Climate-Resilient Buildings and Core Public Infrastructure

Summary of State-of-Practice and Knowledge Gaps on Climate Change Adaptation of Buildings and Core Public Infrastructure

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AASHTO	American Association of State Highway and Transportation Officials
AIA	American Institute of Architects
ANSI	American National Standards Institute
APEGBC	Association of Professionals Engineers and Geoscientists of BC
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
B&CPI	Buildings and Core Public Infrastructure
CBC	Canadian Broadcasting Corporation
CCBFC	Canadian Commission on Building and Fire Codes
CCMC	Canadian Construction Materials Centre
CCRA	Climate Change Risk Assessment
CHBDC	Canadian Highway Bridge Design Code
CPI	Core Public Infrastructure
CRBCPI	Climate-Resilient Buildings and Core Public Infrastructure
CSA	Canadian Standards Association
CUTA	Canadian Urban Transit Association
ECCC	Environment and Climate Change Canada
FHWA	Federal Highway Administration
GCM	Global Climate Model
GHG	Greenhouse gas
IDF	Intensity-duration-frequency
IgCC	International Green Construction Code
INFC	Infrastructure Canada
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standards
LCA	Life cycle assessment
LCCA	Life-cycle cost analysis
LCCBA	Life-cycle cost-benefit analysis
LCI	Life cycle inventory
LEED	Leadership in Energy and Environmental Design
NBC	National Building Code
NFC	National Fire Code
NMS	Canadian National Master Construction Specification
NPC	National Plumbing Code
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
PCF	Pan-Canadian Framework on Clean Growth and Climate Change
PIEVC	Public Infrastructure Engineering Vulnerability Committee
PSC	Public Safety Canada
RCP	Representative Concentration Pathways
TAC	Transportation Association
TTC	Toronto Transit Commission
WUI	Wildland-Urban Interface

Executive Summary

Canada's buildings, bridges, roads, rail transit, potable water systems and wastewater systems provide shelter and safe drinking water, enable transport of people and goods, and collect and treat wastewater. They provide basic and core services for Canadians and are critical to Canada's economy and the nation's quality of life. These buildings and core public infrastructure (B&CPI) are subject to time-varying and uncertain effects due to climate change, as well as more frequent extreme weather events, such as flooding. These climate change-induced pressures could potentially reduce the safety, serviceability, functionality, and service life of Canada's B&CPI. In addition, Canadian B&CPI are aging and deteriorating due to different degradation mechanisms, as well as inadequate inspection and maintenance practices – issues potentially made worse by the effects of climate change.

The Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative was established as a research and development partnership between the National Research Council of Canada (NRC) and Infrastructure Canada to develop new and revised codes, standards, specifications, guidelines and decision support tools to ensure that Canada's new and existing B&CPI are more resilient to the effects of climate change and extreme weather events. Funded by Infrastructure Canada and managed by NRC, the effort brings together experts from across Canada. Initiative priority areas include buildings, bridges, roads, potable water, storm water, and wastewater systems, and rail transit guideways. The initiative addresses resilience to climate change impacts on temperature, precipitation, wind and extreme weather events, including flooding, wildfires and extreme wind, which can affect these types of B&CPI across the country.

The first six months of the 4.5-year CRBCPI initiative were dedicated to reviewing the types of climate hazards that may affect B&CPI; identifying current leading-edge practices for improving the climate resilience of B&CPI; defining knowledge gaps and research needs; and developing priorities for research, development and stakeholder engagement. This report presents the results of that effort, including recommendations for major areas of work to be addressed within the scope of the initiative.

The interaction between climate hazards and different B&CPI systems is complex, and not all climate hazards affect all B&CPI. Flooding, which is becoming a very costly climate hazard in Canada, is an exception, potentially causing serious property damage and risks to health and life safety in almost all types of B&CPI. Wildfires, although rare, are highly damaging, primarily affect buildings and urban roads, and need to be addressed on a community planning basis rather than solely through building and fire codes.

Different levels of vulnerability to climate change and extreme weather have been identified for buildings, bridges, roads, rail transit, and potable water, storm water, and wastewater systems. Buildings and bridges were identified to be vulnerable to the highest number of climate hazards, which could potentially cause functional failure as well as structural failure. Buildings and bridges are also governed by specific national codes that can be used to address climate resilience in new and existing structures. Storm water systems were found to be particularly susceptible to flash flooding which could potentially lead to major financial costs. Roads and buried potable water/wastewater systems were found to be more vulnerable to climate hazards at critical network points, rather than throughout the entire system. Rail transit systems were found to fall between the networked road and potable water/wastewater systems, and discrete buildings and bridges in terms of the nature of their climate vulnerabilities.

The first six months of the initiative also focused on identifying knowledge gaps and research needs in the areas of climatic loads, risk assessment and risk-based decision making, environmental life cycle assessment, and economic life cycle cost/benefit analysis. All areas have significant gaps that need to be addressed. This report details specific needs for each one in the appropriate section. A framework for risk-based decision support for climate-resilient B&CPI has been proposed to help decision-makers comply with the minimum requirements of codes and standards, apply best practice guidelines in guides, and provide more robust decision support tools where higher levels of risk and/or performance are expected.

Finally, stakeholder workshops were held in the areas of climate change and codes, roofing, transit systems, and flooding. These workshops produced useful data and helped to identify partners for future stakeholder collaborations.

Based on the results of the analysis conducted during the first six months of the CRBCPI initiative, it is recommended that significant research and development efforts be focused on the areas of climate-resilient buildings and bridges, flooding and wildfires, as well as supporting technologies such as design codes and guides, and asset management tools for existing B&CPI. In addition, focused research and development should include rail transit, roads, and potable water and wastewater systems.

1. Introduction

1.1 Background

Canada's buildings, bridges, roads, rail transit, and potable water and wastewater systems are critical to Canada's economy and quality of life of Canadians. These buildings and core public infrastructure (B&CPI) provide shelter, enable transport of people and goods, deliver safe drinking water, and collect and treat wastewater. The continued functioning of key B&CPI is also essential for post-disaster relief.

B&CPI are subject to time-varying and uncertain effects due to climate change, including increases in temperature, precipitation, and wind speed, as well as more frequent extreme weather events, such as flooding. These climate effects may lead to increased loads and an increased rate of deterioration, which in turn may reduce the safety, serviceability, functionality and service life of Canada's new and existing B&CPI. Climate change could cost Canada $21–$43 billion per year by 2050 (National Round Table on the Economy and the Environment 2011), with much of the cost associated with B&CPI.

In addition to the effects of climate change, Canada's B&CPI are aging and deteriorating due to the effects of various degradation mechanisms, such as corrosion and overloading, as well as inadequate inspection and maintenance practices. According to the 2016 "Canadian Infrastructure Report Card", one third of Canada's core public infrastructure (CPI) is in fair, poor or very poor condition. The cost of repair and upkeep of CPI to bring it to acceptable standards was estimated at $170 billion (Canadian Infrastructure Report Card 2012). There are wide variations in Canada's infrastructure gap with estimates ranging from $50 billion to $570 billion (Canadian Chamber of Commerce 2013). Climate change and extreme weather may hasten deterioration, thus increasing the amount of rehabilitation and renewal needed to be done.

A research and development partnership has been established between the National Research Council of Canada (NRC) and Infrastructure Canada (INFC) to address these climate change related challenges and provide the science and evidence-based codes, guidelines, standards and decision support tools needed to adapt Canada's B&CPI to climate change. The Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative resulting from this partnership is funded by INFC and managed by NRC, but will bring together experts from across Canada. It will produce updated codes, standards, best practice guides, models and tools to help ensure that Canada's new and existing B&CPI are more resilient to the effects of climate change and extreme weather events. These resilient B&CPI will have systems and components that are able to withstand, absorb, adapt to and/or recover from adverse climate events with minimum loss of functionality and a recovery time that is not disproportionate to the intensity of the adverse events (Lounis and McAllister 2016).

This initiative is essential as the climate (and associated climatic loads) is one of the most important factors affecting the design and operation of Canada's B&CPI. Buildings are designed to resist snow and wind loads and to protect occupants from rain, heat and cold. Storm water systems drain rainfall away from the built environment, while bridges cross rivers that may flood during extreme rainfalls. Climate effects generate direct loads on B&CPI, which can accelerate degradation (aging) of existing B&CPI, eventually leading to the need for their rehabilitation or replacement. Past design guidance for B&CPI took these effects into account and provided tools to ensure that the risk of adverse effects from climate loads and aging was kept at an acceptable level. These tools did not, however, take into account the risks from extreme weather, nor did they consider the effects of climate change. Instead, they assumed that climate is stationary and used past historical climatic data in determining the expected future climatic loads.

As is now well understood, Canada's climate is not stationary but instead subject to very significant changes due to effects of greenhouse gas (GHG) emissions on the earth's environment (IPCC 2014). Canada has responded by developing the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) (Working Group on Adaptation and Climate Resilience 2016), which represents Canada's plan to grow the economy, while reducing emissions and adapting to a changing climate. Canada's First Ministers agreed to take ambitious action in support of meeting or exceeding Canada's 2030 target of a 30% reduction below 2005 levels of GHG emissions, but also agreed to develop adaptation measures as a pillar of the framework. The report from the working group states that: *"Mobilizing action on adaptation will help protect Canadians from climate change risks, build resilience, and ensure that society thrives in a changing climate."* (Working Group on Adaptation and Climate Resilience 2016).

The expected effects of climate change not only include changes to Canada's baseline climate but also increased incidents of extreme weather (Warren and Lemmen 2014). While baseline climate change may reduce the performance and accelerate the rate of deterioration of Canada's B&CPI, extreme weather, such as floods, wildfires, freezing rain, extreme winds, and heat waves, can cause sudden failures in the ability of B&CPI to perform their intended functions. Recent extreme weather events, such as the 2016 Fort McMurray wildfire or the 2013 floods in Calgary and Toronto, led to billions of dollars in damage in addition to causing loss of life. As a result, it has become essential to develop tools to adapt Canada's B&CPI to climate change and extreme weather. These tools are needed to ensure that new and rebuilt B&CPI are designed and built to meet future climatic conditions, not historical ones. They are also needed to ensure that Canada's existing stock of B&CPI, worth trillions of dollars, is managed to minimize the costs of adaptation to climate change and extreme weather.

1.2 Objective and Scope

The CRBCPI initiative is funded by INFC to develop the design codes, standards, best practice guidelines and decision support tools needed to adapt Canada's B&CPI to ensure adequate performance under the impacts of climate change and extreme weather. This work will be underpinned by NRC's research and development expertise, code platforms, and existing networks for working with stakeholders. It will, however, be done with the support of many other organizations and individual experts, including the CSA Group and the Canadian Commission on Building and Fire Codes (CCBFC).

The first six months of the initiative involved a review of current practices for climate change adaptation, determining the state-of-the-art in the subject, identifying gaps in the existing knowledge base, and prioritizing areas of research for buildings and infrastructure for inclusion in the initiative. The current report provides a synthesis of overall knowledge gaps and research needs and identifies the priority areas for potential work within the four years of t the CRBCPI initiative. Not all identified knowledge gaps and research needs mentioned here fall within the scope of the CRBCPI initiative. They have been included in the report for completeness and as a reference for other researchers.

1.3 Report Structure

This report discusses the context for the initiative, including the Pan-Canadian Framework on Clean Growth and Climate Change (PCF); the current status of existing buildings and infrastructure; and the industry that builds and operates B&CPI. The impact of climate on B&CPI and the need for projected future climate loads is then described. Several sections of the report discuss the climate adaptation needs of buildings, bridges, roads, potable water, storm water, and wastewater systems and transit systems. The application of various decision support tools is then described, including risk management methods, life-cycle cost-benefit analysis, environmental life cycle assessment, and decision making frameworks. The report concludes with a synthesis of climate change impacts and research needs, a summary, and recommendations.

2. Context

2.1 Pan-Canadian Framework on Clean Growth and Climate Change

The Pan-Canadian Framework on Clean Growth and Climate Change (PCF) is Canada's plan to meet the country's emissions reduction targets and grow the Canadian economy. Canada's First Ministers agreed on taking action to support meeting or exceeding Canada's 2030 GHG emissions targets. They also agreed to develop climate adaptation measures as a pillar of the framework. The PCF includes four pillars:

i. Pricing carbon pollution;
ii. Complementary climate actions;
iii. Adaptation and climate resilience; and
iv. Clean technology, innovation and jobs.

The focus of the CRBCPI initiative is aligned with the third pillar of the PCF as the main objective of the initiative is to develop Canada-wide codes, standards, guides and best practices for climate-resilient buildings and core public infrastructure.

2.2 Existing Buildings and Core Public Infrastructure

The climate change adaptation of existing B&CPI systems presents additional technical and economic challenges beyond those of adapting new construction. Canada's stock of existing B&CPI was built under a wide variety of conditions, using many different construction materials and techniques, codes and standards. In general, older B&CPI were built under less stringent design guidelines than current ones. In addition, all B&CPI deteriorate over time due to use and environmental effects, thus reducing their capacity to carry out their intended functions. Between these two factors, older B&CPI are generally more vulnerable to climate loads than modern construction. This is particularly the case where the B&CPI have not been well maintained or upgraded over time. In addition, the adaptation of existing B&CPI is much more challenging than the construction of new ones due to the sheer number of existing structures and the higher adaptation costs and indirect costs, and longer times associated with their retrofit.

Canadian buildings are owned by individuals, corporations and different levels of government. They range in size from small single family homes to high-rise apartment buildings, office towers and large building complexes. Buildings are typically maintained by their owners, but different buildings are kept at different levels of maintenance. Owners of large stocks of buildings will typically use asset management and building management systems to ensure the optimal operation of their assets.

Canada's federal, provincial, territorial and municipal governments own the country's core public infrastructure, which, for the purposes of the CRBCPI initiative, is defined as roads, bridges, potable water, storm water, and wastewater systems and transit systems. As noted earlier, the 2016 "Canadian Infrastructure Report Card" rates one third of Canada's municipal infrastructure as being in fair, poor or very poor condition with an increasing risk of service disruption. Renewal and rehabilitation requirements are estimated at $170 billion, a figure that is expected to increase due to climate change. Most infrastructure owners also use asset management systems, but as can be seen from the percentage of infrastructure needing attention, the level of management and amount of resources available can vary widely depending on the municipality. In most cases, small and more remote communities have fewer resources available to support decision making and to implement effective asset management practices than do the larger municipalities.

Persuading owners of existing B&CPI to adapt their assets to climate change requires developing the information needed to demonstrate that the risk of failure of their assets will increase in the future due to climate change. This information needs to be available in forms that can be readily integrated into existing asset and risk management strategies. In addition, it needs to take into account broader indirect socio-economic costs resulting from the deterioration or failure of B&CPI systems. The inclusion of those costs is particularly important for CPI, where the indirect costs of a system failure are likely to be far higher than the direct costs (i.e., costs of rehabilitation and replacement).

2.3 The Construction Industry

New B&CPI are built by the construction industry, which operates in a complex industrial and regulatory environment. Approaches to ensuring new B&CPI are fully adapted to climate change need to take this context into account. Construction is a complex service and manufacturing industry involving thousands of different components that are assembled into products and systems by a large number of workers both on and off the construction site. Basic safety, health, accessibility, maintenance and retrofit, energy efficiency, and B&CPI protection features are addressed in construction codes, standards, specifications, and guides. However, construction is primarily a market activity, the quality of whose products reflects the interplay of costs, time, and availability of materials, skill and knowledge. Provinces and territories regulate the construction of B&CPI, while municipalities generally inspect and enforce the regulations. The federal government provides support to ensure national standards are met. There is considerable additional government presence, as regulator, adjudicator, funder, facilitator, and B&CPI owner.

Lack of capacity means that many construction companies have difficulty innovating or taking up new information. As a result, the major instruments used to influence the practices of the construction industry are building and bridge codes, standards and government issued guidelines, which set minimum requirements on expected performance. Some of the other successful policy instruments in the construction industry include education and training, incentive programs, insurance and warranty provisions, and professional liabilities/responsibilities.

The complex nature of the industry means that there is a considerable degree of risk involved in the construction of new B&CPI, representing the possibility that the structure will not perform as expected. Risk during construction and immediately afterwards is managed through a wide variety of instruments. Determining whether or not a structure was constructed to the applicable codes and standards is often key to determining liability when something goes wrong since design codes, such as provincial building codes, represent the minimal acceptable performance. Given the nature of the industry, modifications to codes, standards and guidelines appear to be an effective approach to ensure that new B&CPI systems are adapted to climate change.

3. Development of Climatic Loads for Buildings and Core Public Infrastructure

3.1 Background

Current methods for the design, evaluation and rehabilitation of B&CPI systems in Canada use climatic loads derived from historical climatic data. In all cases those methods assume that the climate is stationary, rather than examining trends in past data or projecting how it may change in the future under different levels of GHG concentrations. Climate change science is now at a point where we can predict some future climatic data and loads and their associated uncertainties – allowing future loads to begin to be considered in the design of B&CPI. This shift in design methods is critical as most B&CPI have service lives of 50 to 150 years or beyond, which is more than enough for the structures to experience climatic conditions that may be very different from when they were built.

In addition, current design methods are inconsistent in how they deal with extreme weather events, as extremes may not be taken into consideration, may be based on historical data (without taking into account future climate trends), or may use relatively low return periods compared to what may be desirable. Current methods are primarily designed for new construction and assume that the capacity of the structure will remain constant throughout its lifetime. The gradual degradation of existing structures over time adds another level of uncertainty to the assessment of their performance and is generally not taken into account in current design methods.

A key factor for modifying existing methods to account for climate resilience is in understanding how the baseline and extreme climate loads are expected to change over time. Once this information is known, accounting for climate resilience becomes a matter of: a) understanding how the loads will affect the buildings and infrastructure; and b) providing the required level of resilience or robustness in the design of B&CPI components and systems to maintain an acceptable level of risk of failure over their design lives.

This section of the report describes current and projected climate trends and discusses gaps in existing models and practices that need to be filled to provide the level of prediction accuracy needed to develop climate resilience in B&CPI. In addition to published sources, the results of an expert consultation held at NRC (Attar and Lounis 2017) were used to analyze current climate change knowledge gaps related to the design and service life of B&CPI.

3.2 Current Canadian Climate Trends

While current methods of B&CPI design assume stationary climatic conditions, a review of existing data shows that Canadian climate has been changing since at least the 1940s. As with global data and predictive models, the clearest trends have been observed in temperature changes. Precipitation measurements, however, also show long-term trends.

Average temperatures in Canada have already increased by 1.6°C since 1948 (Working Group on Adaptation and Climate Resilience 2016), which represents warming at approximately twice the global rate (Figure 1). Canada’s Arctic regions are, in turn, warming at above the national rate. While warming has been observed consistently across most of Canada, stronger warming trends have been found in the north and west, with warming occurring at a slower rate along the Atlantic coast (Shepherd and Zhang 2017).

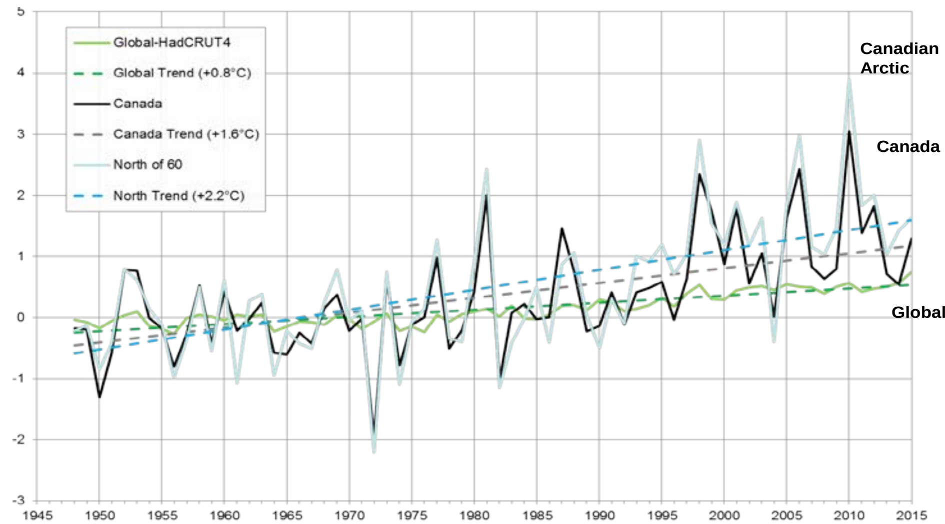


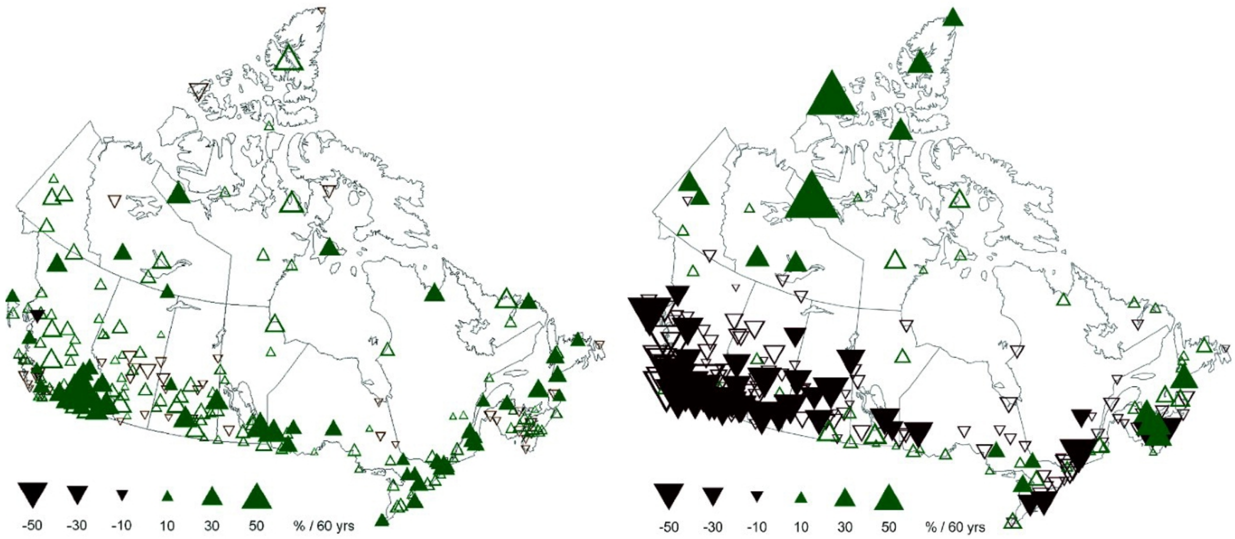
Figure 1 – Observed Changes in Canadian and Global Annual Average Temperatures (°C) (Shepherd and Zhang 2017)[1]

As warm air can hold more moisture, more precipitation events may occur as local temperatures rise. This effect is, however, dependent on local geography, as effects such as rain shadows may prevent increases in precipitation in areas such as the east slope of the Rocky Mountains. Canada has, in general, become wetter in recent decades (Mekis and Vincent 2011), with an increase in annual precipitation of about 16% between 1950 and 2009. This change corresponds to increases in rainfall of about 13% and in snowfall of about 4%. Different regions show, however, different degrees of change (Figure 2), with a shift in precipitation from snow to rain in most of southern Canada, as would be expected with warming temperatures. It is worth noting that although the overall precipitation levels have increased in most regions, regional trends towards droughts have also been noticeable, particularly in the western provinces.

Trends in winds are not as clear over time. While it is possible to define the types of events that create wind hazards in different regions of the country (Vickery 2017), there are insufficient data available to date to determine whether the occurrence of severe winds or damage from them has increased over time. The best historical data appears to be for hurricanes along Canada's Atlantic coast, but even there the data do not allow clear development of historical trends. Historical data has, however, shown that both the frequency and intensity of extratropical storms occurring in the winter have increased in northern Canada (latitudes greater than 56 degrees) and the Maritime provinces, but have decreased in the rest of southern Canada (Wang, Swail et al. 2006).

The lack of knowledge on changing wind patterns is matched with a general lack of understanding of the nature of wind hazards (Vickery 2017). It is known that wind hazards in southern Ontario, Winnipeg and Montreal are dominated by thunderstorms, while wind hazards in Vancouver and most of the east coast are dominated by extratropical storms originating at sea. Hurricanes contribute to wind hazard for coastal New Brunswick and Nova Scotia, with tornadoes being important in the Prairies and Ontario.

[1] Used with the permission of the Minister of the Environment and Climate Change; © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment and Climate Change, 2019.



a) *b)*

Figure 2 – Observed Annual Precipitation Trends: 1950–2009 a) Rainfall; b) Snowfall
(filled triangles indicate a statistically significant trend)
(Mekis and Vincent 2011)[2]

3.3 Climate Change Models and Projections

Climate modelling is a computationally intensive process that examines a global, coupled atmosphere-ice-ocean-land system. As a result, four Representative Concentration Pathways (RCPs) were adopted in 2014 by the Intergovernmental Panel on Climate Change for its fifth assessment report (IPCC 2014). The RCPs are based on different levels of GHG concentrations rather than emissions, but are dependent on the amount of emissions between 2014 and 2100. The highest emission scenario gives an expected 2.6°C to 4.8°C global warming over that time, while the lowest produces a 0.3°C to 1.7°C global warming. The medium-low and medium-high emission levels scenarios correspond to 1.1°C to 2.6°C global warming and 1.4°C to 3.1°C global warming, respectively.

Average temperatures in Canada are expected to rise by 1.5°C to 4.5°C by 2070, based on combined international model results that considered both low and very high GHG emission scenarios (Figure 3). Temperature changes will not, however, be regionally uniform (Collins, Knutti et al. 2013), with the Arctic region projected to warm the most. Seasonal variations in warming patterns are also expected, with the largest temperature increases in winter occurring in northern Canada, and in summer occurring in southern Canada (Warren and Lemmen 2014). Most locations are expected to have more frequent heat waves and fewer cold extremes. The hot extremes will also last longer and be hotter than previously recorded.

[2] Used with the permission of the Minister of the Environment and Climate Change; © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment and Climate Change, 2019.

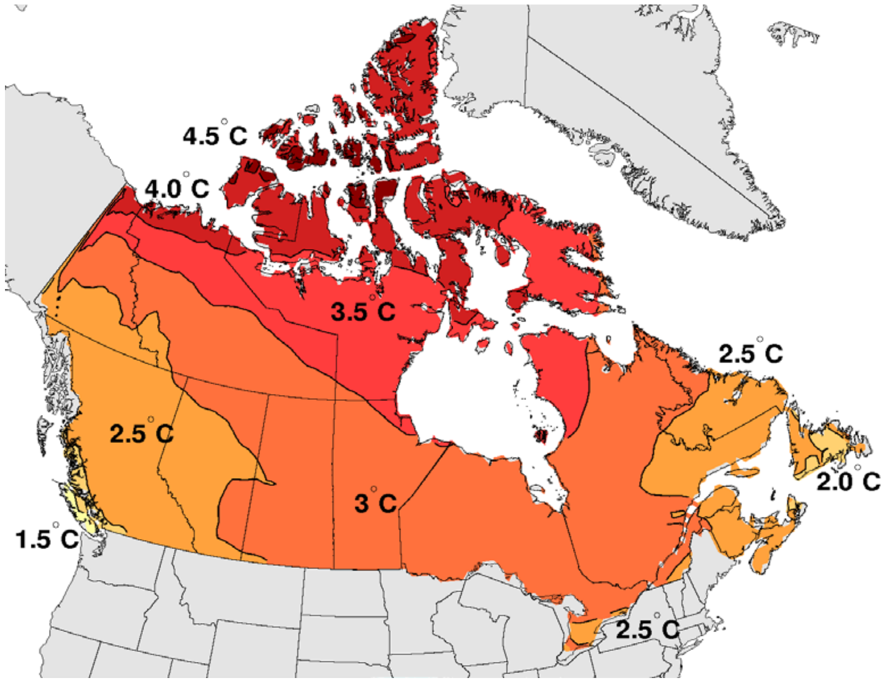


Figure 3 – Projected Increase in Annual Average Temperature: 2041–2070 (relative to 1976–2005) (Ouranos, 2015[3])

There is less certainty about the impacts of rising temperatures on rainfall, wind patterns, sea-level rise and other weather phenomena (Zwiers 2017). Projections of precipitation change are generally less robust than those for temperature change, as there is greater variability among climate models (Warren and Lemmen 2014, Zwiers 2017). It is, however, very likely that global precipitation will increase with increased global mean surface temperature in the long term (Collins, Knutti et al. 2013). Examination of Canadian data shows that changes in the extremes of daily precipitation over the past 50–60 years are detected in observations at a national scale (Zwiers 2017). Such changes are, however, not expected to be reliably detectable in individual station records due to both measurement and climate model limitations. Increased precipitation is expected in general as the amount of water that can be held in the atmosphere increases with increased warming, but the exact amount of annual increase in a particular location is much more difficult to determine. Extreme precipitation events are even more difficult to predict, although they are also expected to increase in frequency.

Even less information is available on the impact of climate change on wind speed and the frequency of extreme wind events (Zwiers 2017). There are fewer studies and most of the research has focused on changes to the frequency and severity of tropical cyclones, such as hurricanes or monsoons. The current consensus of the IPCC with regard to tropical cyclones is that it is likely that their global frequency will decrease or remain constant, but that their mean maximum wind speed and precipitation rate will increase (IPCC 2014). There is, however, low confidence in tropical cyclone predictions for specific regions, including the North Atlantic.

[3] Used with the permission of Ouranos.

Very little work has been done to attempt to determine if the frequency and severity of extreme winds due to thunderstorms and tornadoes will be affected by climate change. In fact, the IPCC makes no reference to tornadoes. Presumably the region of Canada that is impacted by strong thunderstorms and tornadoes will expand to the north (Vickery 2017) as the climate warms, but this assumption has not been tested.

3.4 Flooding

Changes in the frequency and intensity of flood events are one of the most significant extreme weather risks related to climate change. Floods can occur due to local intense rainstorms, rapid melting of snow, ice jams on rivers, storm surges and rising sea levels. Together, they represent a major cause of economic loss and a high potential for risk to the safety of Canadians. In 2013, floods in Toronto and Calgary affected large numbers of people, but some First Nations and remote communities experience serious flooding frequently, creating or worsening serious housing problems. In addition, current infrastructure design assumes climate stationarity, which may lead to an underestimation of extreme precipitation, flood risk and risk of failure of infrastructure systems (Cheng and AghaKouchak 2014). New measures are therefore needed to address flooding and ensure that drainage systems can help manage the current and future flood risks.

Key elements in the design of drainage infrastructure include rainfall intensity-duration-frequency (IDF) curves, which are used to estimate peak storm water runoff rates; the runoff coefficient (*C*), which represents the ability of a rainfall catchment surface to absorb some of the rainfall; and design storm hyetographs, which are used to define the temporal distribution of rainfall during simulations used in the design of ponds and large-scale drainage works. In current practice, all these elements are computed/estimated based on historical data and assume a stationary climate. In the case of coastal flooding, information on rising sea levels and the frequency and intensity of coastal storms is critical. Increasing sea levels may also increase vulnerability to tsunamis and very high tides, which will require special assessments.

Most research to examine the effect of climate change on flooding has focussed on IDF curves. The results predict that, due to the effect of warmer temperatures, there will be more water vapour in the atmosphere with intense precipitation and flooding expected to occur more frequently and with greater severity. The resulting IDF curves will have higher intensities and shorter return periods than those now in use (Cheng and AghaKouchak 2014, Kuo, Gan et al. 2015). Environment and Climate Change Canada (ECCC) provides standard IDF curves for over 500 active and inactive climate stations across the country (Environment and Climate Change Canada 2017). ECCC also provides a free tool for the development of IDF curves under the effects of climate change. Results can be generated for a future time period up to the year 2100 based on 24 Global Climate Models (GCMs) that simulate various climate conditions to local rainfall data and three future climate scenarios ranging from low to high severity. Users can generate results for either pre-loaded ECCC rain stations or for user-created rain stations. The Ministry of Transportation of Ontario and the Ontario Ministry of Natural Resources also provide IDF tools that take into account climate change. The value of the runoff coefficient *C* is typically not affected by climate change, but will change over time due to urban intensification. Climate change effects on design storm hyetographs do not appear to have been addressed by any government bodies to date.

Improvements in flood readiness have been limited over the last 20 years. There is, however, a major Government of Canada initiative underway through Natural Resources Canada (NRCan) and Public Safety Canada (PSC) to address flooding issues (Public Safety Canada 2017). The Federal Floodplain Mapping Guideline series, including the new Federal Floodplain Mapping Framework, are intended to address many of the existing gaps in knowledge and mitigation of flooding in Canada. Planned guidelines that will be part of the Framework include work on the vulnerability of buildings and climate change case studies. Flooding-related activities in the context of the CRBCPI initiative will be coordinated with NRCan and PSC.

3.5 Wildfire

A substantial amount of literature is available on the impacts of climate change on wildland fire within the Canadian context. The Canadian Council of Forest Ministers summarized climate change impacts that are expected to affect wildland fire-related hazards in the future as including (Wildland Fire Management Working Group 2016):

- rising temperatures;
- decreasing soil moisture;
- increasing arid conditions;
- accumulation of vegetative fuel that enables and sustains fire;
- a shift to more drought-resistant and more fire-prone trees and grasslands; and
- decrease in water availability.

Combined, these impacts are expected to increase the length of fire seasons, the number of wildland fires, and wildland fire risk in areas that have not experienced significant wildland fire hazards to date. Both fire occurrence and area burned are expected to increase significantly in Canada as a result of changing climate conditions. For example, national estimates predict an increase in human- and lightning-caused fire of 18% by 2050 and 50% by 2100; regional estimates predict that by the end of the 21st century human-caused fire in Ontario will increase by 50% and lightning-caused fires in Alberta will increase by 80% (Sandick, Kovacs et al. 2017).

3.6 Knowledge Gaps and Research Needs

Adapting B&CPI to improve climate resilience requires reliable information on current and future temperatures, precipitation and wind loads. In the case of temperature, knowledge of not only baseline behaviour is needed, but information on extremes, number of heating or cooling days (when heating or air conditioning is needed) and freeze-thaw behaviour is also needed. Annual 15-minute and one-day rainfall values are important, but information on rainfall IDF is equally important, as are expected snow loads for different return periods. While wind storm speeds, pressures and durations need to be understood, so should the actual hazards presented by those storms. In some applications the likelihood of lightning strikes is also needed.

The review of current knowledge of climate trends and associated climatic loads on B&CPI described in this section of the report identified major knowledge gaps. While baseline changes in temperature can be estimated, changes in temperature extremes, precipitation rates and extremes, and wind speed and extremes are not well understood. Significant research on future climatic behaviour is therefore needed to produce climate-resilient B&CPI.

Specific recommendations related to understanding changing climate loads include:

- Review and update of historical climatic data for the National Building Code (NBC) (Canadian Commission on Building and Fire Codes 2015) and the Canadian Highway Bridge Design Code (CHBDC) (CSA Group 2014) under the stationarity assumption.
- Develop new climatic data for the NBC and CHBDC that account for climate change and extreme weather, including addressing regional climate change variations.
- Develop new climatic data for other CPI systems (roads, water/wastewater, and transit) that account for climate change and extreme weather, including addressing regional climate change variations.
- Work on statistical analysis of historical climatic data (temperature, rain, ice, snow and wind) needs to continue with a view to identifying trends since it sets the groundwork for understanding the projections into the future. Wind data must be evaluated by type (synoptic storms, thunderstorms, tornadoes, and hurricanes) to more accurately determine risks.

- Research into downscaling results from global climatic models must continue with a view to extracting useful information on climate baselines and extreme weather events on a more local basis (finer spatial and temporal scales).
- Research into the limitations of the uniform hazard approach in specifying climatic data and investigation of the development of the uniform risk approach as an alternative.
- Research into the modelling of climate change impacts on precipitation and wind.
- Develop standardized tools and protocols for applying non-stationary climate models to forecast future climatic data, including IDF curves.
- Develop standardized tools and protocols for considering climate change in the construction of design storms and hyetographs.
- Investigate long-term increase in run-off coefficients, *C*-factors and develop approaches and methods for including this increase in the design procedure.
- Review and update flood hazard maps to incorporate the effects of climate change and extreme weather on the determination of the extent of flood plains, and revise definitions of flood levels for different frequencies of occurrence.
- Revise coastal flood maps to include the impact of changing sea levels on different types of flood risk.
- Re-examine the expected loads from storm surges and tsunamis on coastal buildings and infrastructure in light of sea level rises and increasing storm intensities.
- Develop and modify tools to account for uncertainties in GHG emissions and RCP scenarios in a probabilistic model that can be incorporated in downscaled Canadian climate models and local predictions of climate change.

4. Buildings

4.1 Background

Buildings form the single largest group of built structures in Canada. There are currently over 14 million households in Canada, and this number is projected to grow by another 3 million in the next 20 years. Although a growing percentage of Canadians are living in larger condominium and apartment buildings, most live in houses or multifamily homes. Over 15% of all houses in Canada were built before 1946, and roughly half were built before 1981 (Statistics Canada 2011). Similarly, over half of Canada's ~500 thousand commercial and institutional buildings were built before 1980, with over a quarter built prior to 1960 (Office of Energy Efficiency - NRCan 2013).

Building construction in Canada is governed by provincial/territorial building codes, which are modeled on the National Building Code (NBC) (Canadian Commission on Building and Fire Codes 2015), which is published by NRC. Separate national fire (NFC) and plumbing (NPC) codes are also published by NRC. These model codes are designed to ensure the safety of Canadians through minimum acceptable requirements for building design. The NBC uses reliability methods and limit state approaches, which ensure that risk assessment and risk mitigation are an inherent part of the Canadian building code process.

Current (2015) and past editions of the NBC assume stationary climatic data and loads. Updating design practices to take into account the effects of climate change and extreme weather is therefore essential to creating new climate-resilient buildings. However, additional tools are needed to support the assessment of existing buildings for climate resilience and to ensure that retrofit work on that existing stock will also be climate-resilient.

This section of the report examines the climate factors that affect building performance. It also describes the knowledge gaps and work needed to design climate-resilient buildings and to assess the resilience of existing buildings.

4.2 Climate Effects on Buildings

Climate affects buildings in a number of different ways. Some climatic loads (winds, snow load, fire, flooding) can cause serious damage, risk to life safety and immediate loss of the building. Other climatic loads (relative humidity, rainfall, freezing and thawing) can cause the building to deteriorate over time, eventually leading to significant damage. Still other climatic loads affect the comfort of the occupants or the efficiency of building systems. The current (2015) edition of the NBC includes climatic design data (Appendix C, Table C-2) for January and July design temperatures, heating degree-days, rain, total precipitation, moisture index, driving rain wind pressure, snow loads, and wind pressures. The data is based on historical trends and assumes a stationary climate.

Climate change and extreme weather are predicted to impact all of these climate design data and resulting loads (Table 1). The effects may be complex, as buildings are composed of many different systems, and responses to climate change for one system may create other unintended impacts in other systems. As a result, climate change will not only change the way buildings are designed, but will also change the performance of Canada's existing buildings, often reducing their expected service life. An increasing number of extreme weather events, combined with the vulnerability of old building stock, also have the potential to lead to building structural failure with its associated economic and societal costs.

The need for climate resilience in buildings is reflected in a comparatively high number of relevant tools, practices and guides for increasing the climate resilience of new and retrofit buildings. A few notable examples include: the Public Infrastructure Engineering Vulnerability Committee (PIEVC) assessment protocol (Engineers Canada 2011), the Institute for Catastrophic Loss Reduction (ICLR) Home Builder's Guide to promote the construction of disaster-resilient homes (Institute for Catastrophic Loss Reduction 2010), the US Department of

Housing and Urban Development Climate Change Adaptation Plan (United States Department of Housing and Urban Development 2014), the Insurance Institute for Business and Home Safety Builder's Guide for fortifying homes against natural hazards (Insurance Institute for Business and Home Safety 2008), and the US Green Building Council's report, *Green Building and Climate Resilience* (Larsen, Rajkovich et al. 2011). There are also a number of well-developed approaches for Wildland-Urban Interface (WUI) in North America, including the National Fire Protection Association wildland standards (National Fire Protection Association 2017), the International Code Council WUI Code (International Code Council 2011), *FireSmart* (FireSmart Canada 2017) and *Firewise* (Firewise 2017), as well as standards for buildings on floodplains (American Society of Civil Engineers 2014). While these documents may be valuable tools for incorporating climate change impacts in the NBC, considerable work will need to be done to determine the most effective method of integrating the available information into the NBC.

Table 1 – Climate Change Impacts on Buildings

Climatic Hazard	Impact
Flooding	• Increasing incidents of building damage and failure • Increasing incidents of loss of function
Changes in precipitation levels and relative humidity	• Increased rates of building aging due to moisture exposure or rapid wetting/drying cycles • Inadequate rainscreen design
Changes in snow loads	• Increased risk of structural damage or building collapse
Change in range of maximum and minimum temperatures	• Increased cooling loads • Overheating of occupied spaces • Increased rates of deterioration/aging of building materials and systems • Changes in biologically induced (insects, rodents, mold and mildew) damage • Changes in energy system requirements
Extreme heat	• Increased rates of building deterioration/aging • Overheating of occupied spaces
Freezing and thawing	• Increased rates of deterioration/aging of building materials and systems
Extreme winds	• Increased likelihood of damage to building envelope • Increased likelihood of structural damage and failure
Wildfire	• Increasing rates of building loss and failure

4.3 Knowledge Gaps and Research Needs Related to NBC

There are a number of areas in the NBC that could be addressed to increase the climate-resilience of buildings. A key problem is the reliance of the NBC on historical climatic loads that assume a stationary climate. The need to provide updated climatic data is described in Section 3 of this report, but once the updated data has been provided, it needs to be converted into updated climatic loads that can be incorporated into the design of new buildings. The effects of combined dead, live and climatic loads on buildings also need to be re-examined in light of climate change and extreme weather events. Finally, the existing code requirements for regional variation of design climatic loads will need to be assessed to ensure that they reflect future regional variations and produce consistent and uniform risks of failure across the country.

Once expected climatic loads are known, the impacts of those loads on building systems need to be evaluated to determine the instances where the expected service lives will be expected to decrease and where risks to safety will be expected to increase. Selected cases will need laboratory assessment to confirm expected climate impacts and test protocols for construction materials will need to be updated to reflect the expected effects of climate change. Changes to the relevant CSA standards on building durability and construction materials will also be required.

4.3.1 Gaps in Building Code Content

In addition to the need for revised climatic loads, a review of the NBC has revealed some specific gaps in content that will become more significant due to climate change. These gaps include designing for the cooling season and adapting foundation design for climate change. While the Canadian climate has previously forced an emphasis on designing for the heating season, climate change will create a requirement for inclusion of the cooling season, and in particular, for preventing the overheating of indoor spaces. Guidelines for cooling best practices will therefore need to be developed.

Foundations (Figure 4) are an area where work is needed as current geotechnical design assumes stationary climate and time-invariant soil properties. Climate change has the potential to affect the mechanical behaviour of soils and the stability of foundation systems, as well as change of soil bearing capacity, causing settlement or heaving of foundations and leading to foundation failure. There is therefore a need to review the methodology used in geotechnical design to take into account potential changes in properties of soils, rocks or groundwater level, including seasonal and inter-annual variations. These changes will potentially affect most areas of infrastructure as well as buildings. Field, laboratory and modelling investigations are required to gain a better understanding of climate impacts on Canadian soils and update design guidance appropriately.

4.3.2. Roofing Stakeholder Needs

Stakeholders in the area of building roofing were engaged through a workshop held on December 15, 2016 in Ottawa, Ontario, as well as through four additional separate consultations related to specific subject areas, including:

- climate change adaptation of residential roofing;
- thermal impacts of climate change on Canadian building materials;
- effects of extreme weather on Canadian roofs, including thermal bridging; and
- hurricane assessments.

Discussions with stakeholders, along with additional research, identified three major needs that should be fulfilled to ensure roofs are climate-resilient. They include:

1. development of guidelines for commissioning and certifying the resiliency of roofs subjected to extreme weather events;
2. development of reliability-based tools for the design and analysis of roofs to ensure that they can withstand extreme weather events; and
3. codification of climate-dependent building material properties in order to update existing databases, which were developed in the 1990s and assume a stationary climate.

Figure 4 – Foundation damage due to dry soil conditions, Ottawa 2016 (T. Manning photo)

4.3.3. Building Resilience to Extreme Weather

Post-disaster buildings, which are expected to remain functional during and after extreme weather events or other disasters, are designed using enhanced loads through the use of importance factors. These loads do not, however, expressly take into account the expected impact of extreme weather in a changing climate. Other buildings are not designed to account for the same level of extreme weather events.

The current climatic loads used for the design of post-disaster and high-importance buildings need to be re-examined and updated given the expected increases in the intensity and frequency of extreme weather events. In addition, the categories of buildings that are considered post-disaster need to be re-examined in light of current emergency management and recovery plans, which may bring new building types into the post-disaster category. If substantial changes to the post-disaster building procedures are required, techniques for assessing and possibly enhancing the climate resilience of post-disaster buildings will be needed.

The most likely causes of weather-related disasters include wildfire, flooding, extreme winds, excessive snow loads, and ice storms. In the case of ice storms, the major risk is to power lines, which can be addressed through changes to the Canadian Electrical Code. Wildfire, flooding and extreme winds are, however, all issues that can be addressed in building codes. Recent wildfires have resulted in the loss of over 2,700 structures, with the total insured loss estimated to be over $5 billion. The 2016 Fort McMurray wildfire (Figure 5) was the single most expensive disaster in Canadian history. Together the 2013 southern Alberta and Toronto floods had combined insurance losses that came close to the same value as the Fort McMurray wildfire. Atlantic Canada has recently experienced both hurricanes and non-cyclonic windstorms with hurricane force winds, while the Prairie Provinces and Ontario have been experiencing an increasing number of tornado events.

Considerable work is needed in each extreme weather area to better understand their associated risks and provide appropriate design guidance. In the case of wildfire and flooding, additional work is needed to provide supporting documentation and guidelines to cover issues that are not specifically related to building design. A national Wildland-Urban Interface (WUI) fire code or guide for Canada should be developed based on existing best practices, research, modelling, and field work. Potential tools to improve flood resilience in buildings range from the creation of new standards through new design provisions for buildings on flood plains to new mitigation technologies. Best practices that are correlated with revised climatic data and flood plain maps are also needed. Additional flood issues are discussed in other sections of this report.

Figure 5 – Fort McMurray Wildfire, Alberta 2016 (Terry Reith, CBC)

Measures needed to deal with impacts of extreme winds on roofs were identified during a workshop on climate-resilient roofing systems held on December 15, 2016 at NRC. The consultation identified the following three research gaps:

- lack of comprehensive guidelines to assess the capacity of existing roofs after major weather events or to validate the designed capacity of new roofs subjected to extreme weather events;
- need for a complete database of building material properties subjected to extreme climate conditions in Canada; and
- need to develop resilience mapping for roofs in Canada.

Finally, there is a significant need to reassess the snow load provisions in the NBC. One cause is the increasing snow levels Atlantic Canada is expected to receive due to climate change (Section 3). In addition, snow loads on new constructions are higher than those on older buildings as improved insulation and construction techniques allow more snow to accumulate on roofs over the winter. Current snow loads in the NBC assume a certain degree of melting, which may no longer hold true. Excessive snow loads can cause structural damage to buildings, so ensuring the code provisions are accurate is critical to ensuring building safety.

4.4. Knowledge Gaps and Research Needs Outside of NBC Requirements

The NBC currently applies to new building construction, but progress is being made to include retrofit work as well, with the changes to the NBC likely to occur in the 2025 code cycle. This change will gradually create climate resilience in the existing stock of buildings. There is, however, a lack of guidance on the assessment of existing buildings for climate resilience and on appropriate methods to adapt existing buildings to achieve climate resilience. This need is most critical for post-disaster and high-importance buildings, and buildings in remote communities, but is important for all buildings.

Small, remote communities have unique needs and challenges in the face of climate change due to their location and limited technical and financial resources. This is particularly the case for indigenous communities where buildings are not required to meet the NBC, NFC or NPC. A comprehensive climate resilience strategy for new and existing buildings in remote communities would need to be developed in conjunction with Indigenous and First Nation stakeholders. A holistic approach should be taken to encompass not only climate change resilience, but also structural integrity, fire safety, healthy living conditions, procurement and resource challenges, and traditional indigenous knowledge.

5. Bridges

5.1 Background

Bridges are critical links in the road and rail transportation networks where they carry vehicles across major obstacles such as rivers and other transportation systems. Highway closures or lane reductions can generally be alleviated by detours or temporary construction while repairs are made, but there may be no readily available detour if a bridge has added restrictions for heavy traffic or is closed altogether. In addition, potential failures of major bridges have high consequences in terms of socio-economic impact, loss of life, and injuries.

Highway and roadway bridges in Canada are generally designed to the Canadian Highway Bridge Design Code (CHBDC), which is managed by the CSA Group as CSA S6 (Canadian Standards Association 2014). It sets a design life of 75 years with about 0.02% acceptable probability of failure and a reliability index of 3.5 over the design life. The goal for major bridges is to have even longer design service lives, with 125 years being the expectation for the new bridge over the St. Lawrence that will replace Montreal's aging Champlain Bridge. Bridge engineers have traditionally relied upon historical climatic data when designing bridge systems. The climatic loads used in the CHBDC for the structural design of bridges include minimum and maximum temperatures, ice accretion, water and ice loads, and wind pressure. Typically, extreme weather conditions are more critical than the underlying trends, but assumptions that climate is stationary in current bridge design codes are likely leading to bridges operating with higher risks of long-term failure than are generally considered acceptable. Uncertainty over the impact of extreme weather and changing climate on existing bridges, which are over 100 years old in some cases, leads to further complications in estimating climate-related risk to Canada's bridges.

This section of the report describes the effects of climate on bridges and lists the knowledge gaps and research needs that must be addressed in order to maintain Canada's bridges in a safe and functional condition for the future. The information here is generally applicable to both road and rail bridges, although issues related to the top layer of the bridge deck (pavement versus track) obviously differ. The latter topics are covered in Sections 6 (Roads) and 8 (Transit Systems) of this report. Rail-specific bridge design issues are also covered in Section 8.

5.2 Climate Effects on Bridges

A summary of potential climate hazards for bridges is given in Table 2. One of the key impacts is bridge scour, a term that describes the removal of material around or under the bridge piers, causing the pier and potentially the bridge to collapse. The failure of the Bonnybrook Bridge in Calgary in 2013 (Figure 6) is an example of a bridge that failed due to scour.

Table 2 – Climate Change Impacts on Bridges

Climatic Hazard	Impact
Riverine flooding	• Bridge scour from higher flow depth and speed leading to abutment and/or pier failure • Structure dislodged and moved • Roadway/embankment damage • Restriction of hydraulic capacity because of debris accumulation • Damage to appurtenances such as metal beam guard fence and bridge rail, or signage
Changes in precipitation levels	• Insufficient hydraulic capacity for new water flows
Coastal flooding	• Partial or complete bridge inundation or destruction • Corrosion from saltwater intrusion • Reduced navigational clearances • Loss of access to bridge approach • Separation of bridge decks from substructure • Deck-girder damage from negative bending and pier damage • Bridge scour • Damage to bridge superstructures
Change in range of maximum and minimum temperatures	• Deterioration and failure of expansion joints • Deterioration due to freeze-thaw cycles • Increased rate of corrosion of reinforcing steel and structural steel • Settlement due to permafrost thaw • Reduced corrosion due to reduced use of de-icing salts in some regions
Extreme heat	• Thermal expansion of bridge components and deterioration/failure of expansion joints • Increased rates of corrosion and chemical degradation
Extreme winds	• Loss of bridge stability • Stress due to vibration of decks, towers and cable stays
Ice buildup	• Ice jamming may affect condition and safety of bridge components, especially piers • Changes in cable-stayed bridge dynamics may lead to increased bridge vibration and potential failures • Ice buildup on river surface resulting in deck damage and collapse • Public safety risk due to damage to passing vehicles from falling ice
Wildfire	• Direct fire damage to bridge structures • Debris damage to bridge decks • Increased scour due to vegetation loss

Although the CHBDC incorporates extreme climatic loads into the design process, none of them incorporate the impact of climate change. All Canadian provinces and territories have some level of climate adaptation measures in place for their bridge systems, but the most well developed process is in British Columbia, where designing for climate-change-induced loads is mandated by the province. Even in British Columbia, however, no specific design process, scenarios, or extreme-event/climate-change load cases are specified. No unified approach or guidance in the determination of future climatic loads for the design of bridges is currently accepted in any Canadian jurisdictions. In addition, the current CHBDC does not consider the effects of simultaneous extreme weather events on bridge performance, as they are considered too rare to be of concern.

Figure 6 – Failure of the Bonnybrook Bridge in Calgary, Alberta 2013 (Transportation Safety Board of Canada)

5.3 Knowledge Gaps and Research Needs

There are a number of mechanisms or modes that can cause damage or failure in bridges that are not well understood. Two in particular, ice jamming and ice accretion, are poorly understood because they are more likely to occur in Canadian environmental conditions than in the United States or Europe. Ice jamming occurs when river or coastal ice builds up against bridges as a result of wind action and warming conditions (Figure 7). It can cause damage to the substructure and superstructure of the bridge and may produce scour when the ice is suddenly released. Individual studies have been done in this subject area, but there is little known about how ice and bridges interact, how common these problems will become, or the best ways to mitigate the problem.

Ice accretion occurs on bridges due to the buildup of an ice layer on the exposed surfaces of bridge structures due to freezing rain or in-cloud icing. In short-span bridges, the ice acts primarily as an additional load, but for long-span bridges, it can affect the dynamic behaviour of the bridge. This is particularly the case for cable-stayed bridges where ice build-up on the cables will greatly change vibrational behaviour. Ice falling off cable-stayed bridges also frequently forces closures of major transportation links for safety reasons. Climate-change-induced changes in wind loading scenarios also require more investigation.

Figure 7 – Ice jam damage to bridge, Torch River, Manitoba 2017
(Regional Municipality of Torch River)

Other significant knowledge gaps are more universal in nature. Actions to resolve them include:

- Developing new climatic data for bridge design incorporating climate change;
- Reviewing and updating historical climatic data for the CHBDC;
- Developing appropriate load factors for non-stationary climatic data and load combinations;
- Investigating the impact of extreme temperatures and winds on bridge performance;
- Investigating the impact of flooding on scour and bridge performance;
- Investigating the impact of climate change on time-dependent deterioration mechanisms and accounting for them in bridge design and asset management systems;
- Investigating the impact of climate change and extreme weather on bridge condition assessment procedures and life cycle performance prediction; and
- Developing a better understanding of design loads due to storm surges and powerful waves.

Once these knowledge gaps are filled, asset management guidelines for existing bridges can be produced or modified to account for the effects of climate change. Case studies may then be undertaken with bridge owners to validate the guidelines.

6. Roads

6.1 Background

The public road network in Canada has more than 1.13 million kilometers in two-lane equivalent roadways (Transport Canada 2015). Of this length, approximately 40% are “paved,” that is, surfaced with either bituminous or ordinary Portland cement based materials, with bituminous pavement being the most used system. The remaining 60% are “unpaved,” although typically consisting of an engineered structure. This analysis excludes parking lots and other paved surfaces, which are outside the scope of the current initiative. The impact of flash flooding on impermeable surfaces such as parking lots is, however, within the initiative’s scope.

While the surface of the road is the part that is familiar to most people, it is only one component of the total road system. Road alignments include a number of engineered structures, including cuts, fills and embankments. The road itself is composed of a number of layers, which are designed to distribute the load of vehicles across the road, preventing long-term damage. It also includes ditches and slopes designed to shed water from the surface of the road and prevent it from penetrating the structure beneath the road surface. The base layer in unpaved roads also acts as the road surface and needs to be designed with that function in mind.

Changes in climate and the occurrence of extreme weather events can affect all of the engineered structures of a road. Damage to the road surface can occur due to a number of different causes, but the rest of the road structure is highly vulnerable to changes in soil moisture content and, in particular, to flooding. In some cases the visible damage on the surface of the road is caused by problems underneath the surface, and both surface and lower layers need to be repaired or replaced to solve the problem.

Climate change is expected to undermine the ability of road systems to perform their intended functions by inducing costly damage, both directly to the road structure and indirectly through the loss of economic productivity and opportunities (Kirshen, Ruth et al. 2008, Jacob, Maxemchuck et al. 2011, Major, Omojola et al. 2011). Furthermore, some roads have outlived their intended service lives and in some cases were not built in accordance to specifications and guidelines. This section of the report describes the climate issues affecting roads as well as the research needed to develop guidance on producing a climate-resilient road network.

6.2 Climate Effects on Roads

Roads are typically renewed on a 20- to 40-year cycle, depending on the level of use, and mechanical and environmental damage. They broadly represent a case where climate change adaptation can be put in place over the long term, rather than being an immediate need. Climate properties such as air temperature, precipitation, freeze-thaw cycles, wind speed, percentage sunshine, and relative humidity, which affect the placement of pavement, will change over time, but significant changes are likely to occur on the same time scale following subsequent road replacement cycles. In contrast, however, extreme weather can cause problems for road systems in the near term (Figure 8). This difference offers the opportunity to focus on changes to current road construction and management practices to manage extreme weather impacts while monitoring the impact of the changing climate over time and gathering data for future practice changes.

Figure 8 – Washout of Highway and Railway, Peace River Country, B.C. 2016
(B.C. Ministry of Transportation and Infrastructure)

Key impacts of climate change and extreme weather on roads are outlined in Meyers et al., 2014. This information, along with additional impacts to account for particular aspects of Canadian climate, is summarized in Table 3. Examining the table shows that the major potential causes of road damage are likely to result from:

- heat waves;
- flooding and high precipitation; and
- freezing and thawing.

A 2010 survey of Transport Association of Canada (TAC) member agencies identified that the effects of climate change on pavement assets were being assessed by “a few agencies” (Transportation Association of Canada 2013). At that time, 71% percent of federal and provincial agencies were evaluating the potential impacts of climate change on their pavement assets as compared to only 21% of municipalities. It is likely that the largest cities have the capability to respond to climate change and extreme weather, while the smaller municipalities may not have the capacity to respond to climate change at all.

While addressing baseline climate change effects is not as urgent for roads as other types of infrastructure, these effects do have implications for maintenance costs in particular. Potholes and frost heaves do not typically represent structural risks to roads, but do cause traffic problems and may lead to premature road rehabilitation. Decisions to improve resilience to this type of climate effect are likely to be made on the basis of economic factors rather than risk to safety, as would be the case for some types of flooding damage.

Table 3 – Climate Change Impacts on Roads (adapted from Meyers et al. 2014)

Climatic Hazard	Impact
Flooding	• Washouts and other damage
Changes in precipitation levels	• Increased rainfall leading to landslides and slope failures • Excess soil moisture causing faster road deterioration • Road embankments at risk of subsidence or heave • Shrinking of subsurface soils as a result of drought
Increased intense precipitation	• Heavy rain with accompanying mudslides damaging roads (washouts and undercutting), and leading to road closures • Heavy precipitation and increased runoff causing damage to tunnels, culverts and roads in or near flood zones, as well as coastal highways
Sea-level rise and increased storm surge	• Erosion of coastal road base • Temporary and permanent flooding of roads and tunnels • Encroachment of saltwater leading to accelerated degradation of tunnels • Further coastal erosion due to the loss of coastal wetlands and barrier islands removing natural protection from wave action • More frequent and severe flooding of underground tunnels and other low-lying infrastructure
Change in extreme maximum temperature	• Premature deterioration of road surfaces • Damage to roads from buckling and rutting • Concrete pavement subject to extra thermal stresses
Change in range of maximum and minimum temperatures	• Increased freeze-thaw cycles in many locations creating frost heaves and potholes on road and bridge surfaces • Increased slope instability, landslides, and shoreline erosion from permafrost thawing leading to road damage • Reduced frost heave and road damage in some locations

6.3 Knowledge Gaps and Research Needs

While there is generic information available on the effects of climate change on roads, detailed recommendations and knowledge are scarce (Federal Highway Administration 2015). This lack of specific knowledge may be due to the relatively short renewal cycles of roads. Based on the existing knowledge of climate change and extreme weather impacts on roads, specific research needs related to road infrastructure can be categorized into three areas:

- Improving the understanding of the risks associated with the effects of climate change and extreme weather on roads:
  The literature review suggests that there is a lack of robust data on the impacts of climate change and extreme weather on the life cycle performance and costs of failure of roads. Some experimental research may be needed to better understand interactions of certain climatic loads with road materials and structures. Hazard maps and decision support tools are needed to indicate where roads might be vulnerable to climate change and extreme weather. Particular attention should be given to critical roads and highways, such as the Trans-Canada Highway, Ontario's 400 series of freeways, and the Dempster Highway.
- Measures to adapt roads to ensure improved climate resilience:
  Road design and construction methods are relatively standardized, but may need improvement in light of changing climatic loads. Possible areas of work include improved pavement and base materials, changes in structural design, better modelling techniques for road design and long-term performance, and improved monitoring and repair methods.
- Decision support tools for life cycle assessment and life cycle cost benefit analysis:
  As with other types of infrastructure, there is a need for relevant data to support the full implementation of these methodologies as part of the decision-making process.

Other research outside the scope of this initiative is needed to improve the operation of roads in extreme weather conditions.

7. Water and Wastewater Systems

7.1 Background

Water and wastewater systems are essential assets of Canadian communities. While localized failures in the pipe networks that deliver and collect water are inconveniences, breakdowns in the overall operation of these systems can lead to major health risks and potentially to loss of life. Ensuring successful operation of these systems is therefore a key priority in extreme weather conditions.

Water in southern Canada is supplied from sources such as rivers, lakes and reservoirs, purified at treatment plants, and then delivered to users through transmission and distribution pipe networks. Once used, it enters the sanitary sewer system and is, in principle, treated before being returned to receiving waters. Storm waters are collected by storm sewers, but additional infrastructure, such as retention ponds and interceptor tunnels, is generally required to manage peak flows and prevent the storm water from exceeding the capacity of sewage treatment plants and discharging without being treated.

Modern sewer systems typically separate storm and sanitary sewers. Storm waters generally require less treatment than sanitary waters. They also have large differences between peak and minimum flows, while the level of flow in sanitary sewers is more constant. Older sewer systems, which still exist in Canada in urban centres developed prior to the 1940s, often combine sanitary and storm sewers. During heavy rainstorms where high flows exceed the sewer system and/or sewage treatment plant capacity, some flow is diverted out of the sewer system to receiving waters at overflow structures. These overflows are referred to as combined sewer overflows (CSOs) and contain both surface runoff and municipal sewage.

Most Arctic water and wastewater systems operate in a very different fashion to those in southern Canada. Factors such as the extreme cold conditions that infrastructures must withstand, low precipitation (especially in the east), ground-related conditions (permafrost), the extremely short construction season, challenges of transporting construction materials, delays in procuring specialized equipment, and an undersupply of labour present significant challenges that require unique and often site-specific solutions. The high impact of climate change in the Arctic also means that extra effort will be needed to develop climate-resilient water and wastewater systems in that region. These challenges fall outside the CRBCPI initiative, but are included here for completeness.

7.2 Climate Effects on Water and Wastewater Systems

The impacts of climate change and extreme weather on water and wastewater systems are summarized in Table 4. Storm sewers and combined sewers and their related drainage systems are the most vulnerable types of water or wastewater systems in southern Canada. There are generally two types of operational failures observed in an urban storm sewerage system, both of which are related to exceeding the capacity of the sewer, but each has different types of consequences. In the first type, the amount of storm water being directed to the sewer system is so large that the retention ponds, sewer pipes and other parts of the system are unable to remove the water from where it accumulates in a timely manner (Olsson et al. 2013). The consequence is localized or widespread flooding, as was the case in the Toronto 2013 flood (Figure 9). In the second type of operational failure, flooding is prevented by diverting some of the flood waters directly to the receiving waters, either locally or at water treatment plants. In this case the consequence is pollution of the receiving waters. Flooding can cause considerable damage, injuries, illnesses and loss of life, but discharge of untreated sewage to receiving waters can also present significant risks to human health and high environmental impacts.

Table 4 – Climate Change Impacts on Water and Wastewater Systems

Climatic Hazard	Impact
Increased precipitation	• More frequent and intense occurrences of flooding due to lack of storm sewer capacity • Inability to access system components • Damage to system components from flooding or overuse • Need for increased system capacity • Increased inflow and infiltration into sanitary sewers, increasing load on sewer treatment plants • Changes in pipe-soil interactions that may cause pipe failures • Change in Arctic water quality and quantity
Shortened times between precipitation events	• Reduced capacity for water shed surfaces to absorb water
Drought	• Damage to wet ponds and wetlands used for storm water management • Changes in pipe-soil interactions that may cause pipe failures • Changes in water demand, potentially affecting water system capacity • Change in Arctic water quality and quantity
Coastal flooding	• Salt intrusion into sewer systems and coastal aquifers • Increased deterioration of buried infrastructure • Flooding of low-lying facilities such as water and sewage treatment plants
Change in range of maximum and minimum temperatures	• Changes in runoff patterns in winter and spring due to changes in freeze-thaw cycles and the rate of snow melt • Changes in biochemical properties of source, runoff and sanitary waters, potentially affecting treatment plant effectiveness • Change in water demand, potentially affecting water system capacity • Change in Arctic water quality and quantity • Damage to Arctic water and wastewater facilities

Water and wastewater systems do not have as high a risk from climate change, although there are still potentially significant impacts that could affect system operation. Arctic infrastructure assets, on the other hand, rely heavily on the state of permafrost, snow, and ice for stability and function. Higher temperatures due to climate change may compromise system stability, serviceability and accessibility. As a result, Arctic water and wastewater systems may require significant changes or complete replacement to remain functional as the climate changes (Johnson 2017).

Figure 9 – Effects of inadequate storm water drainage, Toronto 2013
(Frank Gunn, Canadian Press)

Storm water drainage systems are typically designed using IDF curves (Section 3.4), or design storms, both of which are expected to be affected by climate change (Peck et al. 2012). Several municipalities (Moncton, Ottawa and Markham amongst others) have made allowances for climate change adaptation by applying a safety factor in the design of new storm sewer systems. The typical approach has been to increase rainfall intensities from the available IDF curves by 20% to 25% in order to produce increased system capacities. It appears that detailed economic analyses to justify levels of investment required for risk aversion are not common practice.

There are limited efforts being made to consider climate change effects in sanitary sewer systems. The situation is similar for potable water systems, but many municipalities have implemented water demand management measures to reduce the amount of water they supply each year. While not conceived to specifically address climate change issues, these measures help to increase the resilience of the potable water supply system by reducing overall demand. In addition, small distribution water mains are typically oversized to accommodate fire flows, reducing the likelihood they would need to be increased to meet increasing demand. The hydraulic capacity of large transmission mains may need to be reinforced if demands increase. In practice to date, however, a certain measure of infrastructure resilience is achieved through redundancy, which invariably means “more of the same” rather than measures that are climate-change specific.

7.3 Knowledge Gaps and Research Needs

Many of the most important knowledge gaps related to storm water sewer systems are actually gaps related to extreme rainfall and flooding. There are, however, specific issues related to preventing or mitigating urban flooding that should be addressed. These include:

- investigating the impact of increasing the area of water impervious surfaces over time in urban environments, which increases vulnerability to storms;
- investigating the effectiveness of local measures such as downspout disconnections and improved sewer maintenance for reducing flooding;
- investigating the effectiveness of green infrastructure, such as pervious road pavements and green roofs, and increasing areas of parks and woodlands as mitigation tools; and
- developing a better understanding of the impact of changing freeze-thaw cycles on drainage systems.

In the case of sanitary sewer systems, there is a need for a better understanding of the effects of climate change on the inflow and infiltration of water from the surrounding soil into the sanitary sewer system. These impacts are generally treated as constant over time, but may change both throughout the year and due to uncertainty and non-stationarity of climatic loads. Operators of potable water systems need a better understanding of the impact of climate change and extreme weather on the biochemical properties of source water, water demand, and water treatment.

General issues for water and wastewater systems in southern Canada include the need for:

- better knowledge of the impact of climate change on the effectiveness of source water and wastewater treatment technologies;
- understanding of the likely effects of climate change on infiltration/exfiltration of water from sewer pipes; and
- improved understanding of the impact of changing temperatures and precipitation patterns on the structural integrity of buried water and wastewater pipes.

The situation for Arctic water and wastewater systems is more challenging. Not only will climate change have a severe impact on the Arctic environment, but there is limited research and knowledge available to support changes to current practices. Key needs for the Arctic water infrastructure include:

- investigating the ultimate impact of climate change on water sources and developing alternative water supplies (ground and surface water) in permafrost environments;
- alternative designs, standards and good engineering practices for raw water intake, storage and treatment;
- alternative designs, standards and good engineering practices for water distribution and sewage collection systems (utilidor pipe and trunk);
- alternative designs, standards and good engineering practices for sewage treatment;
- assessing the impact of effluent quality on receiving waters, community health and the Arctic environment;
- local studies of alternative water sources in Arctic communities; and
- innovative and robust designs/technologies as well as new materials for various components of water and wastewater systems.

Finally, there are currently no facilities available to test and validate new technologies in real Arctic conditions. These facilities need to be developed to provide climate-resilient solutions for the Arctic. As noted above, research into these needs is outside the scope of the CRBCPI initiative.

8. Transit Systems

8.1 Background

Transit systems form a key part of urban and suburban transportation systems across Canada. Many, if not all cities in Canada have bus transit systems. Some large cities also have rail-based transit systems, which can range from street car lines to light rail systems to subways and elevated heavy rail lines.

Bus and rail transit systems are each used in different ways and have different advantages. Bus transit systems typically use existing roads and bridges to deliver their services. The routes are flexible and require little specialized infrastructure, although some cities have dedicated, high-speed-bus-only road systems. Rail transit systems, on the other hand, are designed for heavier traffic loads than buses, operate on permanent tracks and have dedicated infrastructure as compared to other transportation modes. Street car routes may carry 50,000 or more passengers a day (Toronto Transit Commission 2016), while the Toronto and Montreal subway systems each typically carry almost 1 million passengers a day (Dickens 2016).

The major focus of this section of the report is on rail transit infrastructure. Bus transit infrastructure is, in general, expected to be included in the buildings, roads, and bridges portions of the CRBCPI initiative. Bus transit infrastructure issues, not covered elsewhere in this report, are specifically mentioned in this section. While commuter and passenger rail systems are outside the scope of the CRBCPI initiative, these systems will still experience similar climate change impacts and have major overlaps in terms of operators and facilities. The operators of commuter rail and VIA Rail are therefore part of the stakeholder group whose needs should be addressed by the rail transit activities of CRBCPI.

Canadian light rail and subway systems are designed to a variety of system-specific standards, which may continue to use historic practices from the time of construction. Commuter and passenger rail systems follow American Railway Engineering and Maintenance-of-Way Association (AREMA) standards. Climate issues/weather events, such as flooding, are addressed in some aspects of the standards, but not in others. Where climate is addressed in the standards, it is assumed to be stationary in nature. Railway bridges for all types of systems are also typically designed to AREMA standards, with different loads being used in the design process depending on whether the bridge is intended for use by light rail transit, subways or commuter/passenger rail. In either case, standard practice is to include different climate design loads and associated return periods in the design to account for the likely impact of extreme weather on the bridge.

In addition to published information, a key source of information in the gap analysis for transit systems was the NRC/CUTA (Canadian Urban Transit Association) Workshop on Climate Resilience of Transit, which was held on March 3, 2017, at NRC. Co-sponsored by CUTA, the workshop offered the opportunity for owners and operators of Canadian transit systems to comment directly on their capacity and needs with respect to climate change adaptation. A number of recommendations in this section of the report are based on the results of the workshop.

8.2 State-of-Practice for Climate Resilience of Transit

Attendees at the NRC/CUTA Workshop were all aware and concerned about the potential impact of climate change on their systems, but only a few had taken steps to assess and analyze their associated risks and mitigate them. The most advanced systems in terms of climate resilience are Metrolinx in the Greater Toronto and Hamilton Area, TTC in Toronto, and TransLink in Metro Vancouver. Others are just beginning to examine climate resilience or have not considered it at all.

Internationally, well-developed studies appear to have been done in the United Kingdom. The Rail Safety and Standards Board (Arup T1009 Phase 2 Consortium 2016, Marteaux 2016) and London Underground (Transport for London 2015) have both studied climate resilience requirements for the British rail system and are developing mitigation plans. Other European countries have examined specific problem areas, but do not appear to have overall climate resilience/mitigation plans (Marteaux 2016).

A complicating factor in providing guidance on climate change adaptation is that there is no single standard for rail transit infrastructure in use across Canada. The different systems were installed at very different times and have different legacy equipment and standards. Climate change resilience guidance will therefore need to be in the form of best practices, rather than codes or standards.

8.3 Identified Areas of Concern

The major climate hazards identified as a concern to Canadian transit system operators and owners during the NRC/CUTA Workshop included:

- flooding (Figure 10),
- freezing rain and icing,
- freeze-thaw cycles, and
- heat waves (Figure 11).

There were differing opinions on the significance of lightning strikes as a system risk. Snow and wind were mentioned in the context of damage to depots and preventing transit operations. The key climate hazards identified by the stakeholders correspond well with those from other sources (Table 5).

Figure 10 – Metrolinx train stranded during 2013 Toronto flood
(Winston Neutel, Canadian Press)

Figure 11 – Track buckling from heat wave, Australia 2013
(Australian Transportation Safety Board)

Table 5 – Climate Change Impacts on Rail Transit

Climatic Hazard	Impact
Flooding	• Water accumulation in subway tunnels • Washouts and other earthwork damage • Damage to train control signals and other electrical systems • Structural damage to track • Damage to train depots and other buildings
Changes in precipitation levels	• Landslides and slope failures from increased rainfall
Freezing rain	• Prevents switches from operating • Ice accumulating on bridges, power supply cables and power supply towers, potentially causing structural failures • Ice preventing power from being delivered to vehicles or safe operation of track
Change in extreme maximum temperature	• Buckling of tracks • Damage to signals and other electrical equipment • Ventilation issues in underground systems
Change in range of maximum and minimum temperatures	• Increased freeze-thaw cycles in many locations creating frost heaves on tracks

In addition, transit buildings such as stations and depots may have unique climate resilience requirements due to their usage. The basic building requirements will be covered by the changes to the NBC described in Section 4 of this report. The high number of people passing through transit hubs and the need to maintain transit operations after extreme weather events lead to requirements to address unique issues, such as ventilation in underground stations, the ability to evacuate stations under extreme weather conditions, excessive heating of glassed-in waiting areas and corridors, and the ability to protect the buildings from flooding.

8.4 Transit Stakeholder Needs

In addition to the climate hazards mentioned above, the following issues were identified as priorities by transit stakeholders:

1. System-wide climate resilience support:
   Both CUTA and individual transit operators repeatedly emphasized the need to provide climate resilience tools for their entire transit systems, including passengers and staff, operations, vehicles, and infrastructure.
2. Assistance in making the business case for climate resilience work:
   Workshop attendees indicated that climate resilience was not identified as important by all transit owners/operators. Better knowledge about the implications of climate change and extreme weather is needed to ensure that climate resilience is included in enterprise-wide strategic planning.
3. Climate hazards database:
   A national database of climate hazards was suggested by several workshop participants.
4. Opportunities for information exchange and improved collaboration between transit systems:
   Workshop participants were eager to continue to meet together and for other means of information exchange. The need for better collaboration between transit systems that share facilities was also expressed by several participants.
5. Flood proofing/mitigation:
   In addition to flooding being mentioned most frequently as a potential climate hazard, flood proofing/mitigation was specifically mentioned as a system need.
6. Additional funding to support climate resilience:
   The need for additional funding to deal with the climate resilience issues was mentioned at the workshop. Participants raised concerns about scarce resources being diverted from other operational and infrastructure needs.

8.5 Knowledge Gaps and Research Needs

A number of significant knowledge gaps related to climate resilience of transit systems have been identified, including:

1. Lack of information about Canadian transit systems:
   A single database is needed to indicate the Canadian transit systems capability to manage risks, to track climate hazards experienced by transit systems, and to collect infrastructure inventories, as well as other information. The missing information is important for technical guidelines, assessing needs, and developing risk management protocols.
2. Missing information on how climate affects rail transit infrastructure:
   The effects of each of the key climate hazards identified in the NRC/CUTA Workshop on transit infrastructure are not fully understood, while combined effects do not appear to have been investigated at all. Experimental and field research are needed in order to properly assess climate-induced risks in rail transit infrastructure.

3. Lack of climate change adaptation measures:
   Even where climate effects on transit infrastructure are known, appropriate mitigation measures may not be easily identified. Research is needed to develop better solutions and resolve other issues related to climate impacts on infrastructure.
4. Lack of understanding of the indirect impacts of transit infrastructure failure:
   The indirect costs of an infrastructure failure that shuts down a transit system are likely to be far higher than the direct costs of failure, due to loss of productivity, economic activity and potential for illness, injury or loss of life. Larger cities are more likely to be vulnerable to these costs than small ones. Indirect costs are not, however, well understood or well quantified, preventing the undertaking of life-cycle cost-benefit analysis (LCCBA) of different climate change adaptation strategies.

A key issue with regard to climate change and transit is the demand from stakeholders to approach climate resilience on a system-wide basis, rather than on an infrastructure basis alone. Some of the knowledge gaps described above would best be filled in that context. While a system-wide approach is currently out of scope, potential research areas that could be addressed within the CRBCPI initiative scope include:

1. Research into the impact and management of icing on bridges, tracks and transit power transmission systems;
2. Field research into specific issues related to climate impacts on track geometry;
3. Gathering of information on Canada's transit systems and the implementation of a national transit climate hazard database;
4. Development of improved non-contact methods of monitoring stresses in track;
5. Analysis of the likely impacts of increasing temperatures on equipment failures; and
6. Development of guidelines for identifying and mitigating flooding risks, both in tunnels and elsewhere.

Many of these topics will require data and support from transit system owners/operators. In the case of field research in particular, the work may need to be done in collaboration with the commuter rail systems or VIA Rail in order to enable the analysis of known problem areas.

9. Codes, Standards and Guides Development

9.1 Introduction

Codes, standards and guides are the instruments through which governments and industry bodies manage the performance and risks associated with B&CPI. Codes are typically mandatory regulations, which can be enforced by government officials. Standards are typically industry-driven mandatory requirements for the performance or testing of B&CPI components: they may be referenced in code documents or other standards. Guides are often best-practice guidelines and are not mandatory in nature. Codes and standards provide minimum required performances, while best-practice guidelines describe how to achieve optimal performance, which typically requires higher initial cost and yield lower life cycle cost.

Buildings in Canada are regulated through provincial/territorial building codes, which are based on the National Model Construction Codes developed by the Canadian Commission on Building and Fire Codes (CCBFC) and published by NRC. These include the National Building Code (NBC), National Fire Code (NFC), National Plumbing Code (NPC), and the National Energy Code for Buildings (NECB). Each model code is updated on a five-year cycle by experts from across the country. Once approved by the CCBFC, the updated codes are then published by NRC.

The Canadian Highway Bridge Design Code (CHBDC) is developed and maintained by the Canadian Standards Association (CSA) on behalf of the provincial, territorial and federal governments. It is mandatory in all provinces except Manitoba, which also uses the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications.

Networked infrastructure is not built according to specific national codes in the same ways as bridges and buildings. Canadian roads are generally designed according to the Transportation Association of Canada – "TAC Geometric Design for Canadian Roads" (TAC 2017), "TAC Pavement Asset Design and Management Guide" (TAC 2013) and standards or specifications set by individual infrastructure owners, such as AASHTO "Mechanistic-Empirical Pavement Design Guide" (AASHTO 2015). Regulation of water and wastewater systems is governed by overlapping provincial and federal jurisdictions, with varying degrees of completeness in different provinces. In many cases supplying and receiving waters are shared between provinces, creating potential conflicts that need to be resolved at the interprovincial or intergovernmental level. Authority for supplying water and wastewater services is typically delegated by the provinces to municipalities which may choose to follow the minimum (sometimes non-existent) provincial and federal regulatory requirements for different aspects of these services or follow other more stringent guidelines.

The situation with respect to standards for rail transit systems is also complex. Regulation is provincially based, but may be delegated to the system operator itself. Each system also has its own standards, although it is expected that the new Light Rail Transit (LRT) systems being built by Metrolinx will be built to common standards. Perhaps more importantly, the standards have widely differing bases, depending on when the system was built and where the original technology was developed. The AREMA standards are very useful for understanding rail issues that need to be addressed, but may not represent actual practice, with the exception of content on commuter and passenger rail systems.

9.2 Existing Codes, Standards and Guides Incorporating Climate Change Provisions

There are relatively few regulatory instruments that currently address climate change impacts. In Canada, these include APEGBC Professional Practice Guidelines “Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia” (APEGBC 2016), Ontario’s Guide for Ontario Municipalities, Alberta’s “Climate Change Adaptation Framework Manual”, and similar documents developed by other provinces. Internationally, there are some standards and strategies such as the Australian standard AS 5334, “Climate change adaptation for settlements and infrastructure – A risk based approach” (Standards Australia 2013), the “Climate Change Adaptation Strategy and Framework” (United Kingdom Highways Agency 2009) and the “Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance” (US Federal Highway Administration 2015).

9.3 Canadian Codes, Standards and Guides as Instruments to Manage Climate Risks

Both the NBC and the CHBDC already consider climatic data and associated climatic loads as part of the design process; however they are based on historical climatic data that assumes a stationary climate. The resulting risks are managed using reliability methods, but do not, as mentioned earlier in this report, properly account for climate change and extreme weather events. Both documents will be updated in the context of the processes used by the organizations responsible for managing those codes, although special committees are likely to be required in order to ensure a clear focus on climate resilience work. At the same time, a number of standards referred to in the codes are being updated by CSA to ensure that they also include management of changing climate risks. These standards are primarily materials-oriented and include the CSA standards on masonry, concrete, wood, glue-laminated wood, steel, aluminum, and glass. Work on updating the standards associated with electrical power supply is also underway to account for climate change and extreme weather.

Building materials themselves are evaluated for compliance with the NBC by the Canadian Construction Materials Centre (CCMC). Operated by NRC on behalf of the provinces and territories, CCMC develops technical guides describing how to test a construction product and issues reports that describe the performance of a successfully evaluated product and what limitations should be put on its use. The reports are publicly available and are used by municipal building officials to determine whether a particular product is acceptable for use in their community. As the NBC begins to address climate change and extreme weather, CCMC test requirements will change to ensure construction products meet the revised Code requirements. Construction products are re-evaluated every 3 years, providing opportunities to re-examine existing products for climate resilience.

The “TAC Pavement Asset Design and Management Guide” may provide a convenient method for updating climate impacts on road design. Some climatic loads are accounted for in this Guide, primarily those that affect the placing of the pavement and not those that affect the long-term deterioration of the entire road system or the results of extreme weather. Flood risks are, however, dealt with in design standards on the basis of IDF curves, which should be modified to be more appropriate for a changing climate.

Extra work with stakeholders will be needed to develop appropriate approaches for providing guidance on water, wastewater and rail transit systems. In some cases, specific standards may need to be developed, while in others, the best option may be to develop best-practice guidelines. Material standards applied to Canadian water and wastewater systems are often those created by the American Water Works Association (AWWA), ASTM International or American National Standards Institute (ANSI), and will be difficult to amend. Rail transit standards are, as has been noted, system-dependent. It may be possible to develop a standard practice for managing climate change risks for rail transit, but it would need to be written such that any organization can adopt it. Procedures for managing flooding are currently applied in the design of storm water and rail transit systems, and can potentially be updated through the revision of IDF curves. Other climate risks, such as freezing rain, are not currently well accounted for in the existing design standards.

A final potential instrument for managing climate-related risks is the Canadian National Master Construction Specification (NMS), which is also under the custodianship of NRC. The NMS serves as the basis for technical and contractual requirements for construction projects of several federal government departments, as well as for some private sector projects. This bilingual reference document contains approximately 780 master specifications covering not only building construction but also infrastructure and services. NMS specifications do not currently cover climate resilience, but could be updated to improve resilience in areas without existing standards or codes.

9.4 Limitations and Gaps

Some of the limitations of current Canadian codes, standards and guides for B&CPI are described in Sections 9.1 and 9.3. Amongst other issues, key changes to the NBC and CHBDC will be necessary to:

- address alterations or renovations to existing buildings or bridges;
- address the limitation of current uniform hazard based design approaches and develop uniform risk-based design methodologies;
- render the codes forward-looking, rather than being solely focussed on historic risks and failures; and
- ensure that the actual climate risks are being incorporated in the climatic loads in the codes.

There are a number of other technical issues that will need to be resolved to fully address climate resilience:

- Current national model codes only address the resistance to loads (static resilience) and not how quickly buildings and bridges can be repaired and have their functionality restored after a failure (dynamic resilience or rapid recovery of function). Dynamic resilience measures will need to be developed and potentially incorporated in the codes, particularly for critical B&CPI.
- A cost-benefit analysis is currently required to support code changes; this analysis focuses solely on direct benefits and costs. While this approach is generally applicable to commercial buildings and standard bridges, it is not likely to support changes to code specifications covering post-disaster and high-importance buildings and critical bridges. Provisions that consider indirect costs and benefits, particularly for publicly owned buildings and infrastructure, need to be incorporated in the codes.
- Current codes primarily address life safety and health and their provisions represent minimum acceptable performance. Protection of assets and provision of services are a much lower priority. Additional best-practice guidelines may be needed to address continued functionality and protection of B&CPI assets from climate change and extreme weather. These additional guidelines are especially important for critical B&CPI.

- NBC requirements for large buildings are different from those for housing (and other small buildings). Small buildings may not be engineered, which means builders and designers tend to prefer prescriptive requirements over performance ones. The assessment of and design for a risk-based approach is very difficult to achieve with a prescriptive approach: attempts will often lead to costly overdesign. Appropriate approaches for protecting small buildings from climate change and extreme weather will need to be developed.
- Current codes use uniform climate hazard design methodologies. This approach may lead to low and unacceptable levels of reliability in some regions under a specific climate hazard as the use of uniform hazard may yield non-uniform risks across the country. The implications of changing to uniform climate risk design methodologies therefore need to be explored.

9.5 Logistics

Canada's regulatory system for B&CPI is complex, making it necessary to convince many different stakeholders of the need to adopt climate resilience measures. Even in the very well-developed Code development system, there are major logistical challenges:

- With the exception of the NFC, the network of individuals and organizations that administer and enforce the national codes only address the construction of new buildings. They do not address the use of buildings, their maintenance, or the community and urban planning for current or future buildings. A new network is needed that can address the latter issues, which are crucial to increasing the climate resilience of the existing building stock.
- National Model Codes are published on a 5-year cycle. The last possibility to engage the technical committees on any technical change is spring 2018 for the 2020 edition of the NBC. Approval and priority-setting are then subject to input from the provinces, territories and regulators for something as substantial as introducing climate resilience. It may therefore be necessary to aim for the full implementation of climate resilience in the NBC in the 2025 edition, rather than the 2020 one.

10. Climate Risk Assessment for B&CPI

10.1 Background

The assessment and management of the risk of failure of B&CPI systems are essential for their design or retrofit. Risk is defined as the product of the *probability* of a negative event occurring and the *consequences* of that negative event. B&CPI systems and components can experience different failure modes during their service lives, including total or partial loss of serviceability, functionality, and load-bearing capacity. Consequences of failure can range widely, depending on the B&CPI system and failure mode, and can potentially include fatalities and injuries, illnesses, loss of the asset, loss of serviceability, and a wide range of socio-economic impacts. Reduction of risk can be achieved by reducing the probability of failure, or the consequences of failure, or both.

Structural systems of bridges and buildings are designed to ensure life safety and serviceability. Life safety is achieved by ensuring a low probability of collapse of B&CPI during their service lives. Other types of infrastructure are designed based on mechanistic and empirical standards and guides that are known to produce a low probability of either structural or functional failure. The goals of design and retrofit of B&CPI against climate change are to minimize the risks of failure while keeping the costs of construction and future operations and maintenance at acceptable levels during the service life of the structure. In general, a longer service life is specified for important and critical assets such as lifeline bridges or post-disaster buildings. In addition, the more difficult and costly it is to replace a component, the longer service life it is expected to have.

Different levels of acceptable risk can be defined in design codes, standards or guides for each type of new B&CPI and in asset management guidance for existing B&CPI systems. The acceptable levels of risk depend on the type of B&CPI component, the consequences of its failure, the level of redundancy in the system, the governing failure modes (ductile with warning or brittle without warning), and expected quality of construction and inspection. The key objective of the design and retrofit process of B&CPI under the effects of climate change and extreme weather is therefore to keep the probability of failure below an acceptable target value. In the case of the structural systems of buildings and bridges, the target lifetime reliability index is between 3.0 and 4.0, which corresponds to notional probabilities of failure of approximately 0.02% to 0.003% over the structure's service life. Lower failure probabilities have been used for critical buildings and bridges.

Buildings and bridges are discrete assets that are designed using national codes that inherently account for risks. In contrast, roads, water and wastewater systems, and rail transit systems do not have national design codes. They may instead be designed based on local, national or international standards, which may or may not take into account risk assessment processes. Explicit risk assessments are also needed during the asset management of existing buildings and bridges.

A variety of different risk assessment methods are in use for the design and rehabilitation of various B&CPI systems or are found in the literature, ranging from simple qualitative, semi-quantitative to comprehensive quantitative and probabilistic risk assessment approaches. The general approach is often different for each type of B&CPI system. In particular, the risk assessment of roads and water and wastewater systems must take into account their organization as distributed networks, where localized failures may take place without necessarily affecting the whole system. They often have key nodes, such as water treatment plants, where a failure in service is a more serious problem than elsewhere in the system, but they have considerable inherent resilience. Even in the case of storm water systems, failures in service are typically due to the inability of the system to accommodate extreme weather and climate change, rather than a structural failure in the system itself. Rail transit systems fall somewhere between the two, as they are distributed networks, but ones where there is greater vulnerability to system-wide failures. Problems in a switch machine, for example, may affect only a small area of track, while a power supply problem will affect a larger area or the entire system, depending on the cause.

10.2 Current Methods of Climate Risk Assessment for B&CPI

As noted above, climate impacts are considered in the NBC and CHBDC through the use of historical climatic data and associated climatic loads assuming a stationary climate and do not consider the effects of climate change. In addition, the NBC does not currently address extreme weather events, such as flooding. The current state-of-practice for assessing the impacts of climate change on B&CPI is the PIEVC protocol developed by Engineers Canada. PIEVC is a qualitative climate vulnerability assessment tool for public infrastructure. It has been used to assess a number of different types of B&CPI systems, covering all areas under discussion in this report.

Internationally, some countries have been working on climate-change-associated risk assessment, including Australia, the United Kingdom and the United States. In Australia, the standard AS 5334-2013, “Climate Change Adaptation for Settlements and Infrastructure – A Risk-based Approach” (Standards Australia) is consistent with the practice outlined in the ISO 31000 risk management standard (International Organization for Standards 2009). The British Government has developed the UK Climate Change Risk Assessment (CCRA) Evidence Report (Government of the United Kingdom 2012), which provides tools to:

- Analyze the risks posed by climate change over the next 80 years;
- Prioritize and compare those risks; and
- Provide evidence to support government, businesses, and other organizations, in making decisions on adaptation policies and actions.

In addition, British government legislation has required the development of climate risk documents for major areas of infrastructure such as the country’s highways and rail network. In the United States, the Federal Highway Administration has developed a guide for risk-based transportation asset management that focuses on building resilience to climate change in transportation infrastructure through effective asset management (Federal Highway Administration 2015). Efforts are underway in other countries, but have not resulted in publicly available documents.

10.3 Knowledge Gaps

As noted above, the existing procedures for climate risk assessment either do not account for climate change or are qualitative in nature. Better procedures are needed to more accurately assess climate-related risks in order to ensure that the assumed risks used in the relevant codes are accurate and acceptable, and to enable better decision-making when prioritizing B&CPI for rehabilitation or replacement. In addition, quantitative or robust semi-quantitative risk assessment procedures are needed for critical assets and to facilitate community-scale planning for the adaptation of B&CPI to climate change.

As shown in Table 6, the desired end state for risk assessment procedures depends on the type of B&CPI under consideration. Codes for design of buildings and bridges will continue to have implicit risk assessments built into them. Work is underway to develop better guidance in the NBC for requirements pertaining to existing buildings that are altered or renovated, which is likely to be reflected in the 2025 code edition. Once these changes are completed, the retrofitting of existing buildings will also make them more climate-resilient. The rehabilitation of bridges is already covered by the CHBDC for some types of climate-induced loads.

Tools will still need to be developed for the assessment of buildings and bridges to determine whether they should be prioritized for retrofit or rehabilitation work. The recommended approach in this case would be to determine whether the structures should be considered critical (major highway bridges, post-disaster buildings, potentially large occupancy buildings, etc.) or not. Critical structures would be expected to undergo a full quantitative risk assessment as part of a review of climate vulnerability. Other structures would instead use a less costly, but still robust semi-quantitative risk assessment approach. The same approach would also be used for other types of core public infrastructure.

Table 6 – Proposed Risk Assessment Approaches by Building and Infrastructure Type

Building or Infrastructure Type	Implicit in Codes / Standards		Explicit Semi-quantitative		Explicit Quantitative and Probabilistic for Critical Structures	
	New	Rebuilds	New	Existing	New	Existing
Buildings	•	•		•		•
Bridges	•	•		•		•
Roads			•	•	•	•
Storm water systems			•	•	•	•
Wastewater			•	•	•	•
Potable water systems			•	•	•	•
Arctic water/ wastewater systems			•	•	•	•
Rail transit systems			•	•	•	•

The implementation of more robust quantitative risk assessments that address climate risks requires reliable climatic data, understanding of how climate affects B&CPI, knowledge of consequences of failure of B&CPI, and effective risk management tools. Some of these areas are addressed in previous sections of the report, but there are specific issues related directly to risk assessment and management that also need to be addressed. These include:

- Conversion of climatic data into climatic load values:
  Once information is gathered on the effects of climate change and extreme weather, it needs to be converted into specific climatic loads for different types of B&CPI, giving quantitative values for the hazard represented by different climate events. This data will need to be either mapped across Canada or converted into specific climatic loads for different locations, as is currently done for the NBC and CHBDC. Producing climatic load values may require analysis of different climate event scenarios in order to properly assess the impact of individual climatic loads and their associated combinations with other loads used for the design and rehabilitation of B&CPI.

- Definitions of critical buildings and infrastructure:
  Standardized definitions of which buildings, bridges and infrastructure network components require full quantitative risk assessments are needed. These could be adopted from existing definitions or developed by the CRBCPI initiative, but need to take into account climate impacts on B&CPI, modes of failure, and the consequences of failure.
- Frequency estimation:
  Improved tools are needed for the estimation of the frequency of extreme weather events in order to determine which events should be incorporated into design climatic loads.
- Vulnerability assessment and consequence estimation:
  Where explicit risk assessments are needed, probabilistic methods of vulnerability assessment and consequence estimation should be developed that incorporate indirect economic, social and environmental consequences as well as direct costs.
- Risk assessment:
  Risk considers the probability of an event along with its consequences. Appropriate methods for calculating risks related to climate events and existing B&CPI need to be developed and validated, as do the methods for assessing critical components of networked infrastructure.
- Review and development of risk acceptance criteria:
  Actions to reduce risks are generally taken when the level of risk exceeds predefined risk acceptance criteria. Risk acceptance criteria values need to be developed and agreed upon for the assessment of existing B&CPI and for networked infrastructure.
- Climate risk assessment and management tools:
  The information gathered and developed during the course of the CRBCPI initiative needs to be integrated into specific tools that can be used by B&CPI owners and designers as part of their broader risk management strategies.

11. Life-Cycle Cost-Benefit Analysis/Life-Cycle Cost Analysis

11.1 Background

Life-cycle cost-benefit analysis (LCCBA) or Life-cycle cost analysis (LCCA) are the processes of comparing the total cost of a construction project or other project over its entire service life or a specified life cycle to the benefits that will accrue from it over the same time. Traditionally, life cycle cost analysis has included only direct economic costs, although it is also possible to include indirect socio-economic and environmental costs in the process. Similarly, environmental benefits, avoided costs, and social benefits can be incorporated as part of the process. These additional factors can then be used in a total LCCBA or LCCA that accounts for all costs and benefits of a particular project.

LCCBA or LCCA can be expensive processes due to the need to gather the necessary information and conduct the analysis. They are therefore particularly suited to the evaluation of building and infrastructure design alternatives that satisfy a required level of technical performance but may have different initial, operating and maintenance, service disruption and disposal costs. They are less likely to be used for smaller projects such as a single home, but could, for example, be implemented for the design of a housing development or infrastructure system.

The use of LCCBA or LCCA for buildings and infrastructure is reasonably well documented (Nishijima, Straub et al. 2007, Kendall, Keoleian et al. 2008, Padgett and Tapia 2013, ASTM International 2015), but there is much less information available on how to incorporate climate change adaptation into LCCBA or LCCA. This section of the report discusses current practices related to LCCBA or LCCA and climate resilience and identifies key issues that need to be resolved for it to be fully implemented in a climate resilience decision support framework.

11.2 State of the Art / State of Practice

While there is a large body of research and practice related to life cycle costing and a similarly large body of work on the broad cost of climate change (Economics of Climate Adaptation Working Group 2009, United Nations Framework Convention on Climate Change 2009, The World Bank Group 2010), there has been surprisingly little work that crosses both disciplines (Kirshen, Ruth et al. 2008, Larsen, Goldsmith et al. 2008, Marletto, Johansson et al. 2012, Federal Highway Administration 2016). Whether the issue is general life cycle costing or looking particularly at the impact of climate change, the overall methodology for LCCBA or LCCA is, however, similar. The basic methodology (Economics of Climate Adaptation Working Group 2009) is to:

i. determine discount rate;
ii. gather data on owner and user costs, benefits, and expected lifetime use for each design;
iii. calculate the present value of the life-cycle cost of each design;
iv. determine the present value of the benefits that accrue from each design over its life cycle; and
v. determine the ratio of cost-to-benefits for each design.

Although the Canadian federal government through Infrastructure Canada requires that provinces, territories and municipalities undertake LCCA or LCCBA of proposed projects, inclusion of climate adaptation in the analysis is not done consistently across the country. Some jurisdictions do not appear to be considering adaptation in their infrastructure plans, while others (e.g. Ontario and Quebec) mandate the use of life-cycle costing that includes climate adaptation in their planning process. The northern Canadian territories include climate change adaptation in their planning and development processes, as do the Atlantic Provinces. Manitoba is currently determining best practices for improving the resilience of infrastructure to climate change, while British Columbia is encouraging its municipalities to use the PIEVC protocol for assessing climate adaptation needs (Province of British Columbia 2016).

11.3 Limitations and Knowledge Gaps

Despite the extensive literature on LCCBA/LCCA, there are major limitations to their use for climate resilience decision-making, including:

- Determining appropriate costs and benefits:
  Buildings and public infrastructure typically provide benefits over periods of many decades. In some cases, the same basic infrastructure remains in use for a century or more. Therefore, accurately determining the life-cycle cost or life-cycle cost-to-benefit ratio at the time of a decision requires both the costs and benefits expected to accrue over the lifetime of the project or a given planning horizon to be assessed and expressed in terms of present value. Existing methodologies have, however, assumed a stationary climate. Work is therefore needed to determine appropriate approaches to determining present value that take into account climate change.
- Determining net present project value:
  Calculating the net present value of the various design options is another area where additional work is needed. The focus of the analysis is generally on direct economic impacts over the project's life cycle, but the real benefits may be indirect, environmental or social, which are often difficult to monetise. Incorporating the latter factors in LCCBA and other decision-making processes is an ongoing area of research in many areas of economics.
- Lack of data:
  Difficulties in obtaining the data needed to perform LCCBA or LCCA are frequently cited in the subject literature. Performing LCCBA or LCCA without sufficient data on deterioration rates, maintenance costs, failure costs, replacement costs, and indirect costs is likely to be inaccurate, but gathering the data is difficult and expensive. Many models use assumptions or estimates to reduce the difficulty of the calculation, but these assumptions are not necessarily well founded, also leading to inaccurate results.
- Simplistic model assumptions:
  Most models do not consider the deterioration of infrastructure over time even though it has been shown to strongly affect the results (Dong and Frangopol 2016). Instead, a given replacement life is often assigned and the infrastructure is assumed to be replaced after that time period. Interactions between deterioration and external factors such as climate are therefore ignored, leading again to inaccurate LCCBA or LCCA. In addition, most models focus on the LCCBA/LCCA of the building or infrastructure system alone. While this approach simplifies the analysis, it can dramatically underestimate the impact of structural or operational failure of the system being analyzed. Approaches are therefore needed to include system interdependencies in the LCCBA/LCCA.

11.4 Research Needs

Specific research needs identified during this analysis that are specific to LCCBA/LCCA include:

1. national database of infrastructure performance under extreme weather events;
2. appropriate methods to quantify the environmental, social, and economic impacts on B&CPI during their full life cycle;
3. appropriate methods to assess and predict the micro- and macro-economic impacts of climate change and extreme weather on B&CPI, both in terms of the effect on the owner, users/occupants, and on the neighbouring communities and regions;
4. development of standardized best practices for determining life cycle costs and benefits of B&CPI, including social and environmental impacts;
5. determining best practices for discounting and calculating net present value, producing standardized methods that can be used to accurately include the potential future impacts of climate change and extreme weather in current decision-making;
6. tools for incorporating the impacts of external factors and asset interdependencies on LCCBA/LCCA, such as the benefit an improved storm water drainage system would produce for the flood resilience of roads or rail transit; and
7. best practices for incorporating performance-based service lives in LCCBA/LCCA in order to improve its accuracy.

12. Life Cycle Assessment

12.1 Background

Life cycle assessment (LCA) quantifies potential environmental impacts of a product or service over its full life cycle from cradle to grave. These impacts include issues such as energy use, transportation, pollution from by-products of manufacturing and method of disposal, as well as direct manufacturing impacts. LCA is a particularly important tool for assessing and reducing greenhouse gas (GHG) emissions, as it allows the designer, owner, and/or manager of B&CPI to track the amount of GHG produced to build or retrofit B&CPI and determine where significant reductions can be made.

The importance of taking LCA into account in construction projects and their outcome is due to the size of the construction industry. The building sector alone is the country's third largest GHG emitter and accounted for ~12% of total emissions in Canada in 2014 (Environment and Climate Change Canada 2017). Building and operating public infrastructure adds to this total.

Using LCA to determine GHG emissions is, however, only one of the factors that must be taken into account when deciding on a climate adaptation strategy. The goal is to select cost-effective adaptation solutions that reduce risks from climate change and extreme weather while minimizing GHG emissions. Once an LCA has been completed, the GHG emissions can be treated as a cost in a LCCBA or LCCA, where the benefits from reduced pollution can be monetised and incorporated into the LCCBA/LCCA.

This section focuses on the current status of LCA as it applies to climate-resilient buildings and infrastructure. In addition to providing an overview of current practice, it identifies knowledge gaps that need to be addressed. It also makes recommendations for incorporating LCA in the CRBCPI decision support framework.

12.2 LCA Model

The most commonly used LCA framework can be found in International Organization for Standards ISO-14040(2006a) and ISO-14044(2006b), which have been widely adopted in various fields, including construction. Figure 12 shows the four distinct stages of conducting a LCA.

The goal and scope definition stage includes defining the reasons for carrying out the study, the intended application, and the intended audience. It also describes the system boundaries of the study and defines the functional unit of measurement for which the analysis will be carried out (i.e., per one kilometer of 2-lane urban road or per one cubic metre of processed potable water).

Life cycle inventory (LCI) analysis is a compilation of all of the inputs (resources) used and outputs (emissions) produced by the product or system being analyzed during its lifecycle, measured per functional unit. In a complex system, such as a building or infrastructure, the inventory needs to include all of the components used in the construction of the system. The LCI is at the heart of a LCA as it is important to ensure that the data represent reality, which in turn strongly influences the value of the LCA results. Many LCI databases have therefore been developed to simplify the process of determining the inputs and outputs related to a product, building or infrastructure system. The U.S. LCI Database (National Renewable Energy Laboratory 2012) and the Swiss ecoinvent Database (ecoinvent 2017) are two widely used databases. LCIs need, however, to account for local availability of materials, energy sources and transportation costs. As a result, Canada's lack of a national LCI database poses a challenge to the overall quality of Canadian LCAs.

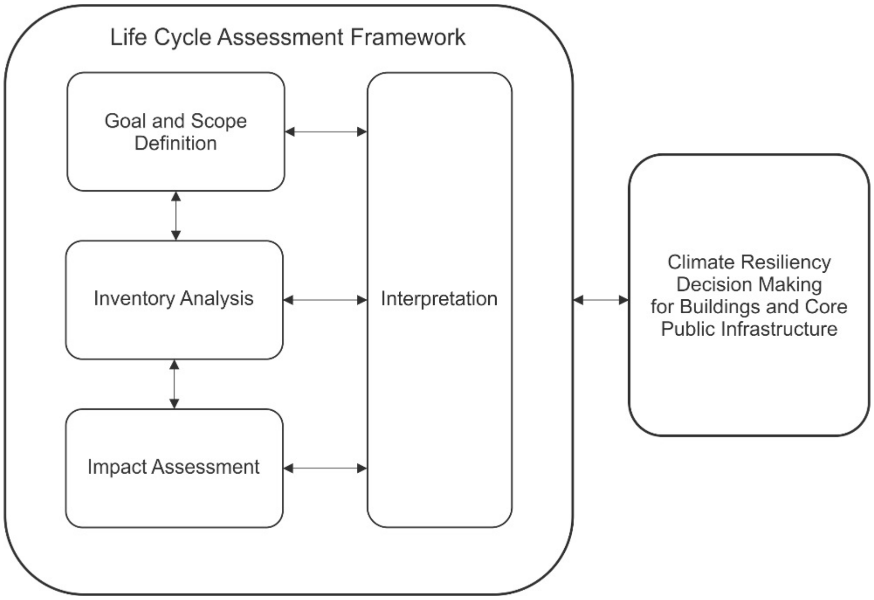


Figure 12 – Stages of LCA (from ISO 2006b)

The life cycle impact assessment stage then converts the results of the LCI into actual environmental impacts. The impacts commonly used in North America are typically grouped into,

- consumption of energy by source category;
- consumption of renewable and non-renewable materials, including water;
- emission of atmospheric units by potential type of damage; and
- emission of hazardous and non-hazardous solid waste.

Finally, during the interpretation phase, results from the previous phases are evaluated, and conclusions and recommendations are made.

While the ISO standards provide the basic LCA framework, there are a number of variations in the approach taken for the analysis. These include the life cycle stages being considered, what type of data is used, and whether the analysis is based on the current state of the life cycle inventory or is intended to help determine what would happen in the future under different scenarios. More work is needed to determine the most appropriate type of LCA to be considered in the CRBCPI decision support framework.

12.3 LCA State of Practice

The LCA of buildings has become more common since the American Institute of Architects (AIA) first acknowledged its use in mainstream architectural practice in the 1990s. Significant examples include the indirect use of some LCA metrics in the Leadership in Energy and Environmental Design (LEED) rating system for new buildings (Canada Green Building Council 2017); the International Green Construction Code (IgCC) for building systems (International Code Council 2015); the ASHRAE 189.1 standard (ASHRAE 2014); the California Green Building Standards Code (California Building Standards Commission 2016); and the ASTM E2921–16a (ASTM International 2016). While the IgCC and California Code are not applicable in Canada, LEED is a very common rating system used to promote building quality, and the ASHRAE and ASTM standards are used where appropriate by Canadian engineers and architects.

Pavement is another area where LCA has been used, having started in Finland (Häkkinen and Mäkelä 1996) and the United States (Horvath and Hendrickson 1998). LCA has been used frequently across North America in assessing pavement performance, sometimes in conjunction with legislation intended to reduce the impact of pavement on the environment. Belgium has recently also begun using LCA as a part of its pavement specifications. In Canada, the Ministries of Transportation of Ontario (Chan, Bennett et al. 2013) and Quebec (Collette 2012) consider LCA and LCCBA/LCCA as the basic tools for choosing the types of pavement for use in a project.

While pavement LCA does have a long history compared to LCA for other types of infrastructure, recent work suggests that there are significant problems with how it has been applied in the past. More development will therefore be needed to develop a full pavement LCA system. LCA for bridges and transit systems is much less common and more work will also need to be done to develop it if LCA is to be integrated into a climate resilience decision support system for those types of infrastructure. LCA for water and wastewater systems is somewhat more common, but has typically been done on system components, such as water pipes, rather than entire systems.

Finally, it should be noted that LCA has generally been applied to new construction and not to rehabilitation projects. Rehabilitation and retrofitting are generally constrained by existing materials and systems, which need to be accommodated. Integrating LCA with the rehabilitation process is another area where more research and development are needed.

12.4 Knowledge Gaps and Research Needs

Three major roadblocks have been identified that may prevent the effective use of LCA in the design and retrofit for climate-resilient B&CPI. Each roadblock will require research to overcome it. The research needs include:

1. Reliable and evidence-based LCA results:
   Current LCA methods have limited accuracy for Canada due to the lack of a Canada-specific LCI database. Development of a national LCI database is needed to accurately reflect the environmental impacts of products manufactured or used in Canadian buildings and infrastructure. At the same time, even a Canadian national database will have inherent uncertainty in the LCI data due to data quality, model design and project-specific factors. A methodology needs to be developed to account for these uncertainties and to allow existing data to be readily translated for the Canadian context.
2. Practical approaches to LCA:
   LCA is inherently expensive due to the large amount of data that must be analyzed to produce an accurate assessment. Practical engineering approaches are needed to reduce the cost and time associated with LCA while still maintaining acceptable accuracy. In addition, robust case studies are required to demonstrate the value of LCA, particularly in cases where choosing the most environmentally sound B&CPI alternative can result in higher project costs and/or different performance.

3. Life cycle performance /service life prediction of B&CPI:

   Knowing the life cycle performance or service life of a building or public infrastructure component is critical for an accurate LCA. Better techniques are needed to predict the service lives of new and existing buildings and public infrastructure, including well-founded stochastic methods to account for the inherent uncertainty in those service lives. These methods need to include the ability to account for the extension of service life provided by rehabilitation methods, so that the decision to replace or rehabilitate a building or infrastructure is made with the knowledge of life cycle environmental impacts.

A fourth area of research is essential for accurately determining the true environmental costs of not maintaining B&CPI:

4. Environmental impacts of B&CPI failure:

   Standard LCA accounts for the normal cradle-to-grave life cycle assessment of B&CPI. However, structural and operational failures of buildings and infrastructure carry their own negative environmental impacts. Overflows from combined sewers overwhelmed by storm water are the most obvious example, but the replacement of a road damaged by a flood or catenary towers damaged by an ice storm can also serve as examples where structural failures produce both direct and indirect environmental impacts. Probabilistic methods need to be developed to account for the additional benefits provided by climate-resilient B&CPI. Similarly, work is needed to understand the environmental impact of B&CPI failure due to extreme weather events, which may assist in assessing the need for improved prevention or mitigation measures.

13. Framework for Risk-Based Decision Support for Climate-Resilient Buildings and Core Public Infrastructure

13.1 Background

Understanding the effects of climate change on B&CPI and developing strategies for their adaptation to it typically require complex, multi-faceted approaches that combine different areas of expertise and activity. As a result, framework plans have generally been adopted for managing the impacts of climate change that provide an overall strategy, with specific actions chosen to meet the goals of the framework. Frameworks for dealing with climate change adaptation exist at different levels, ranging from the global to the very local and from a nation's activities to those of a particular sector or organization. In general, the greater the scope of a climate change framework, the more general the subject matter and the greater the potential impact. As mentioned previously, the *Pan-Canadian Framework on Clean Growth and Climate Change* (2016) includes four pillars:

- pricing carbon pollution;
- complementary climate actions;
- adaptation and climate resilience; and
- clean technology, innovation and jobs.

Similarly, large cities and corporations have frameworks with general goals for managing climate change issues.

Specific climate adaptation frameworks may be general or specific in nature. An example of a general framework was presented by Warren and Lemmen (Warren and Lemmen 2014), who proposed a climate adaptation process with seven steps:

1. awareness of climate change;
2. awareness of the need to adapt;
3. mobilizing resources;
4. building capacity to adapt;
5. implementing targeted adaptation actions;
6. measuring and evaluating progress; and
7. learning, sharing knowledge and adjusting

More specific existing frameworks for climate change impact adaptation are, in contrast, based on risk management principles. As noted in Section 10, risk is defined as the product of the *probability* of a negative event occurring and the *consequences* of that negative event. As discussed earlier, risk can be described in qualitative, semi-quantitative or quantitative manners, stated as subjective descriptions, ratings or in a probabilistic format, respectively.

The most commonly used framework for assessing climate risks in Canada is the PIEVC protocol. The Association of Professional Engineers and Geoscientists of British Columbia developed guidelines for Developing Climate Change-Resilient Designs for Highway Infrastructure in B.C, (APEGBC 2016). The Ontario Ministry of Municipal Affairs and Housing developed a risk-based guide for Ontario municipalities (Enger et al. 2006), while a *Climate Change Adaptation Framework* Manual has been developed for Alberta Sustainable

Resource Development (Alberta Sustainable Resource Development 2010). Australia has developed the standard *Climate Change Adaptation for Settlements and Infrastructure – A Risk Based Approach* (Standards Australia 2013). The United Kingdom has developed climate change adaptation frameworks for highways (UK Highways Agency 2009), railroads (Arup T1009 Phase 2 Consortium 2016) and other infrastructure as a result of an Act of Parliament requiring such documents from public agencies. The United States Federal Highway Administration (FHWA) has also developed a *Climate Change Adaptation Guide for Transportation Systems Management, Operations and Maintenance* (Federal Highway Administration 2015). These frameworks are generally consistent with the practice outlined in the ISO 31000 standard (International Organization for Standards 2009), with only minor alterations. Typically, they include (Wall and Meyer 2013):

1. Establishing the context:
    - Defining goals and objectives and collecting B&CPI inventory and projected climatic data
2. Risk identification:
    - Identifying relevant climate change hazards and identifying likely consequences of climate impacts
3. Risk analysis:
    - Assigning qualitative or semi-quantitative scores to the hazards and impacts
    - In some cases, more complex criteria are used to aid in the analysis
4. Risk evaluation:
    - Ranking of the risk analysis results to identify priorities for adaptation
5. Risk treatment:
    - Development, selection, and implementation of adaptation actions.

13.2 Knowledge Gaps and Limitations

A review of the existing climate change frameworks shows that they have serious limitations in their implementation, which could inhibit their effectiveness. Common issues include (Wall and Meyer 2013, Lounis and McAllister 2016):

- A lack or limited availability of data on climate design parameters that consider climate change.
- A lack or limited availability of data on condition and life-cycle performance of B&CPI systems.
- Uncertainties in the projection of climate change drivers.
- Uncertainties in existing climate models, due to the complexity and variability of the earth’s climate as well as the lack of models that operate at the local and regional scales.
- Assumed stationary climatic loads and climate resistance for B&CPI systems, when both are expected to change with time and may underestimate the probability of failure of B&CPI (Figure 13).
- Use of uniform hazard occurrence probabilities, rather than uniform risk probabilities in specifying design climatic data potentially leaving some regions of the country experiencing higher levels of risk than required.
- Qualitative or semi-quantitative approaches to risk assessment in most design codes, standards, and guides, while the actual structural design is based on reliability theory using a probabilistic approach.
- Interdependencies between different systems are not considered when determining risks in current codes.
- Existing frameworks do not take into consideration the secondary effects caused by the failure of an asset, even when those effects have a much greater impact than the direct effects.

These limitations must be addressed to implement a complete climate change adaptation framework.

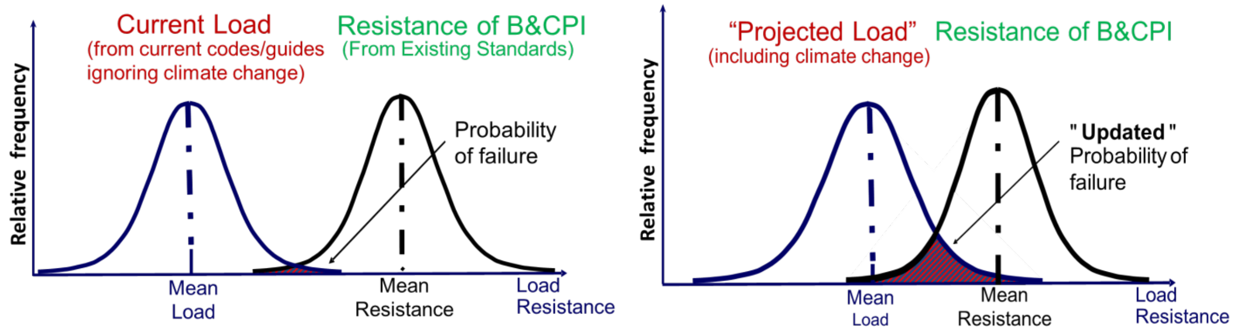


Figure 13 – Modelling of Impact of Climate Change on System Probability of Failure

13.3 Outline of Risk-Based Decision Support Framework for Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI)

The decision support framework being proposed for development in the course of the CRBCPI initiative will identify the foundations, structures, models and tools that will enable decision-makers to consistently integrate climate change adaptation into the design of new assets and in the management of their existing assets. It consists of the following building blocks (Figure 14):

- Objectives;
- Climate hazards;
- Risk-based climate change adaptation;
- Life-cycle assessment (LCA);
- LCCBA or LCCA of climate change adaptation measures; and
- Performance monitoring

The overall outcome of the framework will be climate-resilient B&CPI and communities. Each building block will be discussed in more detail below.

13.3.1 Objectives

The resilience of Canadian communities to climate change depends on the resilience of the assets that provide core services, such as shelter, transportation of people and goods, potable water, removal of waste, as well as health and emergency services. Resilience may, however, refer to different capabilities and concepts. In the case of the decision-making framework being proposed by the CRBCPI initiative, resilience refers to the satisfaction of some key objectives during extreme weather events and under the influence of climate change (Lounis and McAllister 2016). These objectives could include:

- Public safety (e.g., structural soundness of B&CPI);
- Public health (e.g., continued function of sewer systems);
- Functionality (e.g., ability of vehicles to cross a bridge at the intended speed);
- Serviceability (e.g., ability to prevent or restrict damage to a bridge);
- Durability (e.g., resistance to climate-induced aging);
- Low carbon footprint/green infrastructure (intended to optimize environmental impacts in decisions); and
- Cost-effectiveness.

The first stage in using the framework is to define which aspects of climate resilience will be covered by the work to be undertaken. The current initiative will cover all of the areas stated above, although there will be less emphasis on green infrastructure, for example, than on public safety and public health.

13.3.2 Climatic Hazards

The framework requires information on future climatic loads due to climate change and extreme weather. This information will be developed over the course of the initiative, starting with climatic data due to known climate hazards, which will then be converted into climatic loads for use in the risk analysis. Once developed, it will be integrated into the other parts of the framework.

13.3.3 Risk-Based Climate Change Adaptation

Protocols for adapting B&CPI to minimize the risks of failure due to climate change are the key components of the framework. Risks must be determined by combining stochastic measures of the performance of B&CPI systems in the context of a changing climate with the probability distributions for the occurrence of different types of climatic loads in the future and the consequences of system failure. Once these risks have been determined, measures can be taken to minimize risks and reduce the harm that may result from climate change. In addition to the risk assessment process, two other major tools are needed. The first is the modification of existing codes, standards and guidelines for B&CPI to reflect a non-stationary climate by considering the projected climatic design data and developing the corresponding climatic loads and load combinations. This will ensure that B&CPI will provide acceptable performance within their design life under the effects of new climatic loads and associated load combinations.

Different approaches will be taken depending on whether there are national codes that govern the type of B&CPI under examination. The NBC and CHBDC provide minimum standards of performance using a reliability-based design of structures. Following existing approaches, the probabilistic impact of climate change and extreme weather on climatic loads will first be evaluated and then simplified into a deterministic design approach through the introduction of load factors and resistance factors to achieve acceptable probabilities of failure within the design life. These factors will take into account the uncertainties in the loads and material resistances, bias factors, target reliability index, and normally accepted modelling approximations in structural analysis. An outline of the resulting design process, including places where life-cycle environmental and life-cycle cost-benefit analysis or lifecycle cost analysis come into play, is shown in Figure 15.

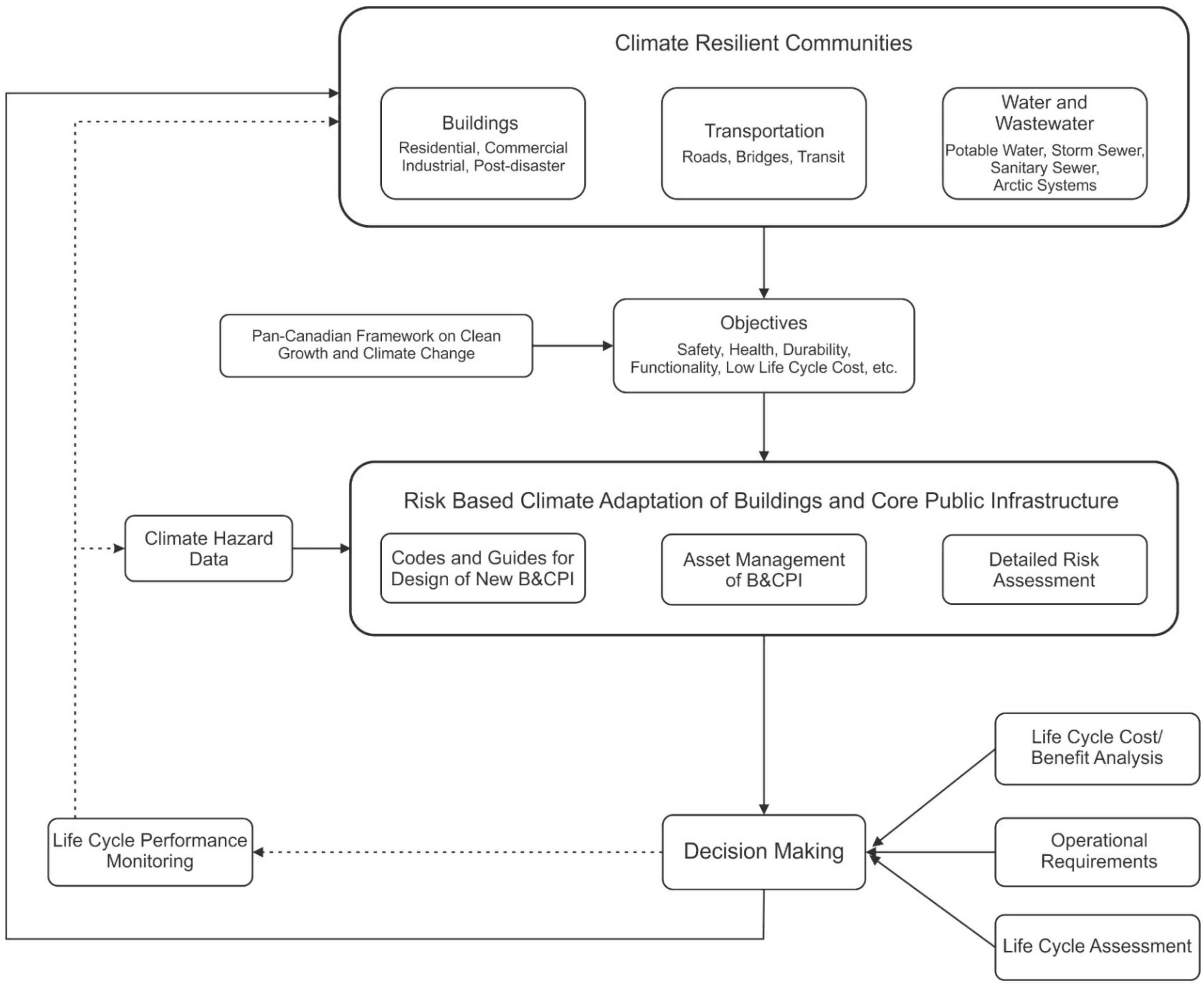


Figure 14 – Risk-Based Decision Support Framework for Climate-Resilient Buildings and Core Public Infrastructure

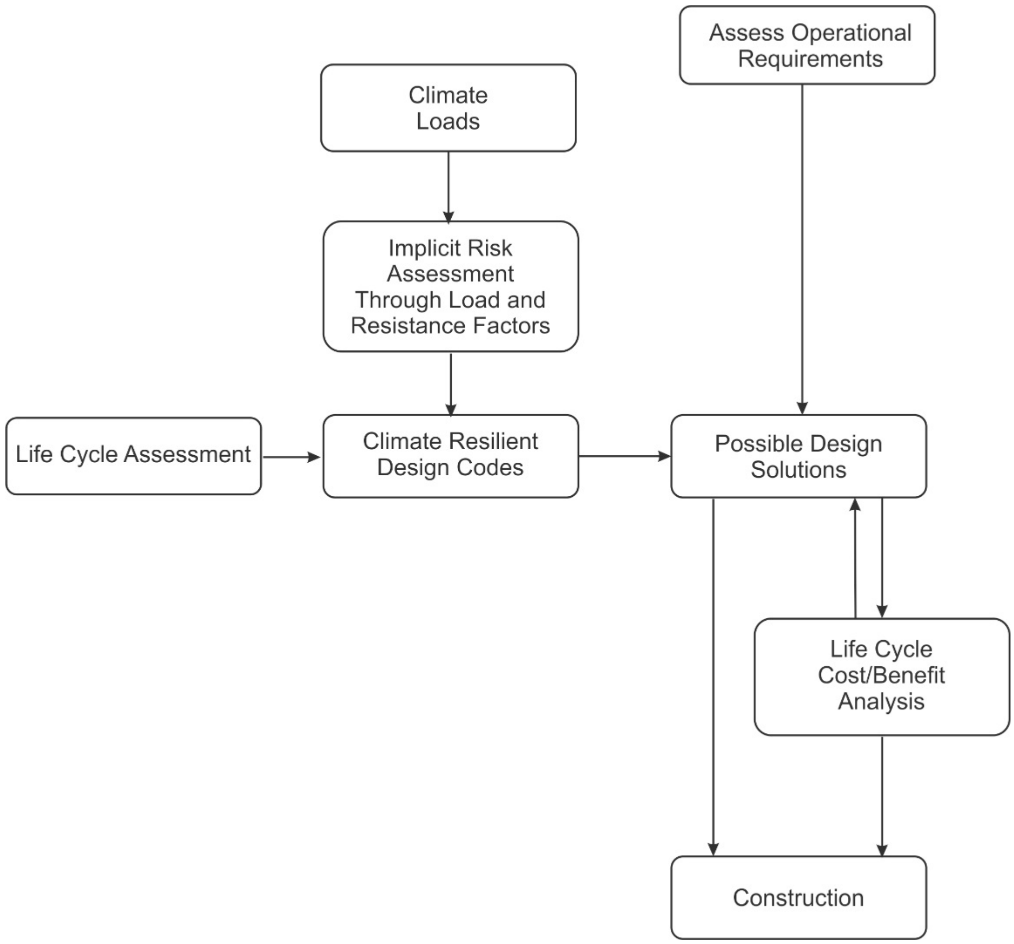


Figure 15 – Minimum Acceptable Design Based on National Codes for Climate-Resilient Buildings and Bridges

In many cases, however, simple design to minimum standards may not be adequate. Minimum acceptable design satisfies life safety and incurs the lowest initial costs, but once life cycle costs and benefits are considered, other more complex design processes can produce better solutions (Figure 16). This type of design will be found in best-practice guidelines as opposed to the minimum requirements of national codes. A key difference is that risks are assessed explicitly using either semi-quantitative or robust quantitative, probabilistic methods. The resulting risk-informed decision-making tools can include models for vulnerability assessment, fragility analysis, and assessment of the probability and risk of failure. This information can then be used to make more robust design decisions. Quantitative risk assessment is significantly more expensive than semi-quantitative methods and is therefore more likely to be used for critical B&CPI.

The final key component of the Risk-based Climate Change Adaptation module of the framework is guidance on the asset management of existing B&CPI systems to enhance climate resilience. Managing existing B&CPI presents three additional challenges beyond those incorporated in the design of new ones:

i. The condition or the resistance of an existing and aging system is, in general, lower than that of a new one and the uncertainty associated with it is typically higher.
ii. Decisions rely on a prediction of the remaining life of the assets, which is generally challenging to determine with reasonable accuracy due to associated uncertainties.
iii. The cost of upgrading existing systems to resist new climatic loads is much higher than including them in the design and construction of a new system.

The acceptable probability of failure for existing B&CPI may, however, be much higher than for new systems. Factors such as reduced expected lifetimes, consequences of failure, redundancy of the system, and quality of inspection and risk monitoring will affect how the acceptable probability of failure is selected. The selection of the best management options will therefore depend on LCCBA or LCCA, and possibly on a life-cycle assessment of all feasible alternatives. The asset management process under development in the CRBCPI initiative is shown in Figure 17. Guides or revisions to existing guides for asset management that integrate climate change will be developed for buildings, bridges, roads, transit assets, as well as water and wastewater assets as part of the current initiative. As with the best design practices, more sophisticated risk assessment methods can be employed during asset management to improve decision-making, including the prioritization of assets for climate change adaptation.

13.3.4 Life-Cycle Assessment and Life-Cycle Cost-Benefit Analysis

Selection of the most cost-effective climate adaptation strategies for new or existing B&CPI systems will depend on an evaluation of their life-cycle costs and benefits, as well as their environmental impacts. Such an evaluation requires the prediction of the service life of the aging system as the climate changes. When estimating costs, it is important to ensure that direct and indirect costs are considered, including the costs of service disruption due to asset failure and its macro-economic impacts on human activities that drive trade and productivity, and support economic development of the community, the region and/or the country. In many cases, adaptation measures that do not appear financially desirable when only direct costs are included may be the optimal choice once the indirect costs of service failures are incorporated into the analysis. Life-cycle assessment is similarly essential to estimate the environmental costs of different solutions in order to ensure that an apparently cost-effective measure will not have a significant negative impact on the environment.

13.3.5 Performance Monitoring

On-going asset management must include monitoring throughout the service life of the building or infrastructure. This process not only includes ensuring adequate long-term performance by identifying problems early on, but also producing more information on the impact of climate change on B&CPI for use in refining models and improving decisions for design as well as in subsequent asset management cycles.

13.4 Implementation of Decision Support Framework

The framework described here is initially being implemented through the CRBCPI initiative to cover changing climatic loads related to buildings, bridges, storm water and combined sewers, roads and rail transit. Specific areas of work are described in the remaining sections of the report. Other types of infrastructure have also been analyzed, but are either out of the scope of the current initiative or will not have as significant of an impact from the effects of climate change. The framework is, however, flexible enough to accommodate the inclusion of other infrastructure assets and services in the future.

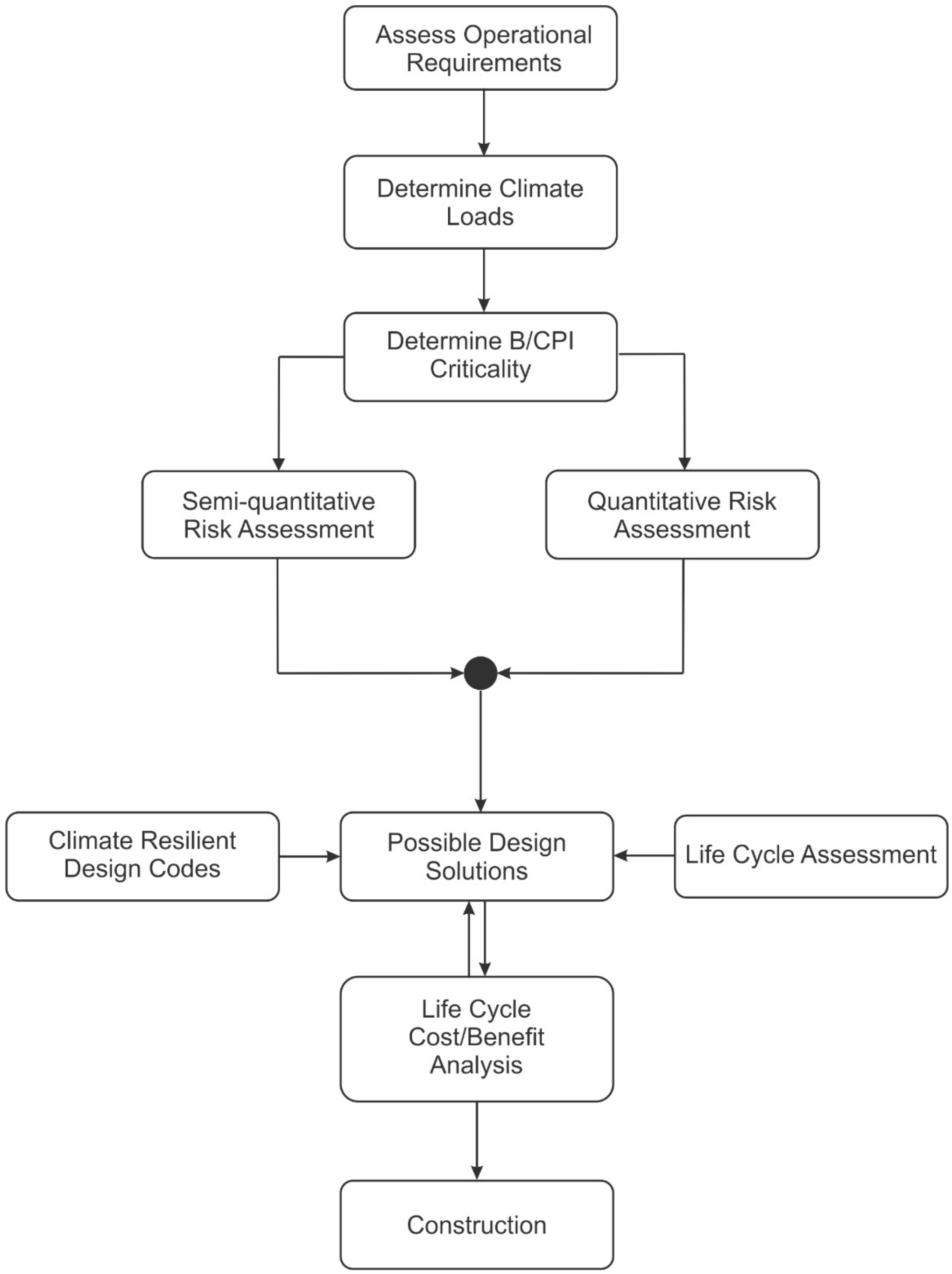


Figure 16 – Best Practice Design of Climate-Resilient Buildings and Core Public Infrastructure

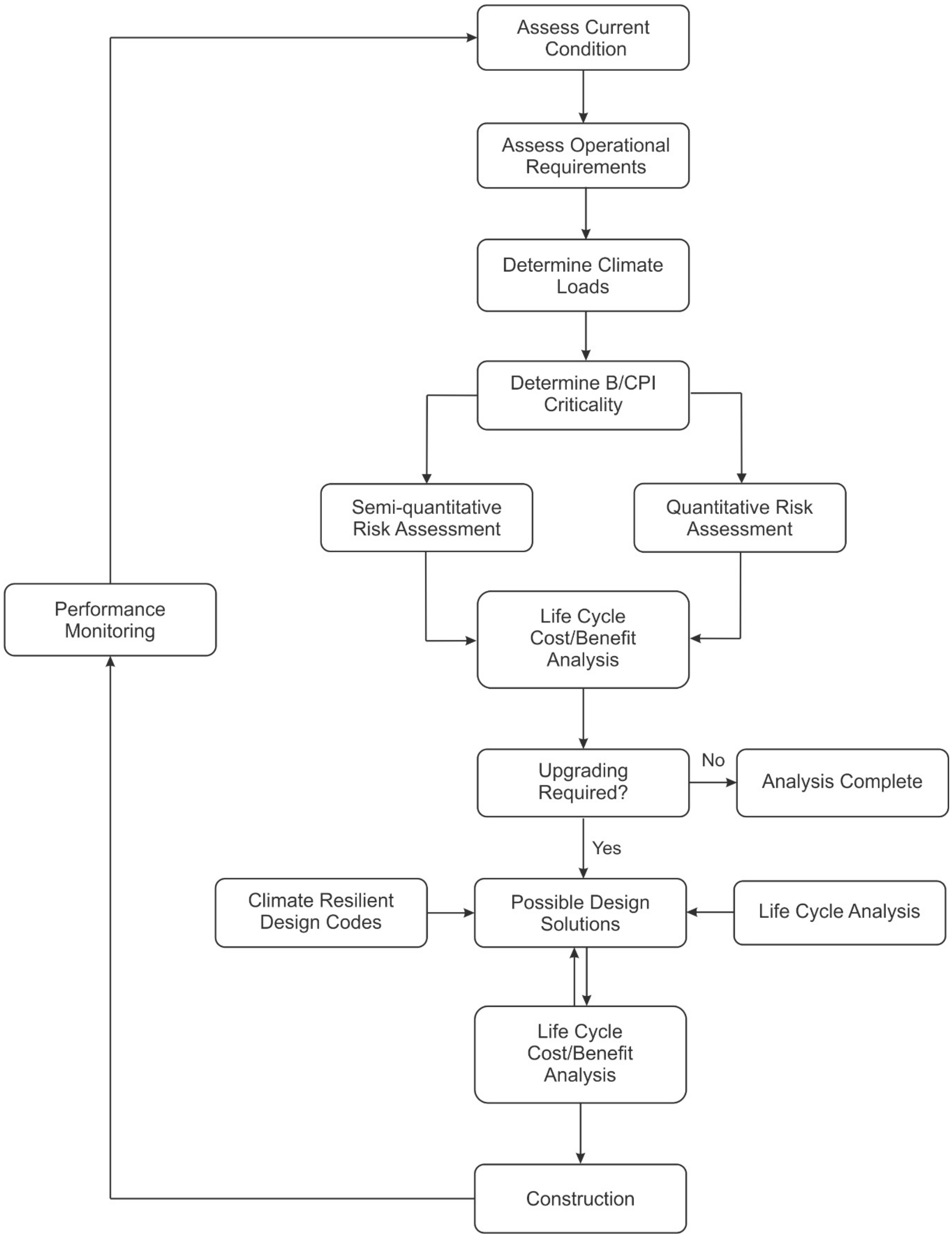


Figure 17 – Management of Existing Assets to Achieve Climate-Resilient Buildings and Core Public Infrastructure

14. Synthesis of Climate Change Impacts and Research Needs

14.1 Summary of Climate Effects on Different Infrastructure Systems

Examination of the analysis done on specific topic areas (Sections 4 to 8) shows that there are a number of common areas of concern with respect to the impacts of climate change on B&CPI. It is also clear that the potential impacts of climate change can vary widely, from hazards that can potentially cause a sudden structural failure due to an overstressed structure through those that prevent proper functioning of the structure and reduction of levels of service.

Table 7 summarizes the identified hazards and classifies them by potential impact.

The qualitative assessments in Table 7 are based on the manner in which the different climate hazards affect the particular building or infrastructure system. In the case of buildings, for example, snow and wind loads can potentially cause severe damage or structural collapse of the affected buildings. If they do not collapse, they may still be required to remain unoccupied for extended periods of time while the building condition is assessed and any needed repairs are made. Increased humidity levels, in contrast, would be expected to accelerate the rate of deterioration of some building components such as oriented strand board sheathing, which might in turn lead to early replacement.

Other impacts of climate change will potentially affect the ability of B&CPI to operate in their expected manner, which may in turn lead to disruption or loss of service. An example is potable water systems, where increased temperatures may not directly impact the infrastructure, but could cause algae blooms or other biological issues that the system may not be able to manage.

Summarizing potential impacts by type of climate hazard (Table 8) reveals that, while all hazard types can potentially have serious climate effects on some types of B&CPI, the extent of the impact varies greatly. Flooding hazards have the most consistent impact, with only some types of buried infrastructure not at risk of sudden failure. Precipitation and temperature changes potentially have serious impacts on a few types of B&CPI and also operational or increased deterioration impacts on others. Wind and wildfire only affect a few types of B&CPI, but may have very serious impacts on those that are affected.

Given the results of the analysis, it is clear that, while all areas of B&CPI need guidance on how to improve climate resilience, there are significantly greater risks associated with some issues than others. The structures associated with buildings, bridges and rail transit systems are strongly affected by most or all hazards; roads, storm water systems and Arctic water/wastewater systems are only affected by some hazards; and potable water and sanitary sewer systems by fewer still. These differences will be taken into consideration in prioritizing areas for work.

Table 7 – Climate Hazard Effects on Buildings and Infrastructure

Building or Infrastructure Type	Potential for Structural Damage	Potential for Functional Issues
Buildings	• Coastal flooding • Riverine flooding • Snow • Winds • Fire • Permafrost thaw • Drought (foundations) • Increased precipitation (foundations)	• Flash flooding • Increased precipitation • Higher humidity • Extreme heat
Bridges	• Riverine flooding • Coastal flooding • Winds • Ice accretion • Fire • Permafrost thaw • Increased precipitation • Ice load	• Extreme heat • Higher humidity
Roads	• Fluvial flooding • Pluvial flooding (tunnels) • Increased precipitation (slopes and earthworks) • Coastal flooding	• Permafrost thaw • Extreme heat • Freeze-thaw cycles • Drought • Fire
Storm water systems	• Riverine flooding • Flash flooding	• Increased high temperatures • Drought • Coastal flooding
Wastewater systems	• Earth load on buried pipes	• Change in temperature range • Drought • Coastal flooding • Increased rainfall
Potable water systems	• Earth load on buried pipes	• Change in temperature range • Drought • Coastal flooding
Arctic water/wastewater systems	• Permafrost thaw	• Drought • Increased high temperatures • Changes in temperature range

Building or Infrastructure Type	Potential for Structural Damage	Potential for Functional Issues
Rail transit	• Riverine flooding • Freeze-thaw cycles • Flash flooding • Heat waves • Freezing rain and icing • Increased precipitation (slopes and earthworks)	• Electrical storms

Table 8 – Initial Assessment of Impact of Common Climate Hazards

Building or Infrastructure Type	Flooding	Precipitation Changes	Temperature Changes	Wind	Wildfire
Buildings	X	X	X	X	X
Bridges	X	X	X	X	X
Roads	X	X	X		X
Storm water systems	X	X	X		
Wastewater systems	X	X	X		
Potable water systems	X		X		
Arctic water/wastewater systems		X	X		
Rail transit	X	X	X	X	

Definitions:

- Flooding includes flash, riverine and coastal flooding.
- Temperature changes include permafrost thaw, changes in temperature range, freeze-thaw behaviour, heat waves, and freezing rain.
- Wind includes extreme winds.
- Precipitation changes include increased rainfall, drought, electrical storms, relative humidity changes, ice accretion, and snow loads.

14.2 Research Needs

The analysis in Section 14.1 reflects the potential impacts of climate hazards and then suggests how work should be prioritized. This analysis does not, however, precisely correspond to the actual research needs, as differing degrees of effort will be required to satisfy the listed needs. The estimated research effort for each of the different areas of work is shown in Table 9. In addition, a column has been added to Table 9 to capture broader, community-planning-related issues that do not fall under one of the B&CPI, but do match the climate hazards and overall themes. Specific examples include:

- Increasing percentages of impermeable surfaces in cities causing rainfall to flow over the surface rather than entering the ground.
- Design of communities to be resilient to wildfire (e.g., by restricting locations of trees and setting up fire breaks between neighbourhoods).

Other areas where research is needed to support community planning may be identified during the course of the initiative. Overarching research themes and supporting research areas are also shown in Table 9.

Some of the areas of research shown in Table 9 are either already being covered by existing research activity or by separate planned activities. Guidance on Arctic water and wastewater needs is within the scope of NRC's Arctic Research Program. NRC is also currently in discussions with Indigenous and First Nations stakeholders on developing guidance for the climate resilience of buildings and infrastructure in remote locations, including northern and isolated communities. These out-of-scope areas are outlined in purple boxes in the table.

Areas of primary research focus are indicated by green boxes in Table 9. These areas have been chosen on the basis of need and reflect the vulnerability of certain types of B&CPI to climate change and extreme weather, as well as the types of hazards most likely to increase the risk of failure.

Areas of secondary research focus, where only specific climate issues will be addressed, are shown in orange boxes in the table. It is worth noting that although rail transit stakeholders expressed a strong preference for integrated climate resilience solutions that would cover all aspects of transit system infrastructure and operations, the scope and funding envelope for the CRBCPI initiative will only address a subset of rail transit infrastructure needs.

Table 9 – CRBCPI Research Requirements

	Buildings*	Bridges*	Roads**	Water/ Wastewater**	Arctic Water/ Wastewater***	Rail Transit**	Community Planning
Overall Themes							
Climate data and loads*	3	3	2	3	3	3	3
Decision support tools*	3	3	2	2	3	3	2
Indigenous communities***†	3	1	2	3	3	0†	2
Climate Hazards							
Flooding*	3	3	2	3	1	3	3
Precipitation changes	3	2	1	1	2	2	2
Temperature changes	2	3	2	2	3	3	3
Extreme wind	3	3	1	0	1	3	2
Wildfire*	2	1	1	1	0	0	3
Supporting Research							
Geotechnical	2	2	3	2	1	3	1
Material and system durability	2	2	2	1	2	2	1
Risk management	3	3	2	2	3	3	3
IDF curves	2	3	3	3	1	3	3

The numeric ratings represent the amount of research needed in an area to meet the requirements of the CRBCPI initiative, rather than research priorities. 1 = low levels of research needed, 3 = high levels of research needed.

* Areas of primary research focus.

** Areas of secondary research focus.

*** Out-of-scope areas.

† Some First Nations own and operate passenger and freight rail services. If these systems are included in rail transit, the research effort should be listed as a “3”.

15. Summary and Recommendations

Climatic factors such as temperature, precipitation and wind play a key role in the design, operation, aging and asset management of B&CPI. The design and management of B&CPI have, however, been based on historical data that do not take into account the impacts of climate change.

Lack of appropriate information and decision support for design and management of B&CPI systems under a changing climate puts Canadians and Canadian communities at risk. Major extreme weather events, such as flooding, ice storms, wildfires and high winds, can cause billions of dollars of damage and loss of life. The accelerated need for B&CPI rehabilitation and replacement due to increased aging and deterioration from climate change will also increase the existing infrastructure deficit in Canada and put additional financial pressures on B&CPI owners. The analysis reported here confirms that substantial efforts are needed to provide the codes, guidelines and decision support tools needed to protect Canadians from climate-change-related hazards and to help B&CPI owners optimize the management of their systems to minimize the risk of failure and reduce the life cycle costs.

The required efforts do not, however, need to be made equally in all areas. As shown in tables 7 to 9, there are major needs in the areas of climate adaptation of buildings, bridges, and storm water systems. Focused research and development will address key aspects of the climate resilience of roads, potable water and wastewater systems and rail transit. These other types of B&CPI are also vulnerable to climate hazards, but the vulnerabilities are more specific, and in some cases are primarily due to changing baseline conditions rather than extreme events. Similarly, flooding directly impacts most categories of B&CPI, while wildfire represents a hazard where immense damage can be caused in a short period of time.

It is therefore recommended that the CRBCPI initiative include:

- Major research and development efforts in the areas of climate resilience of buildings, bridges and storm water management.
- Targeted research and development on other types of infrastructure.
- Additional targeted research and development focus on specific extreme weather events, such as flooding and wildfires.

The work on flooding will need to be done in conjunction with existing federal government initiatives. Issues related to the Arctic and indigenous communities fall outside the scope of the CRBCPI initiative, as does work on decision-making frameworks and LCCBA.

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