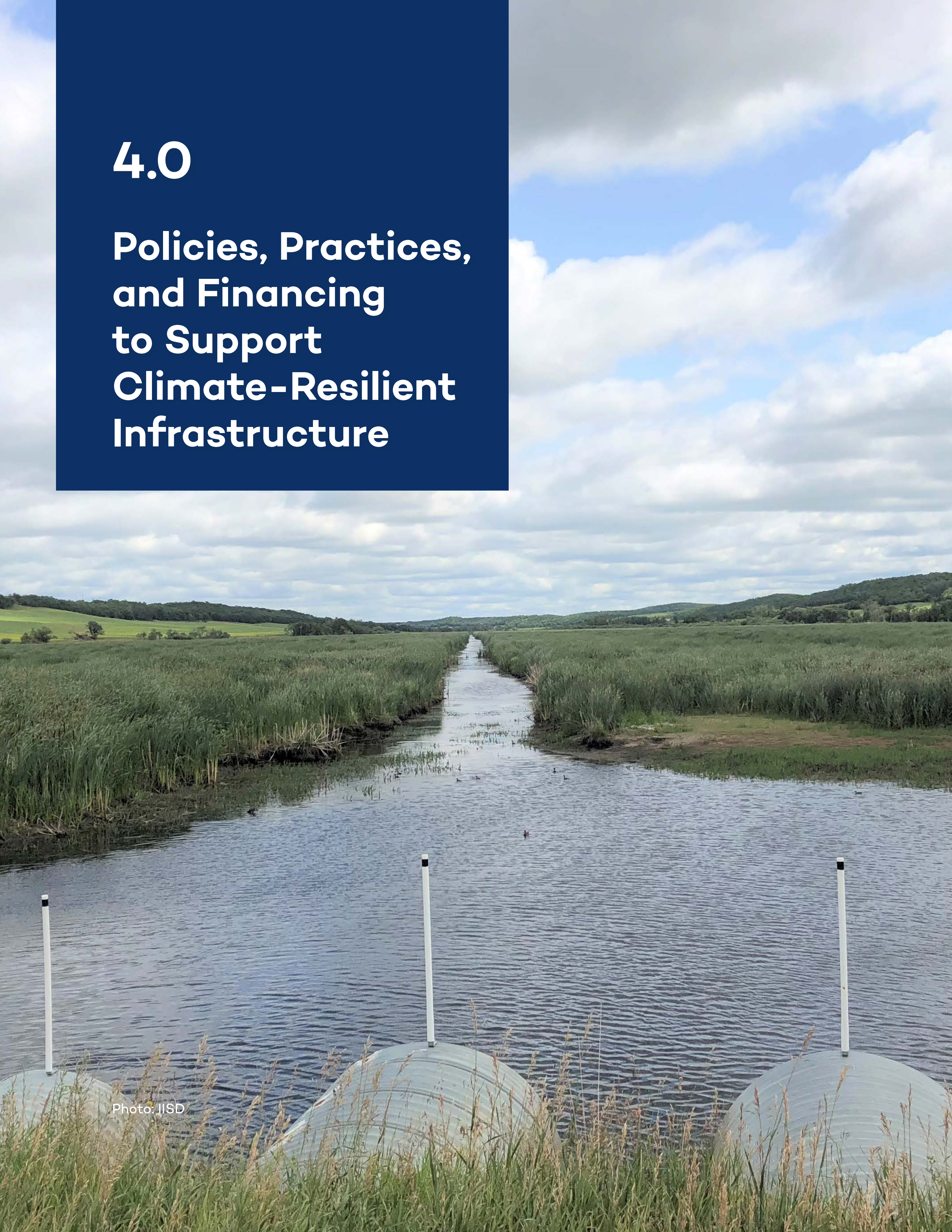


Photo: IISD

Action on climate change has been gaining momentum within Canada and internationally for the past few decades. A watershed moment occurred in 2015 when the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), the 2030 Agenda for Sustainable Development (with its 17 SDGs), the Sendai Framework for Disaster Risk Reduction, and the Addis Ababa Action Agenda on Financing for Development were all signed. Each of these agreements, endorsed by all Member States of the United Nations at the time, emphasized the importance of building resilience to climate change and other hazards in one form or another. This international policy convergence, along with the mounting evidence of the urgency to start adapting to the current and future impacts of climate change, has caused a surge of effort in countries around the world to accelerate efforts to enhance the resilience of their infrastructure, economies, and societies.

Another important indicator of the greater attention being given to the risks (and opportunities) associated with the impacts of climate change can be seen in the discourse related to international and national finance. Today, terminology such as risk-informed investment and sustainable finance is becoming commonplace. In Europe, for example, the European Commission (EC) launched its consultation process on a Sustainable Finance Strategy (EC, 2020) in 2020, building on its 2018 Action Plan: Financing Sustainable Growth (EC, 2018). The latter called for concrete actions related to reorienting capital flows toward a more sustainable economy, mainstreaming sustainability into risk management (including climate risk), and fostering transparency and long-termism. The growing attention being given to climate change in the finance sector is also evidenced by the formation of such groups as the Task Force on Climate-Related Financial Disclosures (TFCD, 2017); the International Platform on Sustainable Finance launched by the European Commission together with the governments of Argentina, Canada, Chile, China, India, Kenya, and Morocco (EC, 2019); and the ISO Technical Committee on Sustainable Finance (ISO/TC 322, 2020).

Against this backdrop of international commitments and growing urgency, action across the federal government and within provinces, territories, and Indigenous communities to increase the resilience of infrastructure to climate change has been gaining momentum. This section takes stock of the array of policies, guidelines, and financing mechanisms that have emerged at the federal level in Canada in support of climate-resilient infrastructure. It also provides examples of international approaches to promoting climate-resilient infrastructure that can inform action in Canada. A comprehensive review of policies, guidelines, and financing implemented by provinces, territories, municipalities and Indigenous communities was not possible within the scope of this report.

4.1 Policies, Frameworks, Strategies, and Plans

In Canada and internationally, a number of recently introduced policies, frameworks, strategies, and plans are shaping government action on the need to increase the climate resilience of infrastructure. This section outlines federal policy action in Canada before highlighting some examples of multilateral, regional, and national initiatives underway outside of Canada.

4.1.1 Federal Policy Action

Over the past decade, the Government of Canada has introduced a range of policies, frameworks, and regulatory mechanisms to advance climate change adaptation across federal government department mandates as well as support the efforts of provincial, territorial, and municipal governments; Indigenous governments; the private sector; and community stakeholders. The **Federal Adaptation Policy Framework** released in 2011 helped set the parameters for the federal government's initial role in adaptation planning and action in Canada. This document "guides domestic action by the Government of Canada to address adaptation to the impacts of climate variability and change" (ECCC, 2011a, p. 2). The purpose of this policy framework is to support the integration of climate adaptation considerations into federal processes; define the role of the federal government relative to other levels of governments, the private sector, and civil society; and ensure that adaptation planning is at the forefront of federal government activities (ECCC, 2011a).

In 2016, Canada released the **Pan-Canadian Framework on Clean Growth and Climate Change** (PCF) to guide national climate change efforts. Developed collaboratively with the federal, provincial, and territorial governments, the PCF enables provinces and territories to design region-specific policies and programs that meet emissions-reduction goals and are supported by funding for infrastructure and clean technologies (Government of Canada, 2016). One of the PCF's four pillars centres on adaptation and climate resilience. The pillar aims in part to ensure that communities and infrastructure are prepared for climate risks and extreme weather events through actions that include (Government of Canada, 2016):

- Building climate resilience through infrastructure by investing in infrastructure that strengthens resilience and establishing new codes and standards for both traditional and green infrastructure construction and management.
- Reducing the impact of climate-related hazards and disasters, such as floods and wildfires, by investing in traditional and natural infrastructure.

A number of programs and initiatives have been set up to support the achievement of the PCF's mitigation and adaptation objectives, including collaborative action between federal, provincial, and territorial governments, as discussed in Section 4.2.

In an effort to advance the federal government's climate change objectives, the Cabinet approved the **Greening Government Strategy** led by the Treasury Board of Canada Secretariat in 2016 and updated it in 2020. With the support of the Centre for Greening Government, the initiative aims to take action to reduce greenhouse gas emissions and increase climate resilience across all federal departments in support of commitments under the Paris Agreement and the PCF. While this strategy focuses primarily on climate change mitigation, resilience policies put forth include: requiring climate-resilience portfolio plans; ensuring all new federal buildings, infrastructure, and major building retrofits conduct a climate change risk assessment that incorporates current and future climate scenarios; using natural infrastructure and similar nature-based solutions to protect physical assets; and integrating adaptation considerations into all aspects of major property projects, such as using climate-resilient building guidance developed by the National Research Council of Canada (Government of Canada, 2021a).

Most recently, the Government of Canada introduced the **Healthy Environment and a Healthy Economy Plan**, which builds on the PCF, aiming to achieve its low-carbon economy objectives while creating jobs and restoring employment to pre-pandemic levels. A key element of this strategy is to invest in the Canada Infrastructure Bank to support the building of clean infrastructure. Of specific importance, this plan commits to developing a **National Adaptation Strategy**, supporting Indigenous climate leadership, and promoting climate mitigation and resilience by applying the climate lens throughout government decision-making processes (ECCC, 2020).

Efforts to increase the climate resiliency of Canadian infrastructure are also buttressed by other sustainable development and environment-focused policies and strategies. This includes the Federal Sustainable Development Act and its associated strategies. The **Federal Sustainable Development Act** (2008) provides the legal structure to develop and implement Canada's Federal Sustainable Development Strategy (FSDS). The purpose of the Act is to "prevent environmental sustainability issues from being pushed to the margins of federal planning and reporting" (ECCC, 2011b, p. 4). Under the Act, 26 federal organizations and 16 other organizations are mandated to develop strategies that contribute to the FSDS (Government of Canada, 2008). The FSDS, updated every three years, identifies the federal government's environmental and sustainability priorities and acts to make environmental decision making more transparent and accountable and in line with goals. Since 2016, the FSDS was modified to align with the United Nations 2030 Agenda and the SDGs.

There are several departmental sustainable development plans that are key to advancing adaptation planning and implementation in regard to infrastructure across the country, such as:

- Transport Canada coordinates the Northern Transportation Adaptation Initiative, a cornerstone of the FSDS, and the Oceans Protection Plan, which implements projects to protect coastal and ocean environments. The Transportation Assets Risk Assessment initiative identifies and implements climate risks and adaptation solutions relating to federal transportation assets and internally; efforts are being made to mainstream climate change considerations and adaptation planning into all decisions regarding federal transportation assets (Transport Canada, 2020).
- Public Safety Canada oversees the Emergency Management Strategy for Canada. This strategy is aligned with the UN Sendai Framework for Disaster Risk Reduction (2015–2030), which connects disaster risk reduction and sustainable development efforts globally. The purpose of this alignment is to strengthen communities' adaptive capacity and resilience in the face of extreme climate hazards. One element of building community resilience is prioritizing build-back-better principles such as accounting for future climate impacts in new and existing physical infrastructure during disaster reconstruction (Public Safety Canada, 2019).

Efforts to increase the climate resiliency of Canada's infrastructure are also being influenced by infrastructure-focused frameworks and initiatives. For instance, the **Arctic and Northern Policy Framework** is a federal policy framework co-developed by Northern communities, Indigenous governments, and six territorial and provincial governments. Several of the framework's priorities directly address the impacts of climate change on communities and the need to invest in energy, transportation, and communications infrastructure. While this framework does not speak to the types of adaptation activities to be taken, it does recognize the need to address climate change impacts and the importance of upgrading and expanding existing infrastructure across the region (Crown-Indigenous Relations and Northern Affairs Canada, 2019).

In 2020, the federal government announced its intention to undertake Canada's first **National Infrastructure Assessment** (Infrastructure Canada, 2020). Building on the experience of countries such as Australia, New Zealand, and the United Kingdom, the National Infrastructure Assessment will use data and evidence to identify Canada's long-term infrastructure needs and long-term vision, strengthen linkages between infrastructure owners and funders, and determine "the best ways to fund and finance infrastructure" (Infrastructure Canada, 2021a, p. 6).

4.1.2 Federal Knowledge and Capacity-Building Initiatives

The federal government has initiated various programs in keeping with the Federal Adaptation Policy Framework's objective of providing Canadians with access to the information and capacity they need to adapt, as well as new commitments under the PCF's Adaptation and Climate Resilience pillar. This includes establishing Canada's **Climate Change Adaptation Platform** in 2012 to promote collaborative climate adaptation. The Platform brings together provincial and territorial governments, Indigenous groups, civil society, academics, and others to share tools and information. Collaboration takes the form of working groups and regional collaboratives (NRCan, 2018a). The Platform's Infrastructure and Buildings Working Group aims to build capacity for municipalities, builders, insurers, engineers, and infrastructure managers to incorporate adaptation considerations into their infrastructure work (NRCan, 2018b).

NRCan also leads Canada's **national adaptation assessment process**, periodically preparing reports that synthesize current understanding of climate risk and adaptation. For example, between 2013 and 2016, NRCan and Transportation Canada collaborated to produce the report *Climate Risks and Adaptation Practices for the Canadian Transportation Sector 2016* (Palko & Lemmen, 2017). The current national assessment of climate risk and adaptation progress, Canada in a Changing Climate: Advancing our Knowledge for Action, began in 2016 and released a synthesis of Canada's past and projected changes in Canada's climate in 2019 (NRCan, 2019). The *Prairie Provinces Regional Perspective* report was released in 2020 (Sauchyn et al., 2020). Additional regional chapters and a national issues report will be released in 2021.

Advancing a commitment under the PCF, in 2018, ECCC launched the **Canadian Centre for Climate Services** (CCCS). It provides Canadians with authoritative information and support to consider climate change in their decision making (Government of Canada, 2021b) and includes a wide range of information, products, and services for users from across sectors. As part of its work, the CCCS is working with experts to develop a focused module at ClimateData.ca on transportation and buildings, which will package and curate information (i.e., climate-related data, case studies, and more) needed to support decisions within these areas of work. Similarly, the CCCS is working with NRCan to develop a database of adaptation action case studies from across sectors (including transportation and infrastructure) to increase knowledge on and the uptake of adaptive measures, that will be accessible through Changingclimate.ca.

4.1.3 International Policies and Initiatives

At the international level, efforts to address the impacts of climate change are guided by the Paris Agreement (UNFCCC, 2015), the 2030 Agenda for Sustainable Development (UN, 2015), and the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015). Resilient infrastructure plays a crucial role in supporting achievement of the goals of these three agreements. The Sendai Framework adopted in 2015, for example, outlines seven global targets to be achieved by 2030. Target D, in particular, relates to infrastructure and calls for countries to "substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030" (UNDRR, 2015, p. 12).[5]

Several other international organizations have published principles, frameworks, and agendas for action that can inform Canadian efforts to enhance the resilience of its built infrastructure. UNEP's ***International Good Practice Principles for Sustainable Infrastructure*** published in 2021, for example, provides integrated, systems-level approaches for policy-makers, including 10 guiding principles that policy-makers can follow to help integrate sustainability into infrastructure planning and delivery (UNEP, 2021a). Principle #2 calls for "responsive, resilient and flexible service provision" and emphasizes the importance of understanding and managing demand, ensuring flexibility and resilience to allow for changes and uncertainties over time, and systems-level planning that promotes synergies for improved connectivity. These principles are complemented by a second publication, *Integrated Approaches in Action: A Companion to the International Good Practice Principles for Sustainable Infrastructure* (UNEP, 2021b). Through these publications, UNEP aims to inform the "forthcoming wave of global infrastructure investment" (UNEP, 2021b).

[5] Implementation of the Sendai Framework has not been without its challenges. A 2017 assessment on the readiness of all participating nations to report on the Sendai Framework targets showed that data on infrastructure damage is often missing, or only takes account of large-scale crisis events, or is calculated in a different manner by different countries (UNDRR, 2020). The UNDRR, the agency backstopping the Sendai Framework, recommends that governments "make greater efforts to set appropriate mechanisms for the collection of detailed data in line with the reporting requirements of the Sendai Framework so that they can take more informed decisions to protect their critical assets" (UNDRR, 2020, p. 40).

The OECD set forth recommendations in 2014 on the **Governance of Critical Risks** (OECD, 2014b). Among its recommendations were that countries:

- **Build preparedness through foresight analysis, risk assessments, and financing frameworks, to better anticipate complex and wide-ranging impacts**. This includes the identification of critical hazards and threats so as to assess them using the best available evidence; understanding risks in terms of their potential likelihood, plausibility, and impacts; and developing location-based inventories of exposed populations and assets, as well as infrastructure that reduces exposure and vulnerability.
- **Reduce critical risks through strategic planning** to build safer and more sustainable communities, paying attention to the design of critical infrastructure networks (e.g., energy, transportation, telecommunications and information systems); fiscal and regulatory options to promote reserve capacity, diversification or backup systems to reduce the risk of breakdowns and prolonged periods of disruption in critical infrastructure systems; and incorporation of risk management decisions, as well as safety and security standards in national and local regulations for land use, building codes, and the design, development, and operations of critical infrastructure.
- **Encourage businesses to take steps to ensure business continuity**, with a specific focus on critical infrastructure operators.

Furthermore, the ***OECD Framework for the Governance of Infrastructure*** published in 2017 emphasized that "public infrastructure needs to be resilient" (OECD, 2017, p. 13). In support of this, the OECD recommends that countries give attention to four key policy questions. Importantly, the first question asks if policies are in place to ensure that key infrastructure assets are resilient if disasters hit, while the second question asks if key structures are designed to sustain a foreseeable shock or if substitute or redundant systems are available. A second set of diagnostics are laid out to gauge if there is management capacity to identify options, prioritize actions, and communicate decisions to the people who will implement them and if tools are in place to learn from past events.

Knowledge sharing around climate-resilient infrastructure is supported by the **Coalition for Disaster Resilient Infrastructure** (CDRI), a global knowledge exchange platform representing a partnership of national governments, UN agencies and programs, multilateral development banks and financing mechanisms, the private sector, and knowledge institutions (CDRI, 2021). Its intent is to promote the development of resilient infrastructure to climate and disaster risks in support of sustainable development. The strategic priorities of the CDRI include technical support and capacity building, research and knowledge management, and advocacy and partnerships.

Also at the global level, in 2020, the G20 Group of Countries presented the **G20 Action Agenda on Adaptation and Resilient Infrastructure** (G20, 2019). The Action Agenda contains a variety of actions on climate change adaptation, disaster risk reduction, and quality and resilient infrastructure at multilateral, bilateral, regional, national, and local levels. Among the actions recommended were the following:

- Taking a comprehensive approach to developing a strategic planning process for adaptation, disaster risk reduction, and sustainable development
- Accumulating and sharing knowledge, information, and best practices for adaptation planning
- Enhancing enabling environments and developing capacities for adaptation, resilience, and disaster risk reduction
- Providing public finance, engaging the private sector, and mobilizing private finance and investment
- Promoting ecosystem-based approaches and enhanced efforts in adaptation and disaster prevention that suit the local situations and conditions.

In Europe, the EC adopted its new **Strategy on Adaptation to Climate Change** in 2021 (EC, 2021). The new strategy highlights that investing in resilient, climate-proof infrastructure pays off in the long run with benefit-cost ratios of 4:1, and, in recognition of this, the EC has developed extensive climate-proofing guidance for new major infrastructure. The strategy also identifies that nature-based solutions must play a bigger role in land-use management and infrastructure planning to reduce costs and provide climate-resilient services. Box 2 profiles the analysis of climate risk to European infrastructure that informs the EC's climate-resilience efforts.

In the United Kingdom, the National Infrastructure Commission (NIC) issued a report in 2020 on resilient infrastructure systems focused on establishing a framework for resilience that includes six key aspects—anticipate, resist, absorb, recover, adapt, and transform (UK-NIC, 2020). The NIC's resilience framework for infrastructure calls on government and the United Kingdom's "energy, water, digital, road and rail infrastructure" sectors to better anticipate future shocks and stresses; improve actions to resist, absorb, and recover from shocks and stresses by testing for vulnerabilities and addressing them; value resilience properly; and drive adaptation before it is too late (UK-NIC, 2020, p. 9). Furthermore, it was noted that much of what is needed is already in place in the United Kingdom, but improvements are still needed, including that:

- Government should publish a full set of **resilience standards** every five years, following advice from regulators, alongside an assessment of any changes needed to deliver them.
- Infrastructure operators should carry out **regular and proportionate stress tests,** overseen by regulators, to ensure their systems and services can meet the government's resilience standards, and take actions to address any vulnerabilities.
- Infrastructure operators should develop and maintain **long-term resilience strategies**, and regulators should ensure their determinations in future price reviews are consistent with meeting resilience standards in the short and long terms.

Box 2. Resilience of large investments and critical infrastructure in Europe to climate change

In 2016, the Joint Research Commission of the EC studied the resilience to climate change of large investments and critical infrastructure in Europe (EC, 2016). The comprehensive study found energy, transportation, and industrial infrastructure to be vulnerable to a range of climate change hazards, including heat, cold, drought, wildfire, floods, and windstorms.

The study sounded the alarm that damages from climate extremes, "which at present total to €3.4 billion/year, could triple by the 2020s, multiply six-fold by mid-century, and amount to more than 10 times the present damages by the end of the century" (EC, 2016, p. 3). The main cause was described as a sharp decrease in the return periods of multiple extreme weather events (e.g., a current 100-year heatwave or 20-year flood that may occur every 1 or 2 years under future climate conditions).

With this evidence, the EC is sending "a strong signal to infrastructure business owners and operators that the current design, construction, operation and maintenance standards and practices should be amended in these sectors" (EC, 2016, p. 4).

4.2 Practices, Guides, Standards, and Codes

While policies, frameworks, strategies, and plans set the direction for efforts to reduce the impact of climate change on infrastructure, the availability of various guides, standards, and codes helps to put these commitments into practice. This section provides information regarding the array of federal-level efforts to develop and make available guidance, tools, standards, and codes to increase the climate resilience of Canadian infrastructure. It also identifies some of the international initiatives informing these efforts.

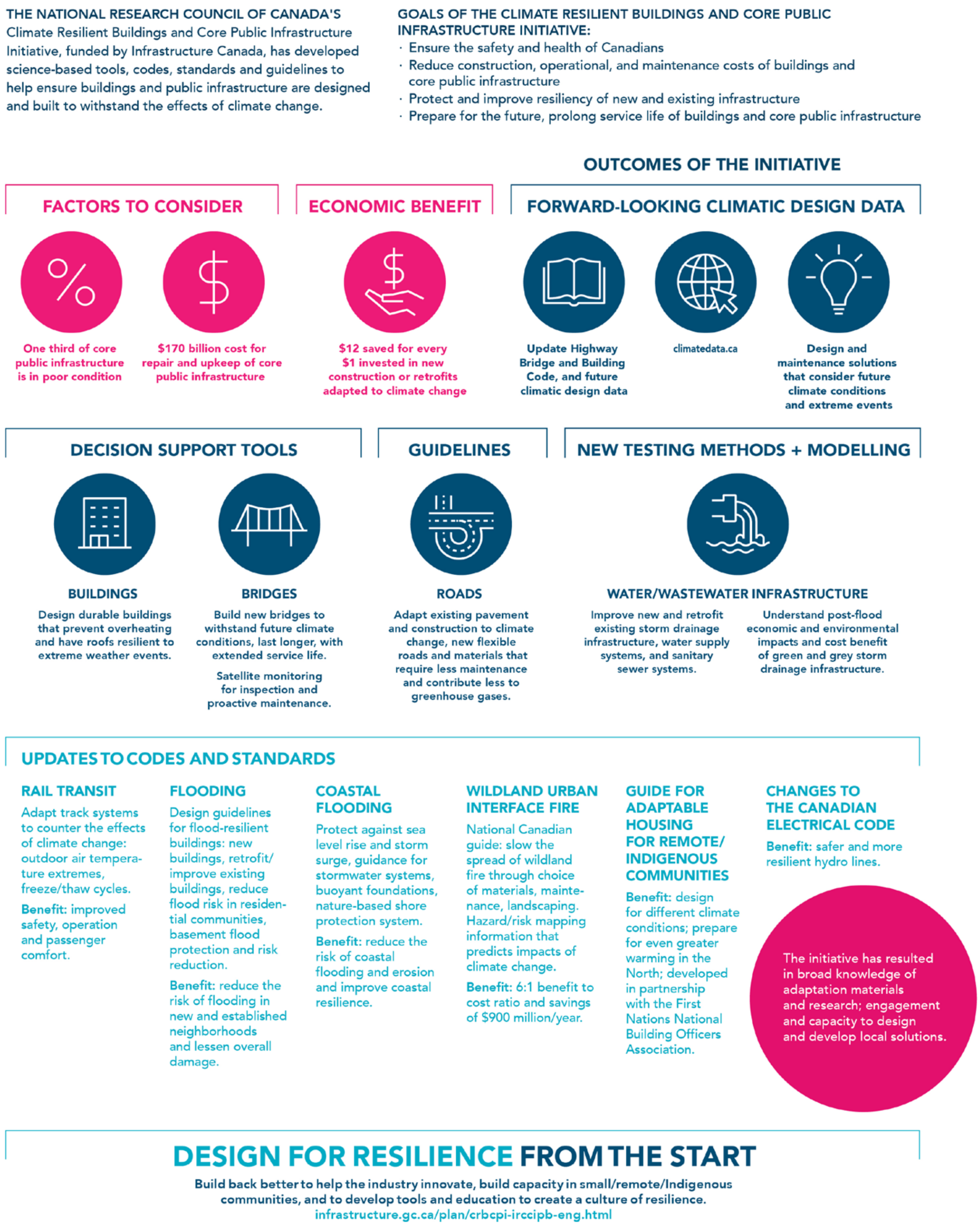
4.2.1 Federal-Level Developments

In the years following the release of the PCF, there has been a surge in the development of guidelines, practices, standards, and codes for supporting climate change adaptation and resilience of Canadian infrastructure. The paragraphs below provide an overview of some of the key developments at the federal level in Canada.

Infrastructure Canada's Climate Lens General Guidance is a horizontal requirement applicable to Infrastructure Canada's Investing in Canada Infrastructure Program (ICIP), DMAF, and Smart Cities Challenge (Government of Canada, 2019c). It includes a Climate Change Resilience Assessment that employs a risk management approach (i.e., ISO 31000, PIEVC Protocol, or similar) meant to anticipate, prevent, withstand, respond to, and recover from a climate change-related disruption or impact. Under ICIP, a climate change resilience assessment is required for projects applying for funding with costs of CAD 10 million or greater and all projects under the Green Infrastructure – Adaptation, Resilience and Disaster Mitigation sub-stream. It is also a requirement for any level of funding under the DMAF national program and for projects with a primary focus on climate change adaptation or mitigation and costs of CAD 10 million or greater under the Smart Cities Challenge Winners stream. To date, the assessments under the Climate Lens General Guidance (for resilience and/or mitigation) have been applied to 85% of ICIP's total federal funding (Infrastructure Canada, personal communication, 2021).

Led by the National Research Council of Canada (NRC) and funded by Infrastructure Canada, the **Climate-Resilient Buildings and Core Public Infrastructure Initiative** (CRBCPI) is developing science-based decision-support tools, codes, standards, and guidelines to develop capacity in Canada's construction industries to adapt to the increasing demands on built infrastructure attributed to climate change (NRC & Infrastructure Canada, 2020). Infrastructure Canada has also been supporting the uptake of natural infrastructure through the CRBCPI, including work on flooding and water/wastewater infrastructure. Figure 4 provides a snapshot of the CRBCPI, including its intended benefits.

Figure 4. Government of Canada's CRBCPI



Source: NCR, personal communication, June 2021.

In 2016 the SCC embarked on a five-year, CAD 11.7 million program entitled **Standards to Support Resilience in Infrastructure** (SCC, 2020). The program is focused on four key areas:

1. Arming standards writers with the tools to fight climate change. It has established the Standards Development Organizations for Climate Resilient Infrastructure Working Group to build the capacity of standards writers and prepare guidance documents such as *Addressing Climate Change Adaptation in Standards for Canada and Understanding Climate Change Models for Standards Development*. It is also supporting the Secretariat of the ISO 84:2020 *Guidelines for Addressing Climate Change in Standards* (ISO, 2020).
2. Getting the most out of weather and climate data, by providing standardization guidance for weather data, climate information, and climate change projections (Ouranos, 2017) so that such data can be better integrated into designing climate-resilient infrastructure. It is also supporting the development of a series of standards for improving access to local and regional weather and climate data for infrastructure designers, planners, owners, and operators to ensure resilience to the impacts of climate change. An update is also being undertaken of technical guidance for climate change-informed rainfall intensity-duration-frequency curves, which are used for designing stormwater drainage systems and traditionally based on historical climate data.
3. Helping Northern communities adapt to a rapidly changing climate. Recognizing that the Northern climate is projected to warm at three times the global rate, the SCC's Northern Infrastructure Standardization Initiative (SCC-NISI, 2020) delivers training videos and a series of climate change-informed standards to help: (i) ensure appropriate drainage systems (CSA Group, 2019d); (ii) address changing snow loads on roofs (CSA Group, 2019c); (iii) improve thermosyphon foundations (CSA Group, 2019a); (iv) manage the effects of permafrost degradation on existing buildings (CSA Group, 2019b); and (v) support geotechnical site investigations for building foundations in permafrost (BNQ, 2017). An update of the CSA 4011 Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, was also developed under the program (CSA Group, 2019e).
4. Supporting the design of infrastructure that can stand up to extreme weather events. The Standards to Support Resilience in Infrastructure program is developing guidance and reporting best practices for reducing the impact of flooding in communities (Intact Centre on Climate Adaptation, 2019; SCC, 2018a), preparing communities to deal with increased wildfires (SCC, 2018b), and mitigating the impacts of high winds on buildings and infrastructure across Canada (ICLR, 2019).

To improve access to guidelines on codes and standards, the CCCS has developed a **central repository of climate-resilience codes and standards documents**, in partnership with the SCC, the NRC, Infrastructure Canada, and the CSA Group. This collection of climate-resilient codes and standards pulls together over 40 relevant documents that can be found on a distinct website: they are also available at the Library of Climate Resources (CCCS, 2021).

While not a federal program, Engineers Canada formed the PIEVC in 2005 to conduct an engineering assessment of the vulnerability of Canada's public infrastructure to the impacts of climate change. The **PIEVC Protocol** is an assessment framework and process for reviewing historical climate information and projecting the nature, severity, and probability of future climate changes and events, as well as for establishing the adaptive capacity of an individual infrastructure as determined by its design, operation, and maintenance (ICLR & CRI, 2021). Over 70 PIEVC infrastructure risk assessments were completed in Canada from 2008 through 2020 (ICLR & CRI, 2021). The PIEVC Protocol has been applied to assess climate risks and vulnerabilities across a wide range of infrastructure systems in Canada including: buildings (residential, commercial, and institutional); stormwater/wastewater systems, roads and associated structures (e.g., bridges and culverts); water supply and management systems; electricity distribution; and airport infrastructure. In March 2020, ownership and control of the PIEVC Program was transferred to a partnership consisting of the ICLR, the CRI, and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (ICLR & CRI, 2021).

An additional resource, ***Guidance on Good Practices in Climate Change Risk Assessment***, was recently released by the CCME. Intended to inform the design of processes that best meet the needs of the user, the guidance provides fundamental information regarding climate risk assessment, questions to be asked prior to initiating an assessment, and an overview of six established frameworks—including the PIEVC Protocol (CCME, 2021).

Because climate impacts and risks are local, resilience measures need to be local as well. Infrastructure Canada works with the FCM through various programs to build community capacity around adaptation planning and asset management. The 5-year, CAD 75-million **Municipalities for Climate Innovation Program** delivered by the FCM and funded by the Government of Canada advances three main themes, namely greenhouse gas reductions, climate change adaptation, and climate and asset management (FCM, 2021). Under the climate and asset management theme, the FCM delivers training and resources for municipal governments to integrate climate considerations into asset management practices.

4.2.2 International Guidelines, Practices, Standards, and Codes

Canadians can look to a number of international standards when seeking to increase the climate resilience of their built infrastructure. In particular, there are three ISO standards that provide guidance related directly to adaptation to climate change: 14090, 14091, and 14092:

- **ISO standard 14090:2019 – Adaptation to climate change – Principles, requirements, and guidelines** provides guidance on how to integrate adaptation into project planning, design, implementation, and decision-making processes (ISO, 2019). This set of standards can inform a broad array of programs, projects, and policies as well as regulatory instruments such as the resilience assessments under Infrastructure Canada's Climate Lens General Guidance.

- **ISO standard 14091:2021 – Adaptation to climate change – Guidelines on vulnerability**, impacts, and risk assessment provides guidance to understand vulnerability and develop risk assessments accounting for present and future climate change risks (ISO, 2021).
- **ISO standard 14092:2020 – Adaptation to climate change – Requirements and guidance on adaptation planning for local governments and communities** is directed toward local governments and communities to support climate change adaptation based on vulnerability, impacts, and risk assessments, and provides guidance to develop and update an adaptation plan (ISO, 2020a).

A number of guidelines prepared by other countries can also inform efforts in Canada to build and maintain climate-resilient infrastructure. The United Kingdom's **Designing for Infrastructure Resilience**, for example, is a comprehensive guidance document that provides frameworks, tools, and best practices to improve the resilience of infrastructure (Department for International Development, 2016). The document emphasizes two key principles that form the basis of their suggested framework: (i) account for the impacts of disasters through technical, solution-based design approaches; and (ii) incorporate climate modelling in infrastructure risk assessments. Key best practices described include:

- Invest in strengthening the resilience of infrastructure prior to any specific climate event
- Ensure that the infrastructure can maintain an acceptable level of service even directly after a climatic event to reduce disruption to communities
- Invest in capacity building and skills to ensure codes, protocols, and guidelines are properly interpreted and implemented.

A Pan-European Framework for Strengthening Critical Infrastructure Resilience to Climate Change presents the main outcomes of research and case studies, and suggests recommendations to communities (EU-CIRCLE, 2020). The main message is that resilience can be achieved through multi-disciplinary stakeholder collaboration at the national and local levels, as well as through collaboration with academia and the private sector. The EU-CIRCLE outlines a risk- and resilience-management framework. To identify risk, the framework suggests a climate risk assessment, development of resilience indicators, and identification of adaptation options. To manage resilience, it offers a four-tiered model. The tiers include identifying which climate hazards cause impacts and whether they are exacerbated by climate change; describing the context of the infrastructure and how it relates to other infrastructure systems; assessing the current adaptive capacity of the infrastructure; and determining the resilience parameters or properties that indicate their capacities. This framework enables stakeholders to assess climate hazard risks, determine how climate change may alter future climate-related risks, and identify climate change adaptation and mitigation options.

The OECD's ***Climate-Resilient Infrastructure*** report provides policy guidance for enhancing infrastructure resilience through structural and management adaptation measures and by mobilizing private and public financing (OECD, 2018a). The document provides international examples of best practices for technical codes and standards, regulatory mechanisms, and national policies. Guidance is also given on scaling up financing for climate-resilient infrastructure. Given the existing financing gap for traditional infrastructure projects, the OECD acknowledges the difficulty of financing climate-resilient projects, in part because of the challenge of determining their cost savings over time. The report suggests several mechanisms to ensure resilience is integrated into infrastructure projects, including using procurement policies to ensure publicly financed infrastructure is resilient, increasing transparency for private investors through measurement and reporting, and improving the sequencing of interrelated projects. The document also includes a compendium of tools, policy guidance documents, and online platforms for practitioners and decision makers to further explore specific topics.

In 2020, the United Nations Conference on Trade and Development reviewed **policies, regulatory approaches, reports, and guidance documents for adaptation for the coastal transportation** sector (United Nations Conference on Trade and Development, 2020). The report provides a brief overview of climate change impacts on coastal transportation and suggested approaches for risk assessments and adaptation measures. Key messages include the need for adaptation strategies to be supported by strong legal and regulatory frameworks that help to reduce vulnerability to climate-related risks; that regulatory tools also provide economic incentives to fund adaptation efforts, promote technology innovation, and contribute to data and tools; and finally that legal and regulatory approaches do not limit future adaptation options for a specific project. International, national, and regional examples of conventions, acts, and laws describe what role policies can play in creating a supportive environment for integrating climate adaptation measures into the design and management of infrastructure projects.

The World Bank's **Resilience Rating System** (RRS) suggests a methodology to track climate-related finance and improve climate-aligned development (World Bank Group, 2021). Specifically, the RRS provides assessment and reporting criteria to track resilience that will also improve transparency, create financial incentives, and help identify best practices while also offering guidance on how to incorporate risk reduction measures into project design. The rating system assesses projects in two distinct ways: resilience of the project design (e.g., the resilience of the assets or outputs being developed) and resilience through the project (e.g., does the project outcome improve resilience to climate change). The rating system is meant to act as a complement to existing methodologies and frameworks used by project designers to incorporate resilience into their project designs. The RRS can be used to determine the effectiveness of the methodologies being used to enhance resilience. In fact, the report provides a rating for commonly used methodologies according to sector.

Some industry-level standards and guidance also inform current efforts to build the climate resiliency of built infrastructure. The **Standard for Sustainable and Resilient Infrastructure** (SuRe), developed by the Global Infrastructure Basel Foundation and the investment bank Natixis, aims to drive the integration of sustainability and resilience aspects into infrastructure development (Global Infrastructure Basel Foundation, 2018). The standard aims to support project developers, the public sector, and financiers in delivering projects that achieve improved levels of performance that go beyond industry norms. SuRe applies to a range of infrastructure projects at each development phase. However, it is encouraged to implement the standard in the early planning phases to gain the most value. Further, the implementation of SuRe is meant to contribute to and advance the SDGs, specifically Goal 9, "Industry, Innovation and Infrastructure," and Goal 11, "Sustainable Cities and Communities" (Global Infrastructure Basel Foundation, 2018).

The **Envision Sustainable Infrastructure Framework** was first released in 2012 and was developed by the Institute for Sustainable Infrastructure (ISI), a not-for-profit education and research organization founded by the American Public Works Association, the American Council of Engineering Companies, and the ASCE (ISI, n.d.). Envision was created to provide a "consistent, consensus-based framework for assessing sustainability, resiliency, and equity in civil infrastructure" (ISI, n.d.). Specifically, the framework does the following: sets the standard for what constitutes sustainable infrastructure; incentivizes higher performance goals beyond minimum requirements; gives recognition to projects that make significant contributions to sustainability; and provides a common language for collaboration and clear communication.

4.3 Financing Climate-Resilient Infrastructure

Significant financing is needed to address Canada's existing infrastructure deficit, which in 2016 was estimated to be between CAD 150 billion and CAD 1 trillion (ACEG, 2016). Addressing this gap while also making additional investments to improve the climate resiliency of infrastructure presents a significant challenge. However, making these investments now is expected to provide net benefits over the longer term. As the GCA concluded in 2019, "adapting now is in our strong economic self-interest" (GCA, 2019, p. 3). The Commission cited net benefits for making new infrastructure resilient to be on the order of CAD 4 trillion globally, with benefit-cost ratios ranging from 2:1 to 10:1 (GCA, 2019). Reflecting the importance of financing in enabling the construction and rehabilitation of more climate-resilient infrastructure, this section provides an overview of infrastructure financing programs and mechanisms in Canada and internationally.

4.3.1 Federal Action

The federal government has established **direct cost-shared public infrastructure funding programs** that integrate climate adaptation and climate resilience. Some of these programs, briefly described in Table 8, are specific to adaptation and are designed to assist the government in delivering on its commitment to invest in resilient infrastructure set out in the PCF. Infrastructure Canada also recognizes the value of nature-based solutions and supports the local use of natural infrastructure through a number of initiatives like the DMAF and the Green Stream of the ICIP.

Other financing programs supported by the Government of Canada are not specifically designed to address adaptation for built and natural infrastructure, but may result in investments that promote resilient infrastructure. Table 9 includes examples of these federal government programs.

Table 8. Examples of federal financing programs that support climate-resilient infrastructure

Financing mechanism	Aim	Description	Examples of adaptation actions
DMAF[1]	To support investments to make public infrastructure more resilient to the impacts of climate change.	National CAD 2 billion merit-based program that provides funding for large-scale (a minimum of CAD 20 million in eligible expenditures) built and natural infrastructure projects that will increase community resilience to natural hazards and extreme weather events. Eligible recipients of the cost-sharing program include provinces and territories, municipalities and regional governments, Indigenous groups, public sector bodies, post-secondary institutions, and not-for-profit and for-profit organizations.	Flood management and protection, shoreline rehabilitation, and wildfire risk reduction.
ICIP[2,3]	To help communities reduce air and water pollution, provide clean water, increase resilience to climate change, and create a clean-growth economy; build strong communities; and ensure access to modern, reliable services.	A CAD 33 billion cost-sharing initiative to support infrastructure investment. Funding is allocated by population and delivered through bilateral agreements between Infrastructure Canada and each of the provinces and territories. The program can fund adaptation projects below the DMAF's CAD 20 million project threshold through the Green Infrastructure stream. The adaptation, resilience, and disaster mitigation sub-stream supports infrastructure projects that increase structural or natural capacity to adapt to climate change impacts, natural disasters, or extreme weather events.	Constructed infrastructure such as dikes, stormwater management, and winter roads, and natural infrastructure such as wetlands and shoreline rehabilitation.
ICIP COVID-19 Resilience Stream[4]	To provide added flexibility to fund quick-start, short-term projects.	A temporary stream of over CAD 3 billion in funding to support quick-start infrastructure projects, including disaster mitigation and adaptation projects. The application-based program is delivered through bilateral agreements with provinces and territories, and projects must be completed by the end of 2021 or the end of 2022 in the territories and remote communities.	Natural infrastructure, flood and fire mitigation, tree planting, and related infrastructure.

Financing mechanism	Aim	Description	Examples of adaptation actions
Northern Transportation Adaptation Initiative Program[5]	To address the effect of climate change on Northern transportation systems.	The program includes a grant and contribution component to help Yukon, Northwest Territories, Nunavut, and communities in Nunavik and Nunatsiavut meet the challenges of climate change. Up to CAD 50,000 can be provided for a project that: develops new knowledge about how climate change is affecting transportation systems in the North; develops tools and practices to respond to these effects; or provides education and training for Northerners to help manage transportation systems affected by climate change.	Generation of new knowledge in regard to how transportation systems are impacted by climate change such as permafrost thawing, and changing ice and water conditions.
Transportation Assets Risk Assessment Program[6]	To make transportation systems stronger and more resilient.	Up to CAD 50,000 per project as a grant and CAD 1.6 million per project as a contribution to assess the impacts of the changing climate on federally owned and/or federally managed transportation assets and identify potential adaptation solutions that could be employed.	Transportation assets and infrastructure components such as bridges, ports, and airports.

Sources: [1]Government of Canada, 2020b; [2]Government of Canada, 2020f; [3]Infrastructure Canada, 2021b; [4]Government of Canada, 2020g; [5]Transport Canada, 2021a; [6]Transport Canada, 2021b.

Table 9. Examples of Government of Canada financing mechanisms that can support climate-resilient infrastructure

Financing mechanism	Aim	Description	Adaptation actions
Canada Infrastructure Bank (CIB)[1,2]	To invest—and to attract investment from private sector and institutional investors—in infrastructure projects.	CIB is a Crown corporation launched in 2017 that will invest CAD 35 billion from the federal government into green infrastructure projects that have revenue-generating potential and are in the public interest.	One of the 13 projects approved as of March 1, 2021 addresses adaptation. The Alberta Irrigation project helps reduce climate impacts while increasing crop production and enhancing water storage capacity.
Climate Change Preparedness in the North[3]	To support Northern communities and organizations to help them adapt to climate change impacts.	The program funds various projects, including vulnerability and risk assessment of climate change impacts; hazard maps and adaptation plans; identification of adaptation options; and implementation of non-structural and structural adaptation measures.	The program supports the implementation of structural adaptation measures for infrastructure at risk. Examples of projects include determining the impacts of permafrost considerations on highways and government buildings.
First Nation Adapt Program[4]	To improve resilience to climate change by improving knowledge of the issues facing First Nations, in order to better plan for the future.	The Investing in Canada Plan includes federal merit-based adaptation programs that build the capacity of First Nations south of the 60th parallel to address climate change impacts.	Includes support to assess and respond to climate change impacts on infrastructure, including assessment of community drainage systems, integration of climate change into community infrastructure plans, winter road realignment studies, and flood mapping to assess risks to infrastructure.
Canada Community-Building Fund (formerly the Gas Tax Fund)[5,6,7]	To provide long-term funding in support of municipal infrastructure.	The federal fund transfers a share of the revenue collected through the federal fuel excise tax on gasoline and diesel to provinces, territories, and Indigenous communities on a per capita basis. The fund provides over CAD 2 billion a year to support local infrastructure priorities, including infrastructure that reduces or eliminates long-term impacts and risks associated with natural disasters, with an additional CAD 2.2 billion added in 2021 as part of COVID-19 response and recovery efforts.	Some provinces require that climate adaptation be incorporated in plans developed to access the funds. Ontario, for example, requires that vulnerabilities to infrastructure caused by climate change as well as adaptation opportunities be assessed, and Nova Scotia requires the development of municipal climate change action plans.

Financing mechanism	Aim	Description	Adaptation actions
Municipalities for Climate Innovation Program[8]	To build sustainable and reliable communities by developing responses to climate change.	The federal government has provided CAD 75 million in grant funding for the five-year program that is administered by the FCM. The program supports climate change adaptation, greenhouse gas reduction, and climate and asset management.	Adaptation initiatives include assessing flood risks, analyzing green infrastructure to help manage risks from flooding and extreme heat, and developing adaptation strategies for energy infrastructure.
National Disaster Mitigation Program[9]	To invest in provincial and territorial flood mitigation projects	Administered by Public Safety Canada, the program has four streams of funding that support risk assessments, flood mapping, mitigation plans to address flood risks, and investments in non-structural and small-scale structural projects to address flood risks. The program was renewed in 2020 with CAD 25 million for two years.	Investments in non-structural and small-scale structural projects to address flood risks include construction of floodways and dikes
Building Regional Adaptation Capacity and Expertise (BRACE) Program[10]	Increase ability of communities, organizations, small and medium-sized enterprises, and practitioners to access, use, and apply knowledge and tools on climate change adaptation,	The BRACE Program is a five-year (2017–2022), CAD 18 million initiative under the Adaptation and Climate Resilience pillar of the PCF.	The program supports regional projects that respond to unique climate change adaptation needs and priorities across the country. Projects are delivered by organizations that are best placed to reach target audiences, using a range of approaches for building skills and expertise on climate change adaptation.

Sources: [1]CIB, 2021a; [2]CIB, 2021b; [3]Government of Canada, 2020a; [4]Government of Canada, 2020e; [5]Government of Canada, 2020d; [6]Asset Management Ontario, 2021; [7]Vogel, 2015; [8]FCM, 2021; [9]Public Safety Canada, 2021; [10]NRCan, 2021.

The federal government is exploring the use of other mechanisms to increase financing for climate-resilient infrastructure. **Insurance** is a risk-sharing and transfer mechanism that can incentivize adaptation action (Chambwera et al., 2014). Insurance penetration is considerable in Canada, and the federal government is working with provinces and territories to address a gap in overland flood insurance (Zerbe, 2019). A task force has been established to examine options for a low-cost flood insurance program to protect homeowners at high risk of flooding and without adequate insurance protection (Public Safety Canada, 2020b).

Green bonds may offer opportunities to finance climate-resilient infrastructure. Most green bonds issued in Canada have been focused on mitigation, with only 3% of the cumulative CAD 15.2 billion in green and climate bonds issued in Canada from 2014 to 2019 used especially for adaptation projects (Climate Bonds Initiative, 2019a). There is a growing interest, though, in using green bonds to finance adaptation investments, as well as in resilience bonds that are at a very early stage of development (Bascunan et al., 2020). In 2020, a flood protection project was the first initiative to receive Ontario Green Bond funding in the climate adaptation and resilience category (Ontario Financing Authority, 2020). The federal government intends to issue its first-ever green bond in 2021/22 to help finance its green infrastructure spending (Government of Canada, 2020c).

Growing investor pressure in regard to **climate risk disclosure** can influence infrastructure owners to identify and report on physical climate risks, such as potential damage to infrastructure from extreme weather events. The Task Force on Climate-Related Financial Disclosures (TCFD), formed by the Financial Stability Board of the Bank for International Settlements, highlighted the “transition” and “physical” risks and opportunities for both public and private institutions stemming from climate change (TCFD, 2017). Implementation of the TCFD framework by major public infrastructure investors, such as Canadian public pension funds, can increase awareness of climate-resilient infrastructure and measures to protect infrastructure assets from climate risks. Several major Canadian cities have already started reporting climate risk in their financial disclosures, using guidance developed by the Chartered Professional Accountants of Canada (CPA Canada, 2019, 2021).

The Government of Canada established the **Sustainable Finance Action Council** in 2021 (Finance Canada, 2021). The Council is tasked with making recommendations “to attract and scale sustainable finance in Canada, including enhancing climate disclosures, ensuring access to useful data on sustainability and climate risks, and developing standards for investments to be identified as sustainable” (Government of Canada, 2020c, p. 91).

4.3.2 International Programs

Various countries have programs that could provide lessons for Canadian initiatives to encourage climate-resilient infrastructure. One example is in the area of providing overland **flood insurance** for disaster risk reduction. The U.S. government’s National Flood Insurance Program supports more than five million policyholders located in communities in high-risk flood areas that are required to adopt and enforce floodplain management regulations. The Federal Emergency Management Agency (FEMA, 2021) manages the program and is responsible for underwriting flood insurance coverage sold under it. In the United Kingdom, the Flood Re program is a reinsurance scheme that makes flood coverage part of home insurance for properties deemed at significant risk of flooding (Flood Re, 2021). The UK government does not provide public funds for the program; instead, it has agreed to provide resources to deliver relief if the country is hit by an especially costly flood (Grey, 2013). Furthermore, with a focus on incenting risk reduction through insurance and investment, the International Cooperative and Mutual Insurance

Federation, with company membership in over 60 countries (including Canada), is collaborating with the UNDRR on ways to integrate disaster risk reduction incentives into insurance and investment decisions, including through closer collaboration between the public and private sector, lawmakers, and regulators for more risk-informed business investment (International Cooperative and Mutual Insurance Federation, 2021).

Revolving funds can be used to incorporate adaptation into infrastructure projects. The Drinking Water State Revolving Fund is a U.S. federal–state partnership whereby the Environmental Protection Agency (EPA) provides grant funds to states. Funds are used for programs and are placed into a dedicated revolving loan fund to provide loans for drinking water infrastructure projects (EPA, 2020b). The funding can be used to incorporate climate resilience such as physical flood barriers, moving a treatment plant out of a floodplain, and adding wind-resistant features (EPA, 2020a).

Green bonds have been used successfully in many countries, and the release of the Climate Resilience Principles by the Climate Bonds Initiative in 2019 is expected to increase investment in climate resilience in both natural and built infrastructure (Climate Bonds Initiative, 2019b). The U.S. federal government encourages private investment in municipal infrastructure by supporting municipal bonds, including green bonds, with tax exemptions and subsidies (Climate Bonds Initiatives, 2021). The State of California is also developing a climate resilience bond. If approved by voters, the state will issue bonds in 2022 in the amount of USD 5.5 billion for projects to address climate risks, including wildfire protection, safe drinking water, drought preparation, and flood protection (Agri-Pulse Communications, 2021).

Some countries have introduced specific incentives to encourage the **disclosure of physical risks** from climate change. France requires that listed companies report on climate change impacts (OECD, 2018a), and the British and New Zealand governments have introduced mandatory TCFD-aligned disclosure for companies (Beauchemin, 2020).

5.0

Conclusions

Photo: iStock

The impacts of a warming climate are increasingly affecting the lives of Canadians, including through damage to critical infrastructure. Slower-onset climate changes, such as permafrost melt and coastal erosion, are already impacting Northern and coastal areas. Extreme weather events like floods and wildfires are becoming more frequent and severe throughout Canada. **The costs of the damage caused by these weather-related disasters are significant and increasing**; they currently amount to billions of dollars annually (CICC, 2020). These slower-onset processes and extreme events damage infrastructure assets and disrupt the services they provide, putting communities, individuals, and businesses at risk.

Relying on experience with past climate as the basis for designing and maintaining critical infrastructure is simply no longer an option. The long lifespan of many infrastructure assets makes it more critical to look to the future when making decisions regarding their location, design, construction, and operation, recognizing that building the climate resilience of infrastructure increases community resilience over the long term. Building this resilience requires investment in new infrastructure that protects communities as well as increasing the general resilience of all existing infrastructure assets.

Investing in climate-resilient infrastructure makes scientific, social, and economic sense. As noted by the Expert Panel on Climate Change Risks and Adaptation Potential, physical infrastructure is an area where action has great potential to reduce climate risk. Addressing this risk requires ensuring that the significant investment needed to address the infrastructure gap in Canada, including for remote and Indigenous communities, is done in a manner that increases the resilience of existing and future built and natural infrastructure. If these investments are made with climate change in mind, positive benefit-cost ratios can be realized and community resilience to climate change achieved. Additional benefits include job creation and economic growth, reduced costs associated with disaster relief, reduced total cost of ownership of public infrastructure assets, and continuity of services for Canadian communities.

As described in Section 3.2, **there is a growing understanding of the risk to built infrastructure posed by climate change and how these risks can be mitigated** through planning and assessment, structural changes, and enhanced monitoring and maintenance. Development and implementation of these strategies requires bringing together diverse groups of experts along with knowledge drawn from professionals such as engineers, climatologists, finance experts, and operational staff. Critically, there is a need to weave Indigenous Knowledge and Western scientific knowledge together in the design and implementation of resilient infrastructure to gain a fuller understanding of risks and potential solutions (Cappell, 2019).

Awareness is also growing of the potential for natural infrastructure to mitigate the effects of climate change, either individually or in combination with built infrastructure. **Natural infrastructure can play a significant role in improving community resilience while also providing other important benefits**, including for mental health, conservation of biodiversity, and ecosystem services such as carbon sequestration. Experience deploying natural infrastructure in Canada and around the world has demonstrated it to be a cost-effective solution. Compared to investing in built infrastructure, it is often a more efficient use of funds as a means of protecting our communities from floods, mitigating damages from floods, filtering our drinking water, reducing our greenhouse gas emissions, and delivering a host of social and environmental co-benefits.

Steps have been taken across Canada to increase the climate resiliency of infrastructure through specific adaptation options implemented by asset owners and through economy-wide strategies and targeted policies and investments. Examples of action at the federal level, stimulated in part by the PCF's commitment to building climate resilience through infrastructure, include the following:

- Resources developed through the CRBCPI
- Introduction of Infrastructure Canada's Climate Lens funding requirement
- Building capacity through the Standards to Support Resilience in Infrastructure program
- Financing through the DMAF
- Support for natural infrastructure
- The Municipalities for Climate Innovation program delivered by the FCM.

The planned development of Canada's first National Adaptation Strategy and forthcoming first National Infrastructure Assessment should provide additional opportunities to understand and plan for climate-related risks for built and natural infrastructure. The latter in particular is expected to guide Canada's future public infrastructure investments.

While progress in Canada toward climate-resilient infrastructure has indeed accelerated over the past decade, there is a need for more action in specific areas, such as:

- **Increased incentive and capacity to apply climate change risk-informed planning and assessment tools in decision making and design**. An increasing number of tools, guides, and standards are becoming available, such as infrastructure-related climate resilience assessments and climate risk disclosure. While programs like the Infrastructure Resilience Professional designation and BRACE are helping to increase the capacity of engineers and planners to apply these resources, there will be an ongoing need to incentivize and support the capacity of new and established professionals to integrate climate change considerations into their practice.
- **Greater capacity to pursue flexible, robust, and redundant pathways for adapting infrastructure**. The uncertainties associated with how the climate will change, the impact of these changes on different infrastructure, the potential for cascading impacts, and the effectiveness of risk reduction strategies suggest that flexible, robust, and redundant adaptation approaches are critical. Such strategies will enable infrastructure to be more resilient to climate change impacts and lessen the risk of maladaptation (Risk Sciences International & Ontario Centre for Climate Impacts and Adaptation Resources, 2015; Swanson & Bhadwal, 2009; Venema, 2017).

- **Improved structural adaptation options for infrastructure**. Although a wide array of solutions have been identified to reduce or eliminate the impact of climate hazards on different types of infrastructure, continued and accelerated research and development will be needed to identify new and improved adaptation options. This will also help update building design codes and practices that consider climate change.
- **Enhanced monitoring and maintenance of infrastructure to account for a changing climate**. Much of Canada's infrastructure is already in need of updating or replacement, and climate change can accelerate the ageing process. Greater investment in asset management and related monitoring and maintenance can help ensure that existing infrastructure continues to deliver its intended services as conditions change.
- **More and diverse financing sources are needed**. Investment of billions of dollars in both built and natural infrastructure is needed to close the infrastructure gap while adapting to climate change. Public–private initiatives, such as those being supported by the Canada Infrastructure Bank, provide a means of meeting this need. Increasing the use of private sector financing mechanisms such as green bonds and resilience bonds is also required, as well as incentives and investment delivered through insurance products and services.
- **Expanded integration of built and natural infrastructure solutions**. While awareness is increasing of the potential for hybrid built and natural infrastructure approaches to increase the resilience of Canada's communities and economy to climate change, application of this approach is currently limited. Further efforts are needed to document, communicate, and facilitate the economic, social, and ecological benefits of integrated solutions.
- **Greater consideration of interrelated social factors**. Socio-economic factors, including inequality and the marginalization of Indigenous Peoples, are crucial to consider in planning and investment for climate resilience, to ensure that responses and infrastructure are inclusive and beneficial for all.[6]

In pursuing such action, **Canadians can continue to stay informed about innovative policies and adaptation options for climate-resilient infrastructure implemented by other countries around the world**. Examples include the United Kingdom's guidance on Designing for Infrastructure Resilience, the European Union's Pan-European Framework for Strengthening Critical Infrastructure Resilience to Climate Change, the ASCE's Envision Sustainable Infrastructure Framework, and the Standard for Sustainable and Resilient Infrastructure developed by the Global Infrastructure Basel Foundation and the French investment bank Natixis, to name a few.

Because infrastructure in Canada is owned, operated, and relied on by individuals, businesses, and governments at all levels, it is crucial for all stakeholders to be engaged in thinking about resilient infrastructure solutions. Therefore, **achieving climate-resilient infrastructure**

[6] As discussed and recommended in Sauchyn et al. (2020).

objectives in Canada necessitates an integrated whole-of-society approach that leverages Canadians' creativity and agency to re-envision infrastructure decisions. Such an approach is already embraced by most international, national, and subnational resilient infrastructure frameworks. Its adoption will help ensure that the ingenuity of infrastructure professionals, policy-makers, and First Nations, Métis, and Inuit knowledge keepers within and across provinces and territories can come together to achieve climate-resilient infrastructure in Canada.

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Appendix 1. Land Transportation Infrastructure: Climate change hazards, potential impacts, and resilience options

Climate hazards	Potential impacts	Examples of resilience options
All climate hazards and related impacts		Planning • Climate risk assessment (i.e., using ISO 31000, PIEVC Protocol, or equivalent and ISO 14091) and other climate adaptation considerations (including guidance from ISO 14090, ISO 14092) • Use of improved standards, codes, and guides • Use of most up-to-date climate data and future climate change projections in design Monitoring and maintenance • More frequent and enhanced monitoring and maintenance efforts
Changing precipitation patterns[1,2,3,6,7]	• Reduced structural integrity and/or accelerated deterioration (bridge scour) • Premature weathering • Flooded structures • Increased risk of critical events (road washout, bridge failures, landslides affecting roads, bridges and railways, fouling of track ballast) • Closure of roads due to higher number of road accidents (especially with freezing rain) • Increased ice accretion on cable-stayed bridges	Planning • Railway-specific strategies: landslide mapping—temporal and spatial, geotechnical assessment of slopes; rail inspections • Seasonal restricted road access for heavy trucks (to avoid damage to roads during spring thaw) Structural • Elevating roads, bridges, and rail tracks • Increasing culvert capacities • Redirecting water flows • Building larger bridges capable of withstanding intense precipitation • Paving gravel roads to reduce washout risks • Using a top layer of water-shedding material for runways • Installing emergency electricity backup at rail maintenance facilities • Installing grooved runways to minimize hydroplaning when landing airplanes • Building rain gardens/retention ponds Monitoring and maintenance • Installing devices to monitor bridge scours

Climate hazards	Potential impacts	Examples of resilience options
Storm surges, higher tides, sea levels, high winds[1,2,8]	• Capacity of culverts and storm sewer systems is more frequently exceeded, resulting in road and runway damage, bridge washouts, and/or underpass flooding • Causeways, bridges, and low-lying roads inundated or damaged • Erosion of estuaries and coastlines • Damaged or flooded structures • Reduced lifespan of infrastructures • Wind damage to infrastructure, including traffic signals • High winds causing fallen trees and other debris that block roads, bridges, and railways, plus causing power outages • High winds bringing foreign objects onto runway and taxiways posing a danger for aircraft • Inland ice jams causing damage to bridges (road and rail)	Planning • Developing alternative routes Structural • Building riprap and dikes • Elevating roads, bridges, and rail tracks • Planting rows of trees (different varieties) beside roads to create a "living snow fence" to reduce wind impacts (blowing snow and wind shear) • Replacing gravel shoulders with articulated concrete mats Monitoring and maintenance • Installing devices to monitor bridge scours
Extreme heat[1,2,4]	• Integrity of asphalt compromised • Shortened life expectancy of highways, roads, and rail • Increase in forest fires potentially damaging infrastructure • Thermal rail expansion (buckling due to heat) • Severe cracking of roads due to desiccation of clay sub-soils • Pavement softening, rutting, flushing, and bleeding • Thermal expansion of bridge joints ("blow-ups") resulting in bridge closures	Planning • Using data (weather station and traffic flow) to determine appropriate pavement material for specific locations on the roadway • Implementing speed restrictions, smaller train car lengths, and reduced load for railway carriers Structural • Using heat-tolerant pavement mixtures for roads and runways • Using low-solar absorption rail coatings • Lengthening runways to allow for longer time to slow airplanes on landing due to decreased air density

Climate hazards	Potential impacts	Examples of resilience options
Seasonal temperature increase (permafrost degradation) and increased freeze–thaw cycles[1,2,4,5]	• Soil and slope instability plus ground movement/ settlement • Increased frequency, duration, and severity of thermal cracking, rutting, frost • Heave and thaw weakening (freeze/thaw) • Soil subsidence and buckling can damage road and runway foundations and/or railway track bed • Shortened winter road season with drainage issues impacting the structural integrity • Reduced lifespan of infrastructures • Road embankment failures • Reduced load capacity	Planning • Rerouting traffic • Land-use and transportation planning • New infrastructure design • Asset management and risk assessment • Emergency response planning • Better information sharing • Permafrost mapping • Soil type assessment Structural • Embankment thickening • Installing geotextiles • Installing berms • Using highly durable and impermeable concrete mixes for bridge decks and curbs/ barriers • Using embankment materials that increase air convection • Installing thermosyphons or other measures to remove heat • Installing solar sheds or other measures to prevent heat absorption • Widening shoulders • Using shallow embankment slopes • Improving drainage – larger culverts and/or clearing debris; redirection of water from the foot of embankment • Using high albedo surfaces • Induced thaw Monitoring and maintenance • Subsurface condition monitoring (e.g., ground temperatures) • Removing snow • Adopting earlier and more frequent maintenance schedules

Sources: [1]Transport Canada, 2016; [2]Bush & Lemmen, 2019; [3]ECCC, 2016; [4]ECCC, 2020; [5]Melillo et al., 2014; [6]D'Auteuil et al., 2018; [7]Szilder et al., 2021; [8]Engineers and Geoscientists British Columbia, 2020.

Appendix 2. Buildings: Climate change hazards, potential impacts, and resilience options

Climate hazards	Potential impacts	Examples of resilience options
All climate hazards and related impacts[authors, 1, 2]		Planning • Use of improved standards, codes, and guides • Use of most up-to-date climate data and future climate projections in design and construction • Conducting climate risk and vulnerability assessment to inform new design, asset management planning, and operational procedures for existing buildings • Development of hazard maps for different types of building products that will provide information on the increased risk of degradation evaluated in relation to local climate conditions • Research and information sharing/awareness raising to support decision making Structural • Building commissioning analysis and investigation that includes climate resilience considerations
Permafrost degradation[3,4,5,6,7,8,9,3,4]	• Subsidence and buckling can damage foundations and lead to cracking of walls, affecting the integrity of buildings • Loss of strength in buildings leading to unstable houses and buildings, which may become uninhabitable • Structural building collapse	Planning • Use of improved standards, codes, and guides: Canadian Standards Association (CSA) S500, CSA S501, CSA Plus 4011, CSA Plus 4011.1, Bureau de normalisation du Québec (BNQ) 2501-500, BNQ 9701-500 • Research and knowledge sharing: permafrost thaw, new engineering designs for foundations and buildings, etc. • Ensuring that new buildings are constructed in areas where significant mapping of permafrost has been completed • Preservation or accommodation of permafrost thaw during construction and the structure's design life, or to induce complete or partial thawing, drainage and consolidation of soils before construction Structural • Protection of existing buildings, including improving ventilation under buildings and adjusting existing structures (such as replacing wooden posts with adjustable steel posts) • Reduction of vulnerability in existing buildings by reinforcing foundations • Structurally enhanced foundations, adjusted foundations and may involve vented systems, gravel pads, phase-change materials, insulation layers, heat sinks, passive or active thermopiles, thermosyphons, freezing systems, and drainage systems

Climate hazards	Potential impacts	Examples of resilience options
(continued) Permafrost degradation [3,4,5,6,7,8,9,3,4]		• Adopting best design practices for foundations, including concrete footings on bedrock or anchored piles • Relocation of buildings to areas with stable ground • Replacing and/or destruction of uninhabitable buildings Monitoring and maintenance • Financial assistance for homeowners with low and modest incomes for preventative maintenance, repairs, and renovations
Seasonal temperature increases resulting in changing freeze–thaw cycles [1,2,10,11]	• Concrete carbonation and corrosion—changes in temperature and relative humidity will accelerate the degradation processes and cause a decrease in serviceability and durability and possibly the safety of reinforced concrete infrastructure • Foundation and building damage from changes in freeze–thaw and drying of soils • Frost decay/deterioration of porous masonry materials (rainfall occurring before freezing)	Planning • Use of improved standards and guides such as CSA guideline S478:19 Structural • Select concrete mixture aggregates that perform better in freeze–thaw cycles • Ensure proper drainage around foundations Monitoring and maintenance • Address gradual changes in temperature through regular maintenance and upgrade cycles, or through adjustments to operation and maintenance policies and procedures
Extreme heat, heatwaves [1,2,11,12,13]	• Warming and humidification can reduce the service life in wooden building components (e.g., mould growth, moisture-related damage) • Heat ageing: accelerated ageing of roofing and cladding components, insulated glass units, plastic fenestration components, polymer-based waterproofing and sheathing membranes, jointing and sealing products, and paints and coatings for cladding • Overheating in buildings—increased indoor air temperature and reliance on cooling systems • Increase in forest fires potentially damaging buildings	Planning • Use improved standards and guides such as CSA S504—fire-resilient planning for Northern communities • Conduct assessments to determine local heatwaves and extreme temperature risk and identify potential areas of concern Structural • Install green infrastructure solutions (i.e., green roofs and walls, shade trees) • Building design that includes cooling strategies (e.g., passive building design, air conditioning, upgraded ventilation, improved window thermal performance, insulation, etc.) based on future climate projections • Retrofit with fire-resistant materials for roofing, siding, windows, etc. • Retrofit with appropriate wall and roof insulation to reduce heat penetration • Install thermally reflective (high albedo) material for the roof and facades of buildings

Climate hazards	Potential impacts	Examples of resilience options
Changing precipitation patterns[2,10,11,12,14,15,16,17,18,19,20,21,22,23,24]	• Increased risk of flooded structures/basements that can lead to property damage, damage to critical equipment • Roof collapse from heavier snow loads on roofs • Increased risk of water entry and moisture problems; leaks can cause water damage and mould (from the pooling of water on roofs, snow and ice melt on roofs) • Increased weathering of materials leading to increased rates and severity of degradation of the fabric of the building • Premature ageing—accelerated ageing of roofing and cladding components, insulated glass units, plastic fenestration components, polymer-based waterproofing and sheathing membranes, jointing and sealing products, and paints and coatings for cladding • Increased wetting increases corrosion of reinforced steel in exposed concrete metals, and deterioration of concrete and masonry materials	Planning • Use of improved standards and codes such as CSA S502-14 Managing changing snow load risks for buildings in Canada's North;[34] and CSA Group's Z800-19 Guideline on Basement Flood Protection and Risk Reduction.[17] • Climate resilience metrics and guidance for building stakeholders, such as guidance for the design of climate resident buildings, such as Climate Resilience Guidelines for BC Health Facility Planning and Design, and decision-support tools, such as the PIEVC Protocol • Capacity building and training for property owners, home inspectors, and building service professionals, such as the Home Flood Protection Program • Disclosure of flood risk and flood mapping • Designation of areas where reconstruction or major repairs are not permitted, as well as no-build areas (e.g., floodplains) • Provision of financial support (such as buyouts) to move to safer areas/withdrawal of government subsidies for flood damage reimbursement • Develop and promote insurance programs with incentives for homeowners to implement adaptation practices • Encourage adaptive loan and mortgage products that encourage long-term investments that increase overall climate resiliency of buildings Structural • Priority retrofits of the most vulnerable "at-risk" structures to a higher standard • Best practices to prevent flooding in buildings such as installation of backwater valves and sump pumps; elevate electrical, communication, and waste disposal systems above expected flood levels or wet flood-proof; and green infrastructure such as roof gardens and rainwater collection systems; and flood protection landforms Monitoring and maintenance • Address gradual changes in precipitation through regular maintenance and upgrade cycles, or through adjustments to operation and maintenance policies and procedures

Climate hazards	Potential impacts	Examples of resilience options
Storm surges, higher tides, changing sea levels [2,25,26,27,28,29]	• Damage to and destruction of buildings • Erosion and the scouring of soil around foundations compromises the integrity of buildings' foundations • Flooded structures/basements • Increased corrosion of metals caused by surface wetness and buildup of salt • Deterioration of concrete	Planning • Four categories of coastal adaptation: no active intervention, accommodation, protection (hard and soft measures), and avoidance or retreat • Smart coastal planning and hazard guidance to inform development and design (e.g., prevent new building in hazardous areas and promote construction of buildings in less vulnerable areas) • Research and information sharing/awareness raising to support decision making in coastal communities • Compensation programs for properties that are uninhabitable • Insurance against anticipated damages Structural • Dry and wet floodproofing for some buildings • Metal product components with enhanced resistance to corrosion after being wetted • Protective structures /dikes/seawalls to prevent flooding Monitoring and maintenance • Coastal erosion and flood risk monitoring and mapping • Rebate programs to encourage changes to protect buildings or move them away from the coast

Climate hazards	Potential impacts	Examples of resilience options
Changing wind conditions, driving rain wind pressure, hurricanes, tornados [2,5,11,30,31,32,33]	• High winds can lead to loss of roof sheathing allowing rain to enter building, as well as loosen the perimeter flashing of the roof leading to roof detachment • High winds and snow drifting damage Northern buildings • Windborne debris can shatter windows and damage exteriors and facades • Increased weathering of materials at the building exterior lead to their degradation • Seals at entry doors and windows may be insufficient to resist the wind-driven rain • Moisture accumulation in building facades from wind-driven rain, and inflow of water through joints, cracks, or porous exterior surfaces damages building envelopes • Destruction and catastrophic failure of buildings.	Planning • Improved standards and guides: CSA S505 • Use of assessment tools (e.g., PIEVC Protocol) • Consider wind pressure and wind tunnel effects when locating and designing buildings • Insurance against anticipated damage Structural • Prevention measures include reinforced roofs/hurricane straps and additional fasteners, impact-resistant glass; and building enclosures resistant to wind-driven rain to prevent moisture from penetrating the building assembly such as sheathing membranes • Metal product components with enhanced resistance to corrosion after being wetted

Sources: [1]BOMA, 2019; [2]Lacasse, et al., 2020; [3]Baraniuk, 2021; [4]Bush & Lemmen, 2019; [5]Feltmate, et al., 2020; [6]Government of Nunavut, 2013; [7]Harries, 2018; [8]Standards Council of Canada, 2021; [9]Tsui, 2021; [10]Andrey et al., 2014; [11]SCC, 2019; [12]GRG Building Consultants, 2012; [13]RDH Building Science, 2020; [14]Chopik, 2019; [15]Credit Valley Conservation, 2013; [16]CSA Group, 2018; [17]Energy & Environmental Sustainability and Integral Group, 2020; [18]ICLR & CRI, 2021; [19]Intact Centre on Climate Adaptation, 2021; [20]Mercer Clarke & Clarke, 2018; [21]Moudrak & Feltmate, 2019; [22]Phillipson, et al., 2016; [23]Rajovich & Okour, 2019; [24]Waterfront Toronto, 2021a & 2021b; [25]Auld, 2019; [26]Mercer Clarke, et al., 2016; [27]New Jersey Climate Adaptation Alliance, 2014; [28]Government of Newfoundland and Labrador, n.d.; [29]Tutton, 2019; [30]Cannon, et al., 2021; [31]Kopp, 2015; [32]Sandink, et al., 2019; [33]U.S. Climate Resilience Toolkit, 2016; [34]CSA Group, 2019c.

Appendix 3. Water Supply Infrastructure: Climate change hazards, potential impacts, and resilience options

Climate hazards	Potential impacts	Examples of resilience options
All climate hazards and related impacts		Planning • Climate risk assessment (i.e., using ISO 31000, PIEVC Protocol or equivalent, and ISO 14091) and other climate adaptation considerations (including guidance from ISO 14090, ISO 14092) • Use of improved standards, codes, and guides • Use of most up-to-date climate data and future climate change projections in design • Integrate climate risks into asset improvement plans Monitoring and maintenance • More frequent and enhanced monitoring of facilities and maintenance efforts • Monitor flood events and drivers
Changing precipitation patterns (extreme precipitation) [1,2,5,6,7,8,10]	• Flooding of treatment plant infrastructure • Reduced structural integrity and/or accelerated deterioration and erosion of dams • Water quality effects from increased runoff, erosion and flooding • Power outages due to storms	Planning • Use up-to-date flood plain maps to locate new facilities outside high-risk flood zones • Spatial flood extent modelling potential based on climate change projections • Relocate infrastructure in lower-risk flood zones • Plan and develop alternate and redundant power supply • Integrated watershed management and natural infrastructure solutions to manage excess water and flooding, including acquiring and managing ecosystems • Develop models to understand water quality changes • Increase treatment capabilities Structural • See Section 3.2.2 on building adaptation options for extreme precipitation • Build flood barriers to protect infrastructure from flooding • Bioswales, constructed wetlands, rain gardens, and bioretention systems • Adopt structural adaptations to dams, weirs, and drainage canals Monitoring and maintenance • Decommission "at-risk" dams • Monitor flood events and drivers

Climate hazards	Potential impacts	Examples of resilience options
Storm surges, higher tides, sea levels[1,5,6,7,8,10]	• Flooding of treatment plant infrastructure due to capacity of culverts and storm sewer systems being exceeded • Saltwater intrusion in aquifers	Planning • Consideration of natural infrastructure solutions • Relocate facilities to higher elevations • Conduct sea level rise and storm surge modelling • Modify land use by studying nearby coastal and inland wetland systems' resilience to storm surge events Structural • Install backup valves and water pumps along with emergency electricity backup • Retention/restoration of wetlands and riparian buffers • Design guidelines that ensure efficient drainage capacity and erosion protection • Enlarge seawalls, dikes, floodwalls, levees, local surge barriers, etc. • Integrated flood protection (e.g., terraced berms, bridge abutments, drainage improvements, bulkheads, beach nourishment, reinforced dunes, offshore breakwaters, living shorelines) • Install low-head dam across tidal estuaries for separating the saltwater wedge and freshwater pool • Implement saltwater intrusion in groundwater sources through injection of freshwater into aquifers Monitoring and maintenance • Establish policies and procedures for post-flood repairs
Permafrost degradation[1,3,4,7]	• Rupture of drinking water and sewage lines • Potential seepage from sewer storage • Failure of frozen-core dams on tailing ponds due to differential settlement • Soil instability plus ground movement/settlement (drier landscapes)	Planning • Consider ground instability in the design of new infrastructure builds • Construct temporary infrastructure facilities that can be easily relocated Structural • Use of polystyrene insulation beneath roads to minimize disturbances in thaw-sensitive environments Monitoring and maintenance • Monitoring and modelling permafrost thaw

Climate hazards	Potential impacts	Examples of resilience options
Changing precipitation patterns (drought, reduced snowpack) [1,2,3,5,6,7,8,9,10]	• Increased water demands and pressure on infrastructure • Reduced source of potable water • Water apportions issues • Increased water quality problems • Increased risk of flooding (cracked earthen dams due to drying, subsidence and erosion) • Increased loadings resulting in overloads and tripping of breakers on pump stations	Planning • Integrated watershed management including consideration of natural infrastructure solutions • Incorporate demand forecasting techniques • Implement water conservation management programs (reduce consumption) and update drought contingency plans • Diversify water supply sources and expand current sources • Deploy systems to recycle water • Deploy conjunctive use of surface and groundwater • Establish mutual aid agreements with neighbouring utilities Structural • Increase water storage/retention capacity (e.g., cisterns) • Bioswales, constructed wetlands, rain gardens and bioretention systems • Use natural and artificial aquifer recharge and storage, including percolation basins and injection wells • Plant urban forests • Adopt structural adaptations to dams, weirs, and drainage canals Monitoring and maintenance • Monitor surface and groundwater conditions • Deploy groundwater and surface water modelling to understand changes, including algal blooms • Monitor intakes and retrofit to accommodate lower water levels

Sources: [1]Bush & Lemmen, 2019; [2]ECCC, 2016; [3]ECCC, 2020; [4]Melillo et al., 2014; [5]Clavet-Gaumont et al., 2017; [6]Amec Foster Wheeler & Credit Valley Conservation, 2017; [7]Lemmen & Warren, 2004; [8]McClearn, 2020; [9]Felio, 2015; [10]EPA, 2021.

Appendix 4. Wastewater and Stormwater Infrastructure: Climate change hazards, potential impacts, and resilience options

Climate hazards	Potential impacts	Examples of resilience options
All climate change hazards		Planning • Consult CSA Standard S900.1-2018 on Climate Change Adaptation for Wastewater Treatments Plans • Climate risk assessment (i.e., using ISO 31000, PIEVC Protocol or equivalent, and ISO 14091) and other climate adaptation considerations (including guidance from ISO 14090, ISO 14092) • Use of most up-to-date climate data and future climate change projections in design • Consider natural infrastructure solutions Monitoring and maintenance • More frequent and enhanced monitoring of facilities and maintenance efforts
Storm surges, higher tides, sea levels[1,2,5,6]	• Capacity of culverts and storm sewer systems are more frequently exceeded • Damaged or flooded structures that reduce treatment efficiency • Need for increased pumping requirements for facilities as a result of sea level rise • Saltwater intrusion that damages treatment plants and infiltrates sewer lines • Potential impact on the strength of wastewater facilities that are usually built on low elevations to take advantage of gravity-fed sewage collection • Sinking of land surfaces • Buildings, tankage, housed process equipment affected by flooding • Overtaxing of drainage facilities • Pipeline ruptures	Planning • Design guidelines that ensure efficient drainage capacity and erosion protection Structural • Backup valves, water pumps • Retention/restoration of wetlands and riparian buffers • Increasing the size of storm sewers and culverts to handle greater volumes of runoff • Build out seawalls, dikes, floodwalls, levees, local surge barriers, etc. • Integrated flood protection (e.g., terraced berms, drainage improvements, bulkheads, beach nourishment, reinforced dunes, offshore breakwaters, living shorelines) • Pump effluent to higher elevations to keep up with rising sea levels

Climate hazards	Potential impacts	Examples of resilience options
Changing precipitation patterns (extreme precipitation and flooding)[1,2,5,6,7]	• Reduced structural integrity and/or accelerated deterioration of wastewater treatment facilities • Premature weathering • Flooded structures • Stormwater infrastructure capacity exceeded • Urban drainage systems could fail, causing problems such as sewer backups • Power outages	Planning • Shift from managing peak flows to controlling runoff volume • Separate wastewater and stormwater sewers • Implement natural infrastructure solutions • Plan and develop alternate power supply • Relocate facilities to higher elevations • Model extreme precipitation events and spatial extent of flooding based on climate change projections • Integrate flood management into land-use planning and integrate climate risks in capital improvement plans Structural • Redirect and slow runoff via bioswales, constructed wetlands, rain gardens, and bioretention systems • Use internal dikes within communities • Reduce impervious surfaces (minimize road width, parking lots) • Increase capacity of stormwater and sewer collection systems (i.e., culverts) • Increased capacity and capabilities of wastewater treatment facilities • Retain rainfall (water capture and storage) from impervious surfaces for treatment and use in local settings • Plant trees and vegetation • Improve soil conditions to maximize infiltration and water storage • Green hard surface (roofs, parking areas) • Reduce inflow/infiltration in sanitary and combined sewers Monitoring and maintenance • Dredge to mitigate increased intensity and frequency of heavy rain events • More frequent clearing of debris from stormwater collection systems (i.e., culverts, intake grates) • Monitor flood events and drivers • Develop policies and procedures for post-flood repairs

Climate hazards	Potential impacts	Examples of resilience options
Seasonal temperature increase (permafrost degradation) and increased freeze–thaw cycles[1,3,5,6,7]	• Increased frequency, duration and severity of thermal cracking, rutting, frost heave and thaw weakening • Soil subsidence instability and ground movement can damage treatment facility foundations • Rupture of sewage lines, sewer storage tanks • Potential seepage from sewer storage • New containment structures in continuous permafrost zone may need to be built	Planning • Emergency response planning • Better information sharing • Permafrost vulnerability mapping • Soil type assessment Structural • Use of phase-change materials to reduce number of freeze–thaw cycles Monitoring and maintenance • Removing snow
Extreme heat and drought[1,2,3,4,6,7]	• Increase in forest fires potentially damaging infrastructure • Higher surface temperatures make meeting water quality standards more difficult • Higher temperature streams and decreased streamflow affecting disinfection and dilution of wastewater	Planning • Adopt natural infrastructure solutions for wildfire prevention and management Structural • Use natural infrastructure solutions (green roofs, urban forests) to increase assimilative capacity of receiving streams • Install effluent cooling systems to reduce temperature of treated wastewater discharge • Enhancements to treatment processes and/or addition of new technologies Monitoring and maintenance • Monitor surface water conditions

Sources: [1]Bush & Lemmen, 2019; [2]ECCC, 2016; [3]ECCC, 2020; [4]Amec Foster Wheeler & Credit Valley Conservation, 2017; [5]Mercer Clarke & Clarke, 2018; [6]Melillo et al., 2014; [7]EPA, 2021.

Appendix 5. Marine Infrastructure: Climate change hazards, potential impacts, and resilience options

Climate hazards	Potential impacts	Examples of resilience options
All climate change hazards		Planning • Climate risk assessment (i.e., using ISO 31000, PIEVC Protocol or equivalent, and ISO 14091) and other climate adaptation considerations (including guidance from ISO 14090, ISO 14092) • Use of improved standards, codes, and guides • Use of most up-to-date climate data and future climate change projections in design • More frequent and enhanced monitoring and maintenance efforts
Seasonal temperature increase resulting in permafrost melt and increased freeze–thaw cycles[1,2,3]	• Soil and slope instability plus ground movement/settlement • Increased frequency, duration, and severity of thermal cracking, rutting, frost • Heave and thaw weakening (freeze/thaw)	Planning • Land-use planning • New infrastructure design suited to permafrost environments • Incorporate adaptation into asset management planning including conducting a climate risk and vulnerability assessment • Permafrost mapping Structural • Embankment thickening • Incorporate best practices to minimize impacts on permafrost thermal regimes (i.e., limit soil disturbance, excavate and install gravel pads in autumn, construct embankments over multiple years to avoid trapping heat, re-establish terrain surfaces prior to freezing to avoid frost heaving) • Use highly durable and impermeable concrete mixes for bridge decks and curbs/barriers • Improve drainage—larger culverts and/or clearing debris Monitoring and maintenance • Adopt earlier and more frequent maintenance schedules

Climate hazards	Potential impacts	Examples of resilience options
Sea level rise, higher tides, high winds, sea ice changes influencing storm surges[1,2,3]	• Erosion of coastlines • Inundation of ports and other key coastal infrastructure • Flooded and damaged structures • Reduced structural integrity of infrastructure impacting lifespan • Wind damage to infrastructure • Increased wave damage to docks and other mooring structures • Sedimentation • Increased shipping traffic in Arctic waters due to less sea ice creating additional and new demand for Northern ports	Planning • Risk assessments that consider increased impacts of climate change (i.e., PIEVC Protocol) • Mapping to identify coastal areas highly vulnerable to impacts of sea level rise • Design regulations (i.e., zoning bi-laws, development standards, land-use regulations, land trusts etc.) to limit marine infrastructure development in vulnerable areas • Set back new land-based structures away from the shoreline taking into account erosion projections • Build flooding considerations into building and infrastructure design (i.e., raised infrastructure, floating buildings, wet/dry flood proofing buildings) • Build considerations for sea ice into dock designs • Incorporate floodproofing and erosion control into building design codes • Relocate infrastructure allowing for natural coastal readjustment or actively restoring habitat (i.e., dunes, salt marshes, vegetation) • Demand forecasting and planning for Arctic shipping and port facilities Structural • Construct physical barriers to reduce or protect from erosion (i.e., revetments, seawalls, breakwaters, retaining walls, artificial reefs, dikes) • Establish natural barriers to reduce erosion impacts (i.e., dunes, living shorelines/ wetlands, beach nourishment, perched beaches, plant stabilization) • Use of physical structures to trap sediment (i.e., groynes) • Accommodate flood water using landscape alterations (i.e., drainage ditches, dredging, bluff drains, detainment pond, constructed wetlands) • Use of natural solutions to act as buffers against erosion and coastal flooding (i.e., salt marshes) • Build riprap and dikes Monitoring and maintenance • Adopt earlier and more frequent maintenance schedules

Climate hazards	Potential impacts	Examples of resilience options
Fluctuations to inland water levels[1,4]	• Low inland water levels (particularly in the GreatLakes) can reduce vessel capacity, and create navigation difficulties. • High inland water levels can help with the navigation of higher volume of cargo but can also lead to flooding and shoreline erosion	Planning • In cases where lower water levels affect navigability, shippers may shift freight to road or rail, change navigation procedures, invest in flow augmentation technologies Structural • In cases of higher water levels, marine authorities may construct physical barriers to protect coastline from erosion (i.e., revetments, seawalls, breakwaters, retaining walls, artificial reefs, dikes) Monitoring and maintenance • Increase dredging of channels

Sources: [1]Palko & Lemmen, 2017; [2]Lemmen et al., 2016; [3]Greenan et al., 2019; [4]Zuzek, 2020a.

Appendix 6. Energy and ICT Infrastructure: Climate change hazards, potential impacts, and resilience options

Climate hazards	Potential impacts	Examples of resilience options
All climate change hazards		Planning • Climate risk assessment (i.e., using ISO 31000, PIEVC Protocol or equivalent, and ISO 14091) and other climate adaptation considerations (including guidance from ISO 14090, ISO 14092) • Use of most up-to-date climate data and future climate change projections in design • Consider Parts I, II and III of the Canadian Electrical Code for climate change adaptation[6] • Integrate climate change data in energy valuation modelling[2,7] Monitoring and maintenance • More frequent and enhanced monitoring and maintenance efforts
Winter storms/ ice storms and high-velocity windstorms[1,3,5,6,8,9]	• Ice buildup can result in snapped power lines, broken or fallen utility poles • Ice on wind turbine blades can affect performance and durability • Winds can bring down utility poles and transmission lines • Increased tree contacts leading to infrastructure damage and power loss • Dam spillway gate blockage due to suspended material • An increase in dirt, dust, snow, atmospheric particles, and others would decrease energy output of solar panels • Increased wave loading on offshore oil facilities	Planning • Install microgrids to enable communities to separate from failed central grids and run on secondary sources Structural • Bury distribution lines • Install anti-galloping devices on conductors and ensure structure designs are stable against strong winds Monitoring and maintenance • Install visual monitors to detect ice loading; boost current prior to ice loading to melt ice • Use of smart grid technology to identify the precise location of failed or upcoming failure in distribution lines and provide on-time maintenance and/or diminish the time for repair • Manage/trim the trees around transmission lines • Ensure a snow removal strategy for solar panels, including considerations for spacing between panels; increasing load tolerance; and automatic rotation to ensure snowpack is routinely removed

Climate hazards	Potential impacts	Examples of resilience options
Changing precipitation patterns (i.e., extreme rainfall, overland and coastal flooding)[1,4,6,8,9]	• Inundation of coastal energy generation plants, substations • Flooding of oil refining and processing facilities • Damage to supporting infrastructure such as copper and fibre-optic cables (used in ICT systems) • Water level fluctuations and drier soils can increase internal erosion of embankment dams • Dam spillway gate performance issues such as abrasion due to increased sediment content of water, blockage due to suspended material • Changes in solar irradiation and cloudiness would affect solar power output; hail can also damage photovoltaic panels	Planning • Use up-to-date flood plain maps to locate new facilities outside high-risk flood zones Structural • Incorporate design features to fortify coastal, offshore, and flood-prone infrastructure • Modify service and/or auxiliary spillways and dam embankments to adapt to projected inundation levels • Install overtopping protection systems on dam embankments • Fortify all flood-prone infrastructure against flooding including burying transmission and distribution lines • Adjust design criteria for transmission lines—increase tower height; use stainless steel materials • Elevate substations and electrical infrastructure components and • Use of saltwater-resistant equipment to prevent flooding damage to coastal infrastructure Monitoring and maintenance • Revise asset maintenance and replacement schedules • Enhanced dam safety monitoring and management
Permafrost melt and changing freeze/thaw cycles[1,6,9]	• Increased damage to transmission and distribution infrastructure, including oil and gas pipelines • Damage to concrte through expansion and contraction of moisture causing cracking and damage to underground vaults and cable chambers • Displaced transmission tower foundations causing structural damage/collapses	Planning • Modify structural designs to permit adjustment of towers when displacement due to permafrost thaw occurs
Wildfires[1,6,9]	• Lines and transmission pole damage and/or destruction • Annealed or damaged conductors • Impacts on oil and gas pipelines	Structural • Bury electrical grid to avoid infrastructure damage from extreme heat/fire Monitoring and maintenance • Keep fire-prone areas clear of brush

Climate hazards	Potential impacts	Examples of resilience options
Temperature increases and heatwaves[1,4,5,6,8,9]	• Reduced transmission efficiency and potential for de-rating/failure for air-cooled transformers; sag in annealing for overhead conductors • Increased stress on the distribution system infrastructure • Temperature fluctuations may induce additional mechanical stresses in concrete dams, including spillway gate performance • Drier soils and water level fluctuations can increase internal erosion of embankment dams • Decreased efficiency of solar panels, thermal plants • Overheating in ICT data centres, exchanges, and base stations • Increases in average daily temperatures can cause the location/density of wireless masts to become sub-optimal • Thermal and nuclear plants may need more water for cooling • Loss of access to water and peak cooling capacity for oil and gas refining and processing	Planning • Incorporate climate scenarios into load forecasts for future demand. Structural • Increase cooling system capacity Monitoring and maintenance • More frequent maintenance and component replacement to reduce stress on the distribution systems • Enhanced dam safety monitoring and management

Sources: [1]CEA, 2016; [2]Feltmate et al., 2020; [3]Hendel-Blackford et al., 2017; [4]Horrocks et al. 2010; [5]Solaun & Cerdá, 2019; [6]CSA Group, 2019f; [7]Fournier et al., 2020; [8]Fluixa-Sanmartin et al., 2018; [9]International Petroleum Industry Environmental Conservation Association, 2013.

Published by the International Institute for Sustainable Development

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