CHAPTER 8:
WATER AND TRANSPORTATION INFRASTRUCTURE

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KEY FINDINGS

- Well-maintained infrastructure is more resilient to a changing climate. This is especially true with respect to gradual changes in temperature and precipitation patterns, which in many cases can be addressed through regular maintenance and normal upgrade cycles or adjustments to operation and maintenance policies and procedures. Key vulnerabilities relate to the impacts of extreme weather events, which can overwhelm the capacity of water infrastructure, leading to flooding and water contamination issues, and cause damage to transportation networks with resulting disruption of access and supply chains.

- The work of the PIEVC (Public Infrastructure Engineering Vulnerability Committee) has been an important driver of progress on understanding how to adapt Canada's infrastructure to climate change over the past five years. The broadly applicable, risk-based assessment protocol developed by the PIEVC allows engineers and planners to view and address climate change as one factor, among many, that affects system resiliency and plan accordingly.

- Consideration of climate change as an element of adaptive asset management encourages consideration of climate factors as part of ongoing system monitoring, and informs decisions regarding the most cost-effective approaches for infrastructure design, operation and maintenance.

- Codes, standards and related instruments (CSRI) are recognized as a potentially important driver of infrastructure adaptation, but there are few examples of CSRI in Canada that considered historic changes or projected future changes in climate when they were developed. Further assessment of current and future climate risks to infrastructure systems is required to inform appropriate adjustments to design codes and standards to address future climate.

1. INTRODUCTION

Infrastructure systems are a key area of concern for adaptation given their importance in supporting a wide range of social, economic and environmental goals, including public health, safety, economic development and environmental protection. Safe and reliable water supplies, protection from flooding, and dependable transportation networks are critical to all of the economic sectors discussed throughout the chapters of this report. In Canada, billions of dollars are spent annually on repairing, upgrading and expanding public infrastructure. For example, in 2011, $1.336 billion was spent to upgrade existing water treatment plants and commission new ones (Statistics Canada, 2013). Recent government budgets include significant and long-term investments in infrastructure funding, and needs for further infrastructure funding have been identified.

Infrastructure is designed to provide services over its lifetime, a period lasting anywhere from 10 to 100 years, and must be adapted over time to meet evolving circumstances, such as changes in technology, society and business (CCPE, 2008). Climate change presents a range of challenges for infrastructure design, construction, operation and maintenance, and is recognized as an additional factor that needs to be considered as Canada strives to maintain and improve existing infrastructure (Figure 1; Félio, 2012).

In the 2008 Canadian assessment, *From Impacts to Adaptation: Canada in a Changing Climate* (Lemmen et al., 2008), climate impacts on infrastructure were noted for all regions of Canada. Moreover, the synthesis of that report highlighted the vulnerability of communities and critical infrastructure to climate change. Since 2008, there has been a small but growing body of peer-reviewed literature focusing on adaptation and infrastructure in Canada, including analysis of the resilience of individual infrastructure systems (much of this work being conducted using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) engineering protocol (Box 1)). In addition, information on climate change impacts and adaptive responses has been incorporated into various planning documents (e.g. the Region of Durham Community Climate Change Local Action Plan), has led to operational and structural changes (e.g. design of culverts for Transport Quebec's road infrastructure is required to account for increasing frequency and intensity of rain events likely under future climate conditions; Ouranos, 2010); and has contributed to development of policy guidance at the regional scale (*see* Case Study 2). However, little of this progress has been documented well within the scientific literature.

This chapter presents an introduction to this emerging field of study by focusing on water infrastructure (water supply, storm and waste water) and certain aspects of transportation. This chapter focuses on climate change impacts and adaptation in relation to physical infrastructure itself rather than the larger water resource or transportation systems of which it is a part[1]. Key sensitivities, impacts and adaptive responses are discussed using case studies to provide additional details on adaptation activities.

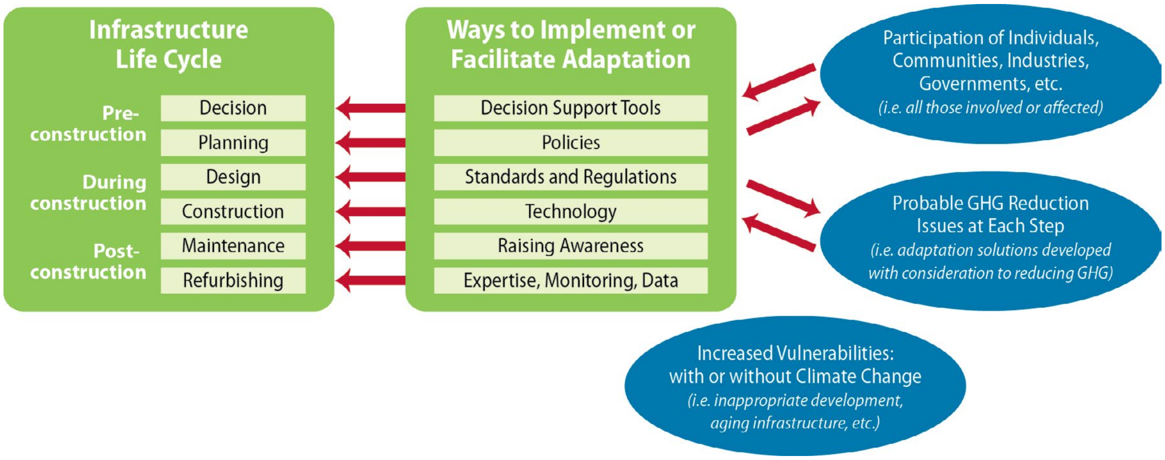

FIGURE 1: Adaptation in the infrastructure life cycle *(Source: Larrivée and Simonet, 2007)*.

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[1] Note too, that a more comprehensive assessment of climate change impacts and adaptation in Canada's transportation sector is currently in development.

BOX 1

CANADA'S PUBLIC INFRASTRUCTURE ENGINEERING VULNERABILITY COMMITTEE (PIEVC)

(http://www.pievc.ca/e/index_.cfm)

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) is a national committee established to conduct an engineering assessment of the vulnerability of Canada's public infrastructure to the impacts of climate change. It involves all levels of government, engineering professionals, and non-governmental organizations. The goals of the PIEVC include ensuring the integration of climate change into the planning, design, construction, operation, maintenance and rehabilitation of public infrastructure in Canada.

The PIEVC initially focused on four aspects of public infrastructure in Canada: buildings, roads and associated structures, storm water and wastewater systems, and water resources. Products include the PIEVC Engineering Protocol, which is a formalized process that can be applied to any type of infrastructure to assess engineering vulnerability and risk from current and future climate impacts (Figure 2). As of September 2013, nearly 30 case studies using the protocol had been completed across the country (Table 1), and more are in progress. Results of using the PIEVC Protocol are also incorporated into a national knowledge base maintained by Engineers Canada, and have been used in a review of infrastructure codes, standards and design.

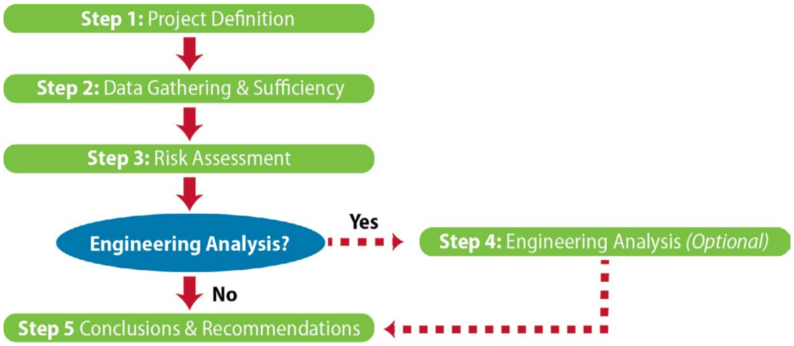

FIGURE 2: An overview of the PIEVC five step process to analyze the engineering vulnerability of an individual infrastructure to current and future climate *(Source: PIEVC, 2007)*.

Case Study Topic	Host/ Partner
Buildings	
Thermosyphon Foundations in Warm Permafrost	Government of Northwest Territories
Government of Canada Tunney's Pasture Campus	Public Works and Government Services Canada
Three Public Buildings in Southwestern Ontario	Infrastructure Ontario
Current Engineering Building and New Addition	University of Saskatoon
Toronto Community Housing Building: 285 Shuter Street	Toronto Community Housing Corporation
Energy	
Toronto Hydro Electrical Supply and Delivery Infrastructure	Toronto Hydro
Transportation	
Quesnell Bridge	City of Edmonton
City of Sudbury Road Infrastructure	City of Sudbury
Coquihalla Highway – Hope to Merritt Section	BC Ministry of Transportation and Infrastructure
Highway 3 West of Yellowknife	Government of Northwest Territories
Culverts	City of Toronto Transportation Department
B.C. Yellowhead Highway 16 Between Vanderhoof and Priestly Hill	BC Ministry of Transportation and Infrastructure
Toronto Pearson Airport Infrastructure	Greater Toronto Airport Authority

Box 1 continued on next page

Case Study Topic	Host/ Partner
Stormwater and Wastewater	
Placentia Breakwater and Seawall Infrastructure	Town of Placentia and Government of Newfoundland and Labrador
Vancouver Sewerage Area Infrastructure	Metro Vancouver
Fraser Sewerage Area Infrastructure	Metro Vancouver
Claireville and G. Ross Lord Flood Control Dams	Toronto and Region Conservation Authority
Sandy Point Sewage Treatment Plan Upgrade	Municipality of the District of Shelburne
Stormwater Infrastructure	City of Castlegar
Sanitary Sewage System	Town on Prescott
Evaluation of Surface Water Drainage Systems in Trois-Rivières Centre	Trois-Rivières
Evaluation of City of Laval Rainwater Harvesting System	Ville de Laval
Stormwater and Wastewater Infrastructure	City of Welland
Water Resources	
Water Resources Infrastructure	City of Portage la Prairie
Water Supply Infrastructure	City of Calgary

TABLE 1: Case studies completed using the PIEVC Engineering Protocol. Reports and summaries of each are available online at http://www.pievc.ca/e/doc_list.cfm?dsid=3.

2. WATER INFRASTRUCTURE

Some of the most significant and pervasive impacts of climate change in Canada will be related to water resources (Lemmen et al., 2008). Key threats to water infrastructure identified throughout the 2008 Assessment include extreme events (flooding, droughts and storms), permafrost degradation in northern regions, and lower water levels in many parts of the country, associated with higher temperatures. Reduced water quality and quantity will be experienced on a seasonal basis in every region of Canada, with remote and First Nations communities being especially vulnerable (e.g. Bourque and Simonet, 2008; Walker and Sydneysmith, 2008). The fundamental importance of water resources to a wide range of activities, including agriculture, energy production, transportation, community and recreation is also reflected throughout Lemmen et al. (2008), as well as in the preceding chapters of this report.

Recent case studies have more precisely identified the nature of potential vulnerabilities of water infrastructure to changing climate and have suggested approaches to enable adaptation (CCPE, 2008; Associated Engineering, 2011). Water infrastructure is essential for supplying water for community, industrial and agricultural use, storm water management, and control of inland and coastal flooding. Although the inaugural Canadian Infrastructure Report Card (Félio, 2012), did not analyze the implications of future climate change, it provided a self-reported snapshot of the state of current infrastructure systems. Stormwater management systems were the best of the infrastructure classes covered, being ranked "very good" in general. However, 12.5% of the systems fell below good conditions, largely due to concerns about pipes (Table 2). Drinking water systems, which include plants, reservoirs and pumping stations as well as transmission and distribution pipes, were rated good overall, with roughly 15% of drinking water systems rated fair to very poor based on the condition of specific components of the infrastructure system (Table 2). Wastewater infrastructure was also rated good overall, though the percentage ranked fair to very poor was considerably higher (e.g. ~30-40%) than for drinking water or stormwater systems (Félio, 2012). These results were based on voluntary input to the project from 123 municipalities across all provinces, representing 40.7% to 59.1% of the Canadian population (depending on infrastructure type).

Type of System	Rating Very Good	Good	Fair	Poor	Very Poor
Drinking water					
• Plants, pumping stations & reservoirs	12.6%	73.1%	9.8%	4.3%	0.3%
• Transmission & distribution pipes	4.2%	80.5%	14.4%	0.3%	0.7%
Stormwater					
• Pumping stations & stormwater facilities	56.8%	30.7%	6.9%	5.0%	0.6%
• Collection systems	40.5%	36.2%	17.7%	4.9%	0.8%
Wastewater					
• Plants, pumping stations & storage	16.0%	43.7%	34.5%	5.7%	0.1%
• Collection systems	33.7%	36.1%	22.4%	6.5%	1.2%

TABLE 2: Summary of Infrastructure Report Card ratings for drinking water, stormwater and wastewater *(from Félio, 2012).*

Adapting infrastructure involves several different approaches, often in combination, ranging from structural changes to non-structural or "soft" measures such as changes in policies and procedures that can be undertaken at different stages of the infrastructure life cycle as it is planned, rehabilitated or replaced (Figure 1). These measures can involve addressing issues directly by redesigning and upgrading infrastructure to deal with specific changes in climate (e.g. upsizing culverts to handle more intense precipitation events), and/or by enhancing the resilience of the system to climate change in general (e.g. regular maintenance of pipes, reducing stormwater runoff).

BOX 2

CODES, STANDARDS AND RELATED INSTRUMENTS (CSRI)

The PIEVC project reviewed its water resource infrastructure case studies to identify recommendations for changes to Codes, Standards and Related Instruments (CSRI). Water resource infrastructure is subject to many types of CSRI, including regulations, codes and standards, local government by-laws and national guidelines. The PIEVC found the climate information used in the development of CSRI was not always readily available or identified, meaning that updating CSRI is not just a matter of updating the climate information contained within them. Recommendations for action on CSRI reflect the loss of stationarity in climate and enabling adaptation related to: 1) improving climate data; 2) the need for CSRI to address incremental options over the life cycle of infrastructure; 3) the need to expand the scope of CSRI to cover physical, functional and operational performance; and 4) the need for flexibility in design to adapt to climate change (PIEVC, 2012).

2.1 WATER AVAILABILITY AND SUPPLY

Robust and reliable water infrastructure is critical for the delivery of clean water. A changing climate can affect water availability through seasonal shifts in river flows (e.g. from earlier snowmelt and spring runoff), more intense precipitation events, longer dry spells and more frequent droughts, and lower lake levels (CCPE, 2008; *see also* Chapter 2). Changing ice conditions are also important to consider; for example more periods of frazil ice (accumulation of ice crystals in water) can block intake pipes (Associated Engineering, 2011).

Key concerns for supply commonly relate to competing demands for water, particularly in the context of climate-related reductions in availability at the same time that population, agricultural and industry needs are growing. Several studies across Canada have shown reduced water availability due to climate change (e.g. Forbes et al., 2011; Tanzeeba and Gan, 2012; *see also* Chapter 2 – An Overview of Canada's Changing Climate), with some regions, including the southern interior of British Columbia, the southern Prairies and southern Ontario being particularly vulnerable. Water supply systems may be limited by the quantity allowed in water withdrawal licenses and priorities of water rights, particularly during periods of drought (Genivar, 2007; Associated Engineering, 2011). In such cases, the focus of adaptation may be on water conservation measures by household and industrial consumers. The City of Calgary has set a goal to increase water-use efficiency, and thus reduce demands on the water system, by 30 percent over 30 years so that they can accommodate future growth while maintaining the amount of water removed from the river at 2003 levels (City of Calgary, 2007). Using multiple sources of water and multiple intake points may also increase resilience by allowing water operators to shift production from one intake to another if one source becomes compromised (Associated Engineering, 2011), by ice blockage or low water levels, for example.

2.2 WATER QUALITY

Water quality can be affected by climate and extreme weather in a number of ways. Key climate change concerns include: flooding, with immediate and longer-term effects on water quality; increased water turbidity and contamination from more intense precipitation events and drought, which could lead to lower water levels providing less dilution; and salinization of groundwater in coastal regions due to sea level rise.

Floods can not only change the quality of water at the water treatment system intake, but also pose risks to physical infrastructure and materials, such as water treatment chemicals stored on site (Genivar, 2007). Intense precipitation events can introduce more contaminants from rural and urban sources into intake water. Heavy rainfall events and subsequent erosion can also increase turbidity of intake water. This may be less of a concern in regions such as the Prairies, which already experience periods of high turbidity, because the water treatment systems usually include settling tanks. However, even in these regions, changes to the operation of the system and additional treatment technologies may be needed over time (Associated Engineering, 2011; Genivar, 2007).

Higher temperatures can result in taste and odour events requiring additional treatment (Associated Engineering, 2011). Wildfires can also negatively affect the quality of source water, with impacts lasting many years. For example, in the four years after the 2003 Lost Creek fire in Alberta, turbidity, total organic carbon and nitrogen in runoff increased, particularly during peak flows after rainstorms and during spring melt (Emelko et al., 2011). Such changes can result in increased water treatment costs (e.g. for chemicals) in systems already equipped to handle the impacts, or may require upgrading of infrastructure where water treatment systems are not sufficient (Associated Engineering, 2011; Emelko et al., 2011). While reservoirs may currently be capable of handling demands during an individual high demand period (e.g. a drought or a heat wave), vulnerabilities may occur when there are repeated periods of high demand (such as back-to-back extreme weather events), as the systems may not be able to replace depleted storage in the reservoir (Associated Engineering, 2011).

In systems that use chlorine, increased amounts may be required because chlorine decays more quickly in warmer water temperatures. While analysis of water treatment plants in Quebec found that most (80%) were able to treat the maximum historical levels of *microsystin-LR*, and that an increase in this toxin due to climate change would not represent a serious threat, other toxins may present challenges if current treatment methods are not efficient (Carrière et al., 2010). In such cases, different chemical treatment methods or other technologies would be needed.

The Portage La Prairie (Genivar, 2007) and Placentia (NFLD), PIEVC case studies identified risks to elements of the water treatment systems due to a changing climate. These included vulnerabilities associated with pre-treatment, softening and clarification, disinfection, storage, chemical storage, and valves and pipes – related to several climatic factors, including flooding, high temperatures, intense rain, drought, ice storms and intense wind (CCPE, 2008). The case studies note that some investment in infrastructure will be required to avoid loss of reputation or more severe future impacts. A similar study in Calgary, AB focused on key climate risks to water supply infrastructure, and concluded that the system was generally resilient to changing climate conditions (*see* Case Study 1).

For groundwater-dependent communities, including all of Prince Edward Island and approximately 90% of the rural population in Ontario, Manitoba and Saskatchewan, previous assessments have noted that changes in precipitation patterns may result in a decrease in recharge, particularly in shallow aquifers (e.g. Lemmen et al., 2008). For coastal communities, saltwater intrusion is expected to increase as a result of sea level rise (e.g. Vasseur and Catto, 2008). Recent analysis of groundwater supplies in several locations in Nova Scotia and Prince Edward Island found that, to date, salinity was due to geologic and anthropogenic factors such as water demand and over-extraction, rather than climatic changes and sea level rise (Ferguson and Beebe, 2012; ACASA, n.d.). In a study of Richibucto, New Brunswick, rising sea levels did play a role in lateral seawater intrusion in shallow- to intermediate-depth aquifers, but the effects were less significant than climate change effects on groundwater recharge and increased pumping (MacQuarrie et al., 2012). Enhanced mapping and assessment of groundwater resources would better enable water system managers to accurately detect the impact of human activity, geologic factors and climate change on water availability and quality.

CASE STUDY 1

CITY OF CALGARY WATER SUPPLY INFRASTRUCTURE VULNERABILITY ASSESSMENT

(Source: Associated Engineering, 2011)

In 2011, the City of Calgary, together with Engineers Canada, conducted a vulnerability risk assessment of its water supply infrastructure. The purpose of the study was to identify those components of its potable water supply system that were vulnerable to future climate change and extreme climate events. The PIEVC protocol was used to estimate the levels of exposure that the infrastructure will face under future climate change, with focus placed on the years 2020 and 2050. The assessment considered the entire water supply infrastructure owned and operated by the City within its boundaries, as well as the Elbow and Bow River watersheds.

Using historic climate data and climate change projections from an ensemble of global climate models, the team determined which climatic conditions pose the greatest risks to the design, construction, operation and management of the water supply infrastructure, as well as impacts on the watersheds with respect to water quality and quantity. Those climate variables expected to impact both the capacity and integrity of the water supply infrastructure are outlined in Table 3.

Infrastructure components		Environmental Variables	
Water source			
• Watersheds • Glenmore Dam and Reservoir • Ghost and Bearspaw Dams and Reservoirs		• Increase in minimum temperature • Flooding • Drought	• River flow changes • Decreased snow pack • Compounding events – forest fires
Raw Water Intakes and Raw Water Pump Stations			
• Glenmore Intake and Raw Water Pump Station • Bearspaw Intakes and Raw Water Lift Stations		• Flooding • Increase in freeze/thaw	
Treatment Processes			
• Pre-treatment Facility • Filtration • Disinfection	• Storage • Chemical Feed Systems • Residuals Treatment	• Compounding events – forest fires • Increase in minimum temperature • Flooding • Drought	
Storage and Distribution			
• Linear Infrastructure • Valves/Pipelines		• Increase in freeze/thaw	
Supporting Systems			
• Supporting Physical Infrastructure • Administration/Operations • Electrical Power and Communications • Transportation		• Increase in extreme temperature • Flooding	

TABLE 3: City of Calgary water supply infrastructure components and negatively impacting climate variables.

Assessment results showed that, overall, the City of Calgary's water supply infrastructure is robust and adaptable to the gradual effects of future climate change, due in large part to the redundancies present within the City's water treatment plants, raw water sources and distribution systems that enhance the resiliency of the system. However, greater vulnerabilities were associated with extreme events such as flooding and drought, and compounding events were identified within these systems. The assessment team also highlighted areas requiring additional study.

Record flooding in Calgary in June 2013 provided a test to the resilience of the water supply infrastructure and its stormwater and wastewater systems. Published analysis of how the flooding impacted system performance was not available when this chapter was finalized. However, both water treatment plants in Calgary, Bearspaw and Glenmore, were able to continue to produce potable water throughout the event. This included a 1:500 peak flow event upstream of the Glenmore Plant on the Elbow River and a 1:100 year event on the Bow River. Some of the new treatment processes in place as a result of recent upgrades were severely tested with high turbidities from this event. Water restrictions were used to keep water demand at a lower level during the flood event (P. Fesko personal communication; City of Calgary, 2013).

2.3 STORMWATER AND WASTEWATER MANAGEMENT

Storm and wastewater management infrastructure represents the second largest category of capital investment in infrastructure in Canada (CCPE, 2008). These systems are often linked through their collection and transmission systems and both are affected by population growth, land use change and climate change.

Vulnerabilities in wastewater systems stem from a variety of sources. More frequent winter thaw events can increase the flow of cold surface runoff in combined sewer systems, reducing the water temperature. These shocks can affect the efficacy of biological nitrogen removal and secondary clarification processes (Plosz et al., 2009). More intense rainfall events and increased rain on frozen ground events are expected to increase the risk of stormwater infiltration into sanitary systems, creating more and larger combined sewer overflows (Urban Systems, 2010; Genivar, 2011). Increased heavy flows will also increase pumping requirements, thus increasing energy costs (Kerr Wood Leidal Associates Ltd, 2009) and in some cases, overwhelming pumping capacity. Pumping stations are also at risk of electrical failure during periods of extreme summer heat due to overheating of building electrical systems (Genivar, 2011). Direct physical impacts on systems from heavier rainfalls include the movement of debris that can block flows to culverts and catch basins, which in turn can result in localized flooding or erosion in surrounding areas, damaging the infrastructure.

There is increasing recognition that innovative solutions arising from interdisciplinary collaboration will be necessary to manage storm and waste water in a changing climate (Smith, 2009; Pyke et al., 2011). Urban flood events over the past two decades, combined with information about future climate change, have provided the impetus for better mapping of areas of risk, improved monitoring and maintenance of drainage systems, the separation of drainage systems from sanitary systems and the use of low-impact development (Marsalek and Schreier, 2009; Pyke et al., 2011).

Low-impact development is an approach to manage stormwater at its source, reduce contaminants in stormwater and slow runoff by changing the imperviousness of the surface and the materials through which water flows. One study found that an increase in rainfall intensities by 20% had the same impact on a combined sewer system as a 40% increase in impervious area (Kleindorfer et al., 2009). Another concluded that reducing impervious cover from 25 to 16 percent can significantly reduce stormwater runoff (Pyke et al., 2011).

Many cities have plans and programs such as downspout disconnection in place to separate storm and sanitary systems and reduce the flow of stormwater into the waste water system. The City of Toronto has increased monitoring and maintenance of its culvert system, while flood-prone communities, such as Cambridge and Milton, Ontario, are performing economic assessments of the implications of climate change for drainage infrastructure design (Scheckenberger et al., 2009). Actions may be more effective if done cooperatively at the basin scale (AMEC, 2012).

2.4 RESILIENCE AND CAPACITY TO ADAPT

While there is insufficient information available to undertake a full assessment of the resilience of water resource infrastructure to climate change across Canada, recent reports suggest that there is significant resilience in well-maintained systems. The PIEVC concluded that properly maintained infrastructure increases resilience to climate change by allowing the system to function as designed (CCPE, 2008). This finding was further confirmed in case studies completed since the 2008 report, and aligns with a broader assessment of the state of Canadian infrastructure, which highlights the importance of improving asset management (Félio, 2012). Several provinces in Canada have increased municipal requirements for asset management planning and have provided guidance to support this call (cf. Government of Ontario, 2012).

The PIEVC also identified the need to adjust engineering practices to adapt infrastructure design and operation to a changing climate. Engineers Canada prepared a draft set of principles of climate change adaptation for infrastructure engineers. This document is presently under consideration by the profession (David Lapp, personal communication). New guidance and tools to assist infrastructure owners are also emerging. For instance, a new guide for the assessment of hydrologic effects of climate change in Ontario was published (EBNFLO Environmental AquaResource Inc, 2010) and is complemented by on-line training.

Since conditions new to one region may already be experienced elsewhere, the exchange of information between owners/operators/engineers across regions can be helpful. In British Columbia, multi-year collaborative efforts on revising sea dyke guidelines in the province contributed to the development of a Sea Level Rise primer, which is applicable to other coastal regions as well (*see* Case Study 2).

Surveys provide an indication of current preparedness of system operators to address climate change. In 2012, the Canadian Water and Wastewater Association surveyed 100 Canadian water utilities representing a range of population sizes to determine their preparedness to manage projected impacts of climate change. They found that larger utilities (serving populations of 150 000 or more) were most advanced in terms of identifying risks of climate change.

CASE STUDY 2

BRITISH COLUMBIA'S SEA DYKE GUIDELINES

Over the past six years, actions within British Columbia have facilitated the incorporation of new scientific information about changes in sea level into policy and planning processes. Analysis of regional vertical land motion (due to tectonics, glacial rebound, sediment loading and other factors) and global projections of sea level rise produced new estimates of future sea level changes (Bornhold, 2008; Thomson et al., 2008), with significant implications for the current system of sea dykes, which protect important infrastructure and property in the province. Subsequent analyses were undertaken by the BC Ministry of Forests, Lands, & Natural Resource Operations, the Association of Professional Engineers and Geoscientists of British Columbia, and others with the objective of helping policymakers and planners incorporate sea level rise into flood risk assessment, coastal floodplain mapping, sea dyke design and land use planning. Guidelines for sea dykes were established for the years 2050, 2100 and 2200, with provisions for regional sea level rises of 0.5 m, 1 m and 2 m, respectively.

Outputs from that analysis included:

- A recommended 'Sea Level Rise Planning Curve' indicating that coastal development should plan for SLR of 0.5 m by 2050, 1.0 m by 2100 and 2.0 m by 2200.
- Technical reports to guide calculation of sea dyke crest elevation and flood construction levels, considering sea level rise, wind set-up, storm surge and wave run-up (Figure 3).
- Guidance for sea level rise planning, including designation of 'sea level rise planning areas' by local governments.
- A report comparing the costs of a variety of adaptation options from dyke construction to flood proofing and managed retreat. The study estimated that the cost for upgrading infrastructure works required along 250 km of dyked shorelines and low-lying areas in Metro Vancouver to accommodate a 1 m rise in sea level, including necessary seismic upgrades, would be about $9.5 billion.
- Professional practice guidelines for engineers and geoscientists to incorporate climate change in flood risk assessments.
- Seismic design guidelines for dykes focusing on factors to be considered in the seismic design of high-consequence dykes located in Southwestern BC.

This regional analysis has spurred municipal action. For example, the City of Vancouver offered workshops to engineers, developers and municipal staff on adapting coastal infrastructure. In turn, these workshops led the city to review their flood-proofing policies and agree on interim measures. One of these measures is to encourage applicants with projects in identified flood-hazard areas to meet an interim Flood Construction Level (FCL) equal to the current applicable FCL plus 1 m (City of Vancouver, 2012).

Building on these outputs, a working group that included local, provincial and federal government representatives, industry, academia and practitioners worked to develop a national Sea Level Rise Primer (www.env.gov.bc.ca/cas/adaptation/pdf/SLR-Primer.pdf) with examples from British Columbia, Québec and the Atlantic provinces. The Primer helps communities to identify, evaluate and compare adaptation options, and showcases planning and regulatory tools, land use change or restriction tools, and structural and non-structural tools.

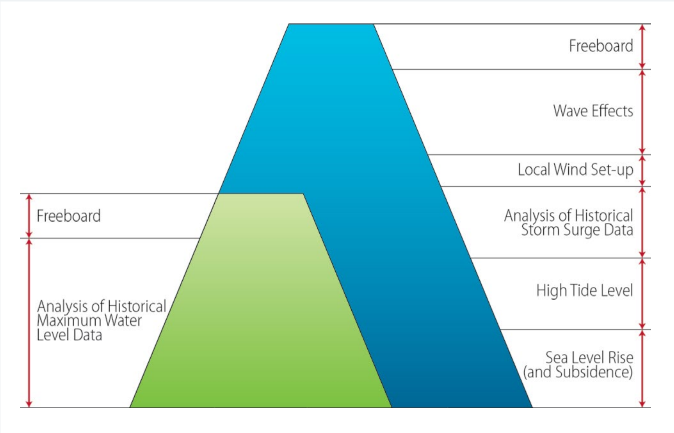

FIGURE 3: Conceptual differences between old and new sea dyke design approach *(Source: BC Ministry of Forest, Lands and Natural Resource Operations, 2012).*

Many respondents cited a lack of information about climate change impacts and risks to water systems as a gap that needed to be addressed. Also in 2012, a survey of 244 senior water utility executives from ten countries examined their preparedness to meet water supply challenges to 2030. While there were regional variations in concerns, most expected increased water stress by 2030 and identified demand management as a key action to address it (Economist Intelligence Unit, 2012). These surveys suggest that while there is growing awareness of climate change as a risk for water management infrastructure, the focus for action continues to be on issues such as replacement of aging infrastructure as well as dealing with increasing population and changing regulatory requirements. The role of changing codes, standards and related instruments (*see* Box 2) has received less attention.

There is also growing recognition of the importance that interdependencies among infrastructure systems, as well as management systems, play in adaptation planning (Zimmerman and Faris, 2010, PIEVC case studies). For example, water systems are often dependent on surface water sources that are also used for electrical generation or flood control. Operation of the system must therefore consider multiple and possibly conflicting needs. The availability of electrical power, including backup power, has emerged as a common and significant risk to systems that process and manage water. Several case studies identify the need to protect power supply systems to ensure the continued functioning of water treatment, management and control systems as part of an adaptation strategy (Genivar, 2007; Associated Engineering, 2011). Extreme weather and associated hazards can also prevent workers who operate water infrastructure from accessing facilities. Calgary has addressed this risk by implementing cross-training programs to ensure that trained staff/system operators are available at all times (Associated Engineering, 2011).

3. TRANSPORTATION INFRASTRUCTURE

Transport is inherently sensitive to climate, with numerous examples of transportation disruptions and delays related to weather events and seasonal conditions (Table 4). Such events were identified as key climate change-related concerns in many of the sectoral chapters of this report. Indeed, similar to water infrastructure, climate impacts on transportation systems have implications for most sectors in Canada, including natural resources, agriculture, fisheries, tourism, insurance and health, all of which depend upon a safe and reliable transportation network. In turn, Canada's transportation system, which includes four main components – air, marine, rail and roads – is sensitive to changes in other sectors with respect to demand and operations. Transportation services account for 4.2% of the Canadian GDP (Transport Canada, 2011), with the Canadian transportation system having an asset value in excess of $100 billion.

Summary	Date	Reference
Winter roads in Manitoba turn into quagmires	3-Jan-12	CTV News (2012)
Flights cancelled due to low visibility and fog	17-Jan-12	Ptashnick and Hayes (2012)
Rainfall-induced underground slide creates sinkhole 200 m wide x 5 m deep on Hwy 83 in Manitoba	3-Jul-12	CBC News (2012c)
Ice build-up in E. Arctic damages ship and causes delay in unloading sealifts	29-Jul-12	CBC News (2012d).
Early winter storm in Alberta delays transit, cancels flights, and makes sidewalks and roads treacherous	23-Oct-12	Zickefoose.(2013)
Wawa in a state of emergency due to runoff from rain.Total damage > $10 million dollars	27-Oct-12	Metro News (2012)
Hurricane Sandy causes flight cancellations in Atlantic Canada	29-Oct-12	The Telegram (2012)
The Trans-Canada Hwy in Newfoundland closed due to damage from a landslide	19-Nov-12	CBC News (2012e)
Sailings from Vancouver Island cancelled due to winds, wave height and sea conditions	19-Dec-12	Lavoie (2013)
Record snowfall affects transport in southern Quebec	27-Dec-12	Radio Canada (2012)
VIA Rail uses the "snow fighter" to clear the train tracks during snowstorms	24-Jan-13	Pinsonneault (2013)
Roads closed in Northwestern Ontario as drifting and blowing snow impacted highways still affected by freezing rain	30-Jan-13	CBC News (2013a).
Road and marine travel delayed by winter weather	18-Feb-13	National Post (2013a)
Unusual warm days in Fort Chipewyan AB threaten to cut the northern community off from the rest of Alberta	25-Feb-13	CBC News (2013b)
Roads and highways were closed near Fort McLeod and many flights were cancelled due to limited visibility and icy roads	4-Mar-13	National Post (2013b)
Road floods after heavy rains	3-Jun-13	Radio Canada (2013)
Barge supply to western Arctic interrupted by ice	3-Sep-13	CBC News (2013c)

TABLE 4: Examples of weather-transportation news stories from 2012-2013.

The climate sensitivity of transportation systems is reflected in design and construction standards, asset management expenditures, and mobility and safety outcomes. Impacts are associated with extreme weather events, such as heat waves and heavy rainfall, as well as more gradual changes such as permafrost thaw, higher temperatures, sea-level rise and declining water levels in freshwater systems. Previous analyses of climate change, including those in the various chapters of Lemmen et al. (2008), indicate that disruptions from extreme events, such as floods, fire and storms are the main climate concern for most regions with respect to transportation, and that some of the most vulnerable transport systems in Canada are integral to remote and resource-based community life, particularly in northern and coastal areas, and/or related to the transport of natural resource products (*see also* Chapter 3 – Natural Resources). More recent research also indicates that climate change has important implications for the operation and maintenance of transport systems in the most densely populated regions of Canada (*see* Section 3.1).

This section discusses key climate change vulnerabilities for transportation infrastructure in general, as well as some specific climate change issues for northern transportation systems, coastal regions and shipping in the Great Lakes (all with respect to the infrastructure, rather than the system as a whole). As such, it is not intended to present a comprehensive assessment of impacts and adaptation issues for the transportation sector. A more inclusive and in-depth perspective on these issues will be presented in the upcoming (2015-2016) Transportation Assessment, being co-led by Transport Canada and Natural Resources Canada.

3.1 KEY ISSUES FOR TRANSPORTATION INFRASTRUCTURE

Over the past six years, there has been a significant increase in the international engineering community's attention to climate change impacts. Much of the focus has been on future projections of heat waves, heavy rains, and other extremes including winds, given their implications for design standards and guidelines (Auld, 2008; Vajda et al., 2012), and on system-wide vulnerabilities to changing conditions (e.g. Capano, 2013; Dzikowski, 2013).

Projections of temperature extremes indicate that more frequent, longer and more intense heat spells are expected across much of North America (*see* Chapter 2). This can result in increased heat-related stresses, such as pavement rutting, rail buckling, and cargo overheating. Mills et al. (2007; 2009) confirm that projections of summer temperatures in parts of southern Canada (e.g. Windsor, Ontario) are expected to result in occasions/locations where there is pavement softening, rutting, bleeding and/or the need to specify a different asphalt cement oil grade. Municipalities and the engineering community are increasingly aware of these issues, especially in trucking corridors (Meyer et al., 2010), and agencies are beginning to reconsider road design/materials (e.g. culverts, asphalt binders) in light of the warming trend (Jacobs et al., 2013).

Heavy rainfalls can lead to flooding and washouts, cause slope failures and even trigger major landslides. Increases in heavy rainfall are expected across most of Canada, and in some cases could require revision of existing design and maintenance practices. For example, the Province of British Columbia has observed that "increased rainfall intensity could require updated policies and procedures regarding design and maintenance of highway infrastructure" (Nyland et al., 2011). Environment Canada (2013) provides intensity-duration-frequency curves for 563 locations across Canada—many of which have been recently updated; however, Peck et al. (2012) argue that such updates may not be sufficient to represent future rainfall patterns. While recent work has led to improved understanding of past rainfall extremes (e.g. Cheng et al., 2009), large uncertainties remain in representing extreme precipitation in future simulations (Maraun et al., 2010). There is also evidence that other weather conditions that are disruptive of transport networks and operations may become more frequent under climate change. For example, there is evidence that freezing rain events are likely to increase in south-central Canada (Cheng et al., 2007; 2011). Sequenced events (e.g. rain on freezing rain, or rain on snow), also pose risks to transportation. Researchers note that methods are needed to incorporate increasing trends in extreme weather events into infrastructure design standards (Cheng et al., 2012).

Most freight transporters and much of freight infrastructure (e.g. rail lines, airports and seaports) are managed by not-for-profit, non-share capital corporations or by private interests, and so risks and opportunities related to climate change are less frequently described in either the peer-reviewed or publicly accessible grey literature. Some insights can be gained through examination of Carbon Disclosure Project (CDP) questionnaires (both Canadian Pacific (CP) and Canadian National (CN) Railways have participated) and reports from meetings, such as a summit of key players involved in freight transportation in the U.S., including CN Railway (Camp et al., 2013). From the summit, many of the identified risks were associated with weather extremes that can close networks and delay shipments. CN specifically identified precipitation events as a major climate-related concern affecting the railroad industry because of associated risks of flooding, erosion and landslides, as well as wildfires because of service disruptions and damage to wooden bridges (Camp et al., 2013). Such events have impacted railway systems in the past, a recent example being the train derailment caused by a bridge failure associated with the spring 2013 floods in Calgary (Graveland and Krugel, 2013). High-temperatures are also a recognized risk for rail track integrity (e.g. Transportation Safety Board of Canada, 2013a,b), and heat waves have specifically been identified as a concern because of the potential for increased frequency of rail buckling/sun kinking and slow orders (CSIRO, n.d.; National Research Council, 2008; CBC News, 2012b).

3.2 ISSUES SPECIFIC TO NORTHERN REGIONS

There is widespread recognition that northern surface transport systems serving the Yukon, Northwest Territories and Nunavut, as well as the northern reaches of many provinces, are vulnerable to changing climate in a number of ways. Much of these regions are underlain by permafrost, have marine access during only a relatively short summer season, and often rely on a combination of ice roads, barge transport, air services, and limited rail access for commercial activities and community supply. In addition, the sparse nature of transportation infrastructure in the North means that service interruptions can have serious consequences. The Northern Transportation Systems Assessment (Prolog, 2011) provides an overview of the roles, usage and importance of certain elements of transportation systems in Canada's north, and identifies a range of strategies, such as alternate routes, to ensure access under changing climate conditions.

Considerable progress has been made in understanding cold regions processes and in exploring how transportation infrastructure designs might be adapted to withstand climate extremes and be more resilient in the face of changing thermal and moisture regimes (e.g. Doré and Zubeck, 2008; McGregor et al., 2010). There have also been several recent examples of northern vulnerability assessments and hazard mapping studies of relevance to transportation infrastructure (NRTEE, 2009; Champalle et al., 2013), and a number of site-specific assessments of permafrost conditions and degradation have been completed for existing transport infrastructure, ranging from northern Quebec airports (Fortier et al., 2011; L'Hérault et al., 2011) to roads in the Yukon (Lepage et al., 2010) and Northwest Territories (*see* Case Study 3).

CASE STUDY 3

NORTHWEST TERRITORIES TRANSPORTATION INFRASTRUCTURE

The Northwest Territories' (NWT) transportation system of 2200 km of all-weather roads and 1450 km of winter roads produces substantial benefits at local, regional and national levels. Roads improve connectivity between communities and provide residents with cheaper, easier and safer access to regional services such as health care, education and recreational activities.

The Government of Northwest Territories, Department of Transportation (GNWT-DOT), has acknowledged that its transportation infrastructure is vulnerable to the effects of climate change (GNWT-DOT, 2012). A PIEVC case study (*see* Box 1) of a 100 km section of Highway 3 located between Behchoko (Rae-Edzo) and Yellowknife was undertaken because it traverses highly variable terrain within an area of warm, discontinuous permafrost. Many sections of the highway exhibited various forms of embankment instabilities, ranging from differential settlements, shoulder rotations, and cracking of the pavement surface (Figure 4; Stevens et al., 2012). The case study examined more than 1100 highway climate event/infrastructure component combinations in order to identify potential vulnerabilities and to quantify the risk of future climate change impacts (GNWT-DOT, 2011).

The vulnerability assessment identified the sections of highway built on ice-rich permafrost as most vulnerable and recommended that additional baseline information be obtained for these sections (GNWT-DOT, 2011). Remote sensing techniques were subsequently used to analyze a 48 km section of the highway to detect changes to the highway corridor and identify sections that may require future remediation and adaption measures (Wolfe, 2012). The highway embankment was determined to be seasonally stable over 67% of the 48 kilometres analyzed, with moderate downward displacement (-3 to -6 cm per year) over 2% of its length. Many embankment side slopes were found to be steeper than the recommended grade as a result of surface displacement caused by the thawing of ice-rich permafrost terrain (Stevens et al., 2012).

Identifying areas most impacted by changing climate assists in the planning of annual road maintenance, evaluating the effectiveness of highway remediation projects and identifying areas where further data is required. For example, based on the vulnerability assessment, test sites were established along Highway 3, and are being monitored on an ongoing basis by the Government of the Northwest Territories. Such analysis will ultimately reduce the costs of constructing and maintaining the highways and help ensure safe driving conditions.

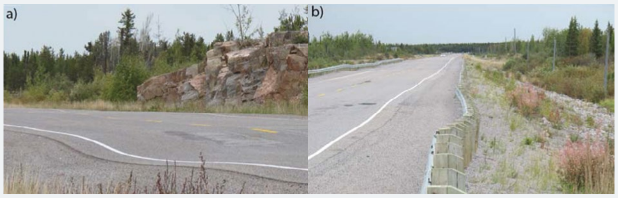

FIGURE 4: Photographs of Highway 3 indicating **a)** differential subsidence of the road surface and **b)** guardrail displacement caused by rotational down slope movement of the highway embankment side slope *(Source: Stevens et al., 2012)*.

Winter roads (also called ice roads) make up seasonal transportation networks located primarily on the surfaces of lakes, rivers and bays. Found in the Northwest Territories, Manitoba, Ontario, and to a lesser extent in the Yukon, Nunavut, Alberta, Saskatchewan, Quebec, and Newfoundland and Labrador, these roads provide access to communities and mining operations. While there remains little published scientific research related to ice road seasons and use (cf. Lemmen et al., 2008), media reports and grey literature provide evidence of shortened seasons (e.g. CBC News, 2012a); identify approaches for extending the season, such as ice-road spraying, plowing off roads to enhance the freezing effect, and restricting hauling to certain hours; and demonstrate the potential of ice-road alternatives, such as cargo airships (e.g. Winnipeg Free Press, 2013a; 2013b). The Tibbitt to Contwoyto Ice Road in the Northwest Territories, the world's longest heavy-haul winter road, illustrates challenges and potential adaptations associated with climate change. In 2006, approximately 1200 loads had to be transported by air during the summer and autumn following a shortened ice-road season (JVTC, 2013). The Tibbitt to Contwoyto Joint Venture is conducting research using ground-penetrating radar (Mesher et al., 2008) with a long-term goal of optimizing load capacity and vehicle speeds based on ice properties and water depth information. In addition, a new geographic-information-system-based asset management framework is being developed, and the research has been extended to other ice roads, ice bridges and ice platforms in Canada (Proskin et al., 2011).

Marine transport in northern regions is also important. While most of the Arctic is likely to continue to have only seasonally restricted marine operations, changes are occurring (e.g. Stroeve et al., 2012; *see also* Chapter 2 and 5), and their implications for shipping continue to be studied.

3.3 ISSUES SPECIFIC TO COASTAL COMMUNITIES

Projected changes in sea level, sea ice cover, and the intensity and frequency of storm events (*see* Chapter 2) will result in higher risk of coastal erosion, storm surge flooding and submergence. Previous assessments highlight the sensitivities of transport infrastructure in Atlantic Canada and parts of the British Columbia coast to such risks (Warren et al., 2004; Lemmen et al., 2008).

On the Atlantic coast, studies have examined the effects of storm winds and surge activity for various activities and sites. In terms of maritime transport, analysis suggests that hazards in Channel-Port aux Basques, Newfoundland, are likely to have negative economic impacts on transportation systems in the region (Catto et al., 2006). A risk assessment of three coastal roads in Nova Scotia led to recommendations that include engineered shoreline protection and relocation of selected roads further away from the coast (McGillis et al., 2010). Several climate change adaptation plans developed over the past five years make direct reference to coastal transportation infrastructure, including Halifax Harbour (Forbes et al., 2009; Halifax Regional Municipality et al., 2010; Richardson, 2010); Stratford, Prince Edward Island (Greene and Robichaud, 2010); and Yarmouth, NS (Manuel et al., 2012).

On the Pacific coast, the effects of climate change and sea-level rise on transportation are concentrated in areas where the terrain is relatively flat, such as the Roberts Bank – Fraser Delta region in Greater Vancouver and the northeastern coast of Graham Island, Haida Gwaii (Walker and Sydneysmith, 2008). From a transportation asset perspective, Vancouver has the greatest exposure to sea-level rise of all Canadian cities. A recent study identified Vancouver as being among the 20 cities in the world that are most vulnerable to climate change-related flooding (Hallegatte et al., 2013). In July 2012, Vancouver became the first municipality in Canada to adopt a comprehensive climate change adaptation strategy (City of Vancouver, 2012), which included a coastal flood risk assessment as one of the primary actions.

3.4 GREAT LAKES SHIPPING

The Great Lakes–St. Lawrence Seaway, stretching 3700 km from the head of Lake Superior to the Gulf of St. Lawrence, is an important international shipping route in one of the most industrialized parts of North America. Vessels carrying dry and liquid bulk commodities must conform to the size limitations of the Seaway, and therein lies the main concern related to climate change (Millerd, 2008, 2011). Projections of warmer temperatures translate into expectations of lower water levels in the Great Lakes system, despite past trends and future projections of increased precipitation (McBean and Motiee, 2008). Lower water levels translate into changes in available vessel drafts. Estimates of changing water levels vary considerably by climate change scenario and model (e.g. Angel and Kunkel, 2010, IJC; 2013), creating uncertainty as to the magnitude of the associated economic impacts and the need for adaptation. Recent media coverage underscores the extent and serious impacts of low water levels, especially when coupled with currently existing maintenance dredging shortfalls (Barrett and Porter, 2012; Associated Press, 2013). For example, one study concluded that for each centimetre decrease in water level, ship capacity decreases by six containers, or 60 tons (Transports Québec, 2012).

3.5 ADAPTATION APPROACHES

Increasingly, transportation agencies are using asset management systems for monitoring and decision-making in order to arrive at the most cost-effective approach for designing and maintaining the system. As noted by Meyer et al. (2010), "incorporating climate change-oriented risk appraisal into asset management is the key challenge to using the asset management framework for climate change". To date, there is little evidence that this challenge has been taken up in a comprehensive way, although the implications of climate change for transport infrastructure are increasingly being considered in professional meetings and research projects.

In the context of road networks, the most ambitious Canadian project of its kind was undertaken by Mills et al. (2007, 2009) with the objective of understanding how projected climate futures would affect pavement deterioration processes in Canadian highways. After quantifying changes in pavement deterioration processes and outcomes, the report identifies potential adaptation strategies related to construction and maintenance. Asset management approaches can also be used by other transportation modes, such as airports and port facilities.

Also of relevance to climate change and road transportation is the issue of variable load restrictions. This is of particular importance in the spring, on roads that carry resource commodities. These low-volume roads typically do not warrant alternate, more expensive designs. However, during spring thaw, physical changes can weaken the pavement structure, resulting in premature deterioration. Recent and ongoing research is facilitating the development of models for site-specific calibration of thaw weakening, so that the timing of spring-load restrictions can be optimized (e.g. Baiz et al., 2008). Because of climate variability, this type of adaptation has benefits both for today and for the future as conditions change even more, and would have relevance nation-wide.

In the Great Lakes, where lower water levels are an ongoing concern, there are a range of potential adaptation responses for operators and regulators. These include both structural measures (e.g. relocating facilities, updating docks and slips) and non-structural measures (dredging, using navigational aids and pilotage technologies). Adaptive management approaches (*see* Case Study 4), which involve monitoring, adjusting, experimenting and re-evaluating, are well suited under the uncertainty inherent in projections for the Great Lakes. Similarly, recent studies on adaptation to climate-related hazards in the North (e.g. with respect to ice roads and ice conditions) highlight the need for continual review of plans in light of climate change (Pearce et al., 2010).

CASE STUDY 4

ADAPTING TO CHANGING GREAT LAKE WATER LEVELS: USING AN ADAPTIVE MANAGEMENT APPROACH

Changes in Great Lakes water levels as a result of changing climate and other factors were identified in the 2008 assessment as a major regional (Chiotti and Lavender, 2008) and international (Bruce and Haites, 2008) concern. Since then, the International Upper Great Lakes Study (IUGLS) has evaluated the management of water levels and flows in the upper Great Lakes to meet present-day and future requirements. Analysis has demonstrated that regulation of Lake Superior has limited influence downstream. While building of new infrastructure for additional multi-lake water level and flow management was assessed, it was ultimately discounted at this time because of construction costs and significant environmental and institutional constraints. Instead, the study suggested an adaptive approach to coastal zone management, supported by monitoring and research to detect and manage emerging climate change risks (Leger and Read, 2012).

Adaptive management (*see* Chapter 9, Case Study 4) uses a structured, iterative process to address the uncertainties associated with climate change and the potential for extreme events. The International Great Lakes–St. Lawrence River Adaptive Management Task Team (2013) laid out a detailed plan and institutional arrangements to implement two key elements: i) ongoing review and evaluation of the performance of existing regulation plans; and ii) development of new solutions, beyond lake level regulation, related to extreme water level conditions. This effort seeks the coordinated participation of multiple partners across the basin to gather and share data, assess information, identify impacts, develop adaptation strategies and assess performance.

4. CONCLUSION

Well-functioning infrastructure and systems are critical to Canada's economic and social well-being. All sectors depend upon reliable access to clean water, effective stormwater maintenance, effective treatment of wastewater and a safe and efficient transportation network. A changing climate presents risks to these services in several ways, as discussed throughout the chapter. Extreme events emerge as the key concern, evidenced by numerous examples of heavy precipitation overloading stormwater-handling capacity and disrupting transportation corridors. However, slower-onset changes such as higher temperatures, sea level rise, permafrost thaw and declining lake levels are also important factors to consider in infrastructure design, operation and maintenance. The focus for both water and transportation has been on risks, with limited attention given to potential opportunities.

The past five years has seen progress on climate change adaptation and infrastructure. The scope and depth of research have both expanded, and there has been increased engagement of professional communities, attributable, at least in part, to the impact of the PIEVC program. As such, climate change is beginning to be considered by engineers and planners, as well as hydrologists, water and wastewater treatment operators, in the design and maintenance of infrastructure in Canada. Adaptation to date has generally been approached in the context of ongoing maintenance and upgrades, which in many cases will be sufficient to deal with a changing climate, especially gradual change. There are also some examples of specific adaptation measures that take a changing climate into account. Future adaptation will involve further technological advancements and incorporation of climate change into design standards and maintenance practices, and fundamental research is underway to inform these developments. A stand-alone assessment of transportation in Canada, also in development, will increase the baseline of knowledge on climate change impacts and adaptation actions for the sector.

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