Vulnerability and Adaptation of Water Infrastructure to Climate Change

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1 CONTEXT

It is fundamentally clear that climate change represents a profound risk to the performance of engineered systems and to public safety in Canada and around the world. As such, engineers, asset managers and decision-makers must address climate change adaptation as part of their primary mandate – the protection of the public interest, which includes life, health, property, economic interest and the environment. Climate change results in significant modifications of statistical weather patterns and consequently can have impacts on design data. Physical infrastructure systems designed using this inadequate data (i.e., data that is less relevant because actual conditions have changed) are vulnerable to failure, compromising public and economic safety.

Engineering vulnerability and risk assessment form the bridge to ensure climate change is considered in engineering design, operations and maintenance of civil infrastructure. Identifying the components of the infrastructure within a system that are highly vulnerable to climate change impacts enables cost-effective engineering, operations and policy solutions to be developed.

This paper is not intended as an exhaustive literature review on the subject. For this, the reader is directed to a recent report by Boyle et al. (2013) entitled *Climate Change Adaptation and Canadian Infrastructure - A review of the literature*. The authors found that "the adaptive capacity of various infrastructure is directly shaped by the extent to which policies, regulations and other market mechanisms support and incentivize actions that build climate resilience." Furthermore, they state "though relatively nascent, these tools are beginning to shift from being reactionary in nature to having a stronger focus on ensuring the longer-term adaptive capacity of critical sectors."

Boyle et al. (2013) identified and describe four key levers of action:

1. Current Government Policy Responses and Related Tools. This includes enabling adaptation frameworks and funding at the federal level in Canada, as well as in the North, Atlantic Region, Quebec, Ontario, Prairies and B.C. Additional examples from outside of Canada are also provided by the authors given their potential relevance in the Canadian context.
2. Codes, Standards and Related Instruments (CSRIs). The authors consider the extent to which national building codes and other standards support climate resiliency. Also considered is the development of other important tools and resources, such as the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol and the Canadian Standards Council Northern Infrastructure Standardization Initiative, that support the integration of climate considerations into infrastructure planning.
3. Markets, Financial Incentives and Liability Rules. The private sector, and in particular the insurance (and reinsurance) industry, also has a key role to play. Here, the authors have identified the most recent thinking and potential tools available in this respect.
4. Industry Responses. Finally, we explore actions taken by key cement/concrete industry actors in shaping responses to sustainability challenges more broadly, and the linkages being made to adaptation and climate resilience specifically.

The PIEVC Protocol is one of the tools highlighted in the paper by Boyle et al. (2013).

1.1 Objectives and Limitations

This paper intends to inform decision-makers and infrastructure practitioners about some of the tools that consider climate change impacts to infrastructure, from planning to operations and maintenance. It offers a brief review of selected methodologies that can be used to develop community adaptation plans, to assess the climate components in policy, and to evaluate the engineering vulnerability of infrastructure assets and systems. It focuses on processes and methods that have been used by public agencies and municipalities to identify and quantify risks, as well as to develop climate change adaptation solutions. It is not intended to provide an exhaustive list of all the methodologies that have been used or have been published on the subject.

The fact that a particular tool is presented in this article does not constitute an endorsement. If a tool has been omitted, it is because of space or scope limitations, and should not be construed as a rejection of the tool as beneficial.

The information and statements expressed in this article are those of the author and do not reflect the views, opinions or any official position of any organization.

1.2 Current and Future Climate

The changes in global climate have been, and continue to be well documented by a number of Canadian and international organizations such as the Intergovernmental Panel on Climate Change (IPCC) which produced its Fifth Assessment Report (AR5) in November 2014. In brief, the report tells policymakers what the scientific community knows about the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.

From an infrastructure's perspective, the story of climate change can be seen in the increasing number of occurrences of extreme weather events and their impacts. Table 1 presents the "billion dollar years" of payouts by Canadian insurers. Of note is the increased frequency of those devastating years, and the fact that 2013 was the first time ever insurance companies paid in excess of two billion dollars for losses.

Table 1. Billion-dollar payment years from Canadian insurance companies (Source: McGillivray, 2014)

Year	Main event(s) causing losses
1998	Due solely to the Eastern Canada ice storm
2005	Greatly due to the August 19 Greater Toronto Area (GTA) rainstorm
2009	Mainly due to back-to-back windstorms in Alberta
2010	Due greatly to large hailstorm in Alberta
2011	Mainly because of the Slave Lake wildfire
2012	Caused mainly by one large and two smaller hailstorms in Alberta
2013	Due to the Southern Alberta flood and GTA flood. First time ever for two billion-dollar events

It is therefore no coincidence that the Institute for Catastrophic Loss Reduction (ICLR) reported that:

> “Large insured losses from extreme weather appear to be ‘the new normal’ for the Canadian insurance industry, expecting that large-loss years will no longer be rarities.” (Canadian Underwriter, November 2012).

1.3 Canada’s Infrastructure Context

Public infrastructure systems are complex, many are underground and therefore difficult to access and inspect. It is standard practice to differentiate between linear assets (pipes, roads, cables, etc.) and non-linear or discrete assets (pumps, plants, bridges, culverts, etc.) since each category presents different type of management challenges. However, providing services to the public requires all the components within a system to perform adequately since the robustness – and therefore the safety and quality of the service is dependent on its weakest link.

Infrastructure assets also have very long service lives – water or sewer pipes for example are commonly in use for 80 years, 100 years or longer – four generations or more. It is therefore critical that these assets be properly planned and managed.

Figures 1 to 3 show the condition distribution of some core public infrastructure systems reported by the 2012 Canadian Infrastructure Report Card (CIRC). In general, the report card shows that water resources infrastructure (systems for potable water, wastewater and storm water management) are in good or better condition.

It is important to note that the data reported is about the physical condition of the infrastructure. Although the 2012 CIRC attempted to collect information on other performance indicators, particularly capacity, the data received was not sufficient to provide statistically relevant results.

In regards to the physical condition of stormwater systems, it should be noted that these are “young” relative to other core infrastructure such as potable water or wastewater systems. Regulations regarding managing stormwater, particularly in new residential developments, are recent and therefore it is expected these infrastructures are in a better condition, as confirmed by the data.

The data in Figures 1 to 3 are but snapshots of the condition of various infrastructure systems. The 2012 CIRC also found that asset management is, and will continue to be a critical activity to maintain and improve levels of service under the financial constraints municipal governments’ experience. For example, the CIRC 2012 found that the majority of municipalities reported using some type of asset management system, whether computerized or/and paper based as follows:

Drinking water	90% of respondents
Wastewater systems	68.8% of respondents
Storm water management	50.5% of respondents
Roads	85.6% of respondents

It is therefore interesting to note that one of the municipal infrastructure systems that can be significantly impacted by increased extreme precipitation events – stormwater management, had the lowest use of asset management systems in 2012.

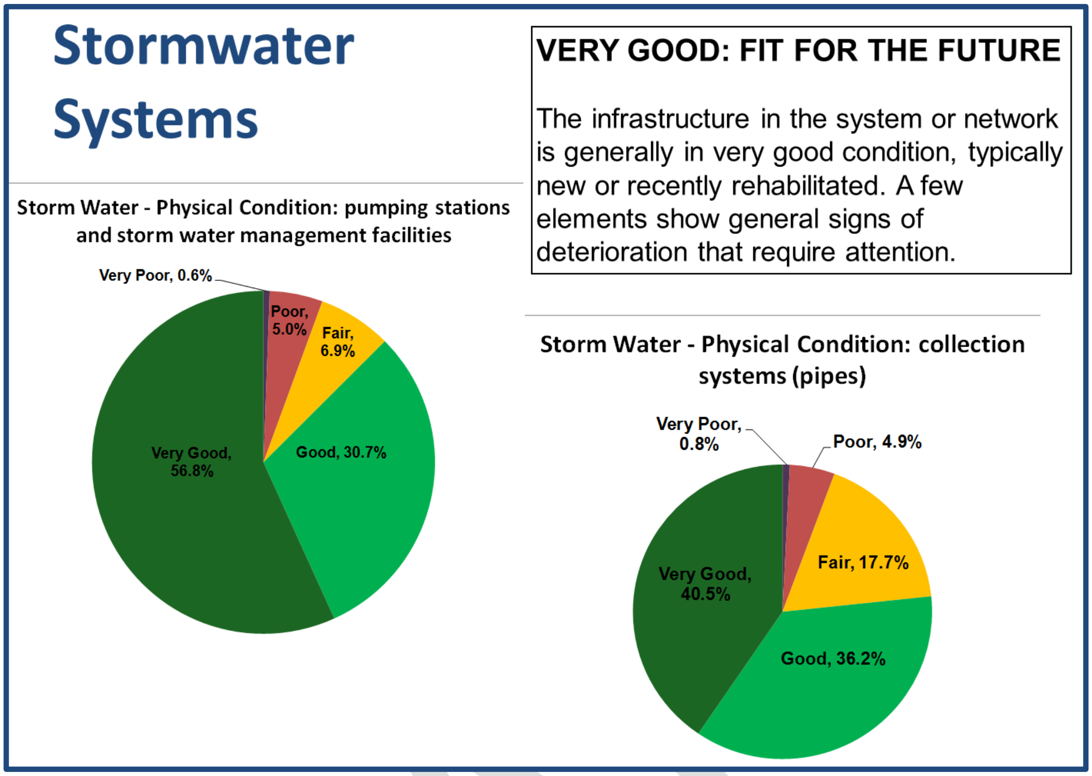


Figure 1. Canadian Infrastructure Report Card (2012) Results for stormwater systems

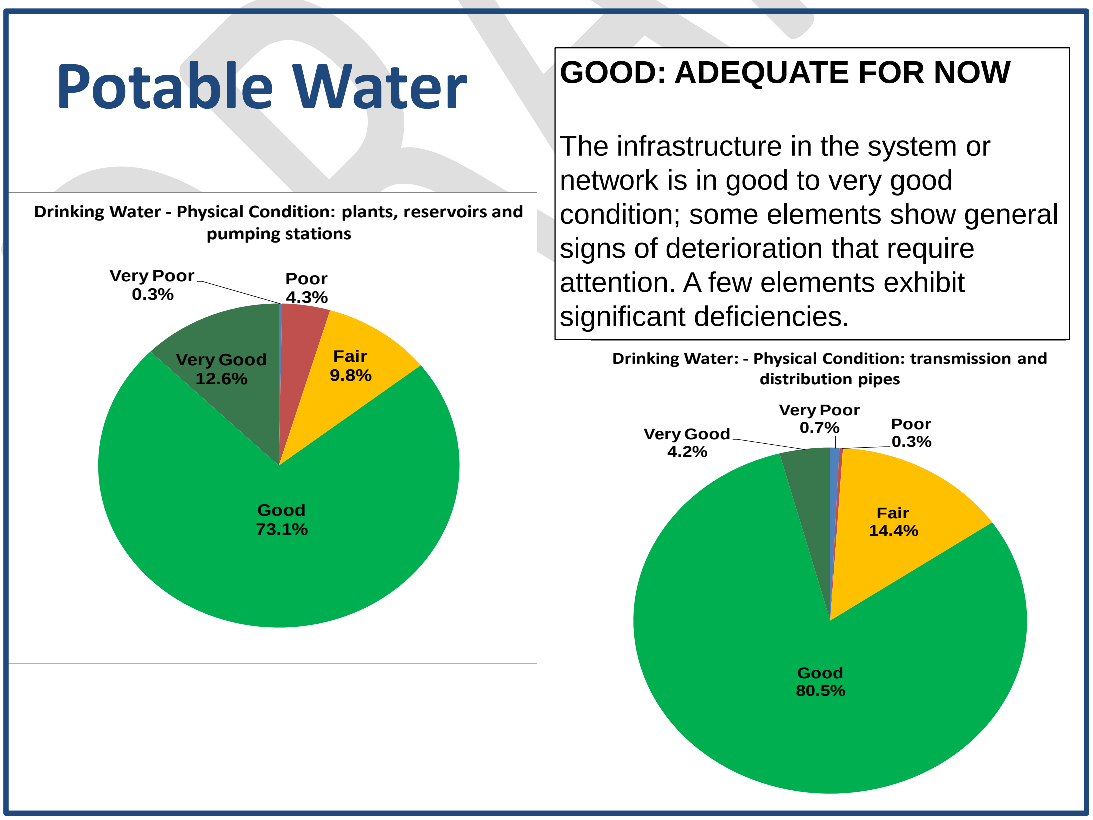


Figure 2. Canadian Infrastructure Report Card (2012) Results for potable water systems

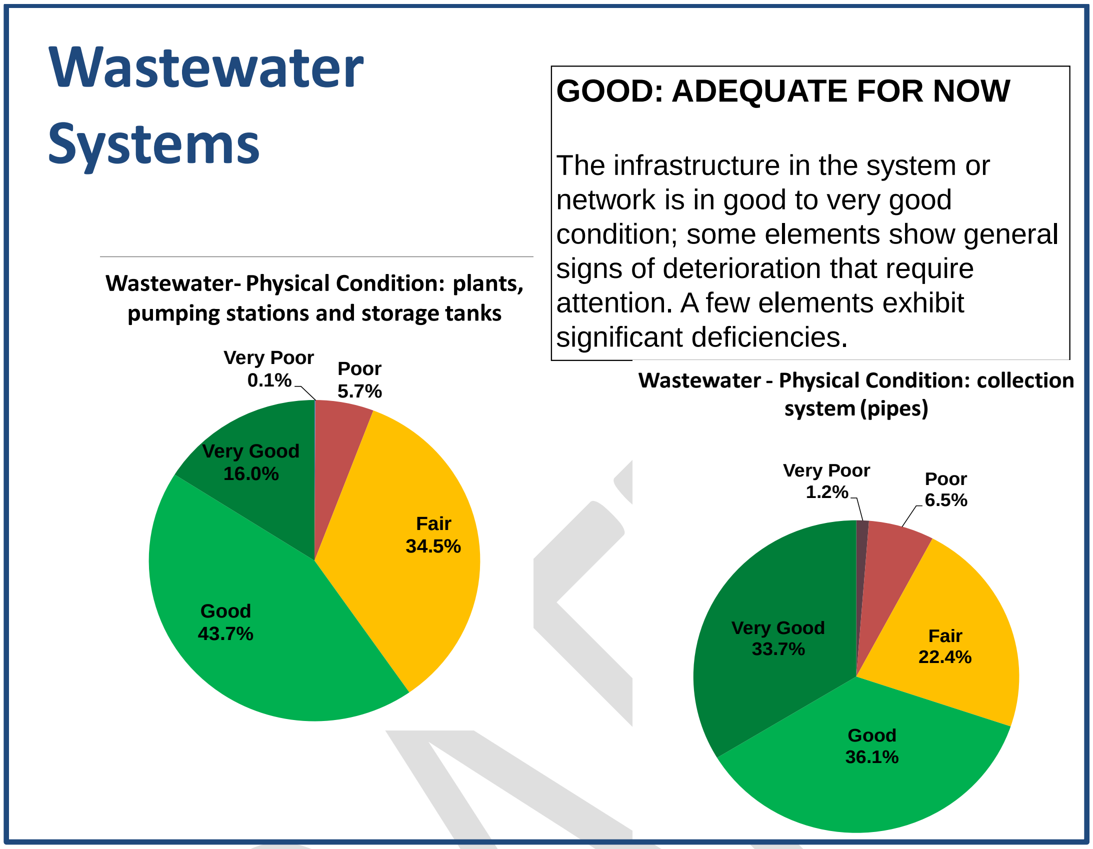


Figure 3. Canadian Infrastructure Report Card (2012) Results for wastewater systems

As a result, the report card partners issued an Asset Management Primer in September 2014. In the context of risk management, the Primer indicates:

> "Understanding and managing the risks associated with the failure of an asset is a key element in many AMPs (Asset Management Plans). The risks in municipal infrastructure are impacted by the physical condition of the asset and the social, economic and environmental consequences that would occur if the asset fails to provide the service for which it was designed."

1.4 Managing Infrastructure and Risks

Establishing the exposure and sensitivity of infrastructure to threats, whether from natural sources such as extreme climate events or earthquakes, or from man-made sources is an integral part of sound asset management. Figure 4 illustrates an asset management framework developed by the author and inspired by the InfraGuide best practice DMIP 7 – Managing Infrastructure Assets (2007) that is compatible with the intent of ISO 55000 – Asset Management. Providing the details of this framework is beyond the scope of this paper. There are however a number of steps in this framework that relate to and are influenced by current and future climatic conditions. For example, future loads on the infrastructure, whether from increased utilisation or changes in climate, may affect the physical condition, functionality or capacity of the infrastructure. This, combined with the infrastructure's current condition, can produce vulnerabilities and risks that require short term attention or that will need to be addressed in future capital or maintenance plans.

2 INFRASTRUCTURE SUSTAINABILITY, VULNERABILITY AND RESILIENCE: TOOLS AND PROCESSES

2.1 Definitions

In 1987, the Bruntland report from the World Commission on Environment and Development defined sustainability as "meeting the needs of the present generation without compromising the ability of future generations to meet their needs."

Sustainable Infrastructure

The US-EPA interprets this definition in the context of infrastructure as:

> “Sustainable (infrastructure) means having an active and effective program for renewal and replacement of components at a rate that allows for that infrastructure to continually serve our communities into the future. Achieving sustainability requires the establishment of a long-term plan to gradually and continually replace all infrastructure assets—a plan that ensures wise spending practices and a stable revenue stream for continuous support of needed future investments.”

Infrastructure Vulnerability

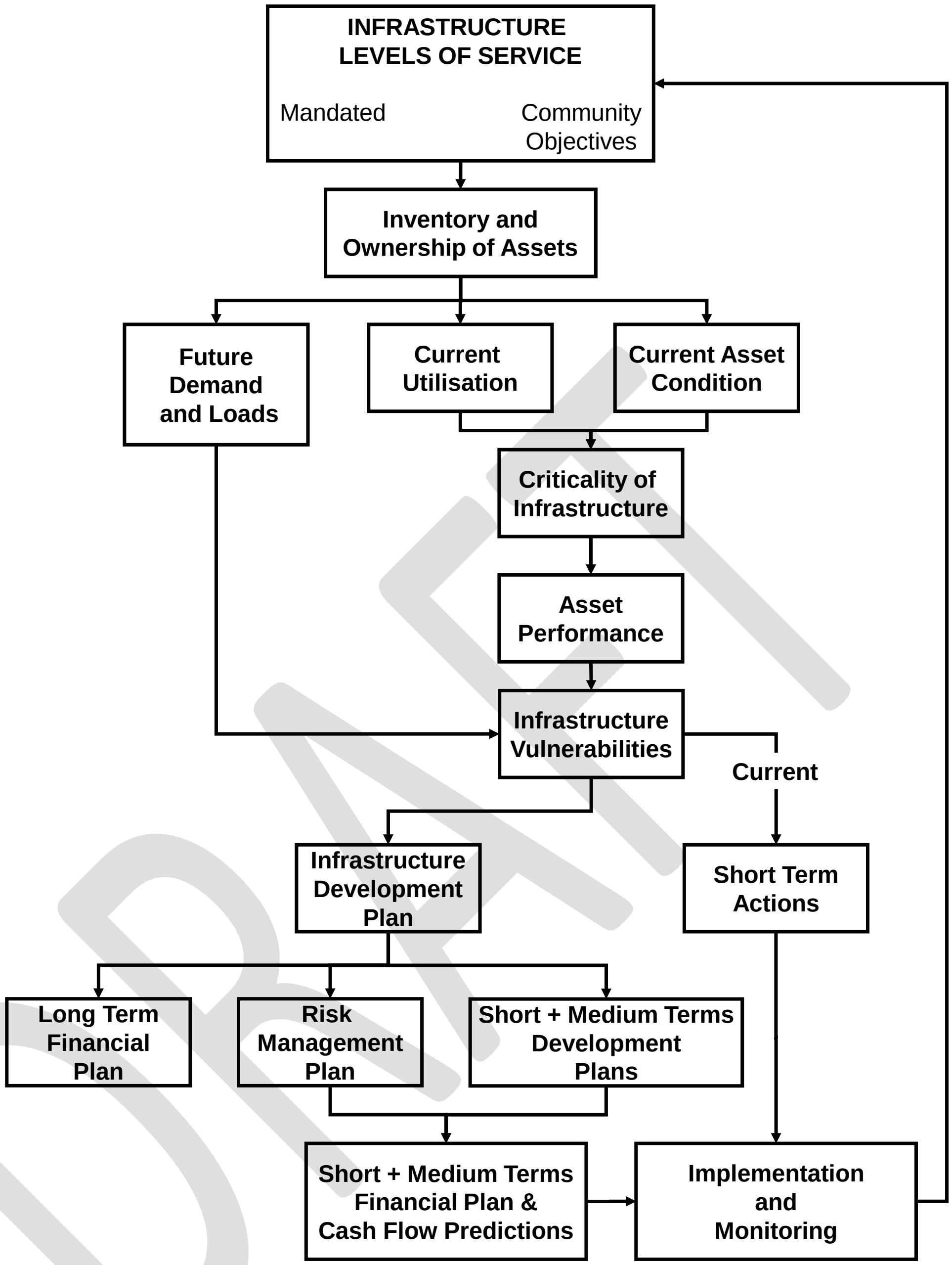
Engineers Canada’s PIEVC Protocol defines the engineering vulnerability of infrastructure as:

> “The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.”

Engineering vulnerability is a function of:

- Character, magnitude and rate of change in the climatic conditions to which infrastructure is predicted to be exposed;
- Sensitivities of infrastructure to the changes, in terms of positive or negative consequences of changes in applicable climatic conditions; and
- Built-in capacity of infrastructure to absorb any net negative consequences from the predicted changes in climatic conditions.

A vulnerability assessment will therefore require assessing all three elements above. Although this definition is given in the context of climate change, it is applicable to any hazard or threat the infrastructure may be exposed to.



Notes:
- Future Demand is based on community growth and vision.
- Asset performance measures structural performance, capacity and functionality, and relates to the mandated levels of service, community objectives and regulatory requirements including codes/standards.
- Risk is assessed with respect to health, safety, economic and environmental (e.g. climate change) impacts.
- Short term actions are to remedy any deficiencies for which short term risk is not acceptable.
- Long-term plans include: demand management, alternative service delivery, partnerships, etc.

Figure 4. Example of asset management framework incorporating risk management planning (Source: author)

Infrastructure Resilience

Resilience, on the other hand, is the capacity of the infrastructure to withstand and operate under hazards or threats. The UN International Strategy for Disaster Reduction defines resilience as:

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

2.2 Sustainability Rating Tools

In general, sustainability rating tools include climate change risks to infrastructure and buildings as part the assessment. Some provide very basic methodologies on how to assess risks associated with natural hazards, including those from extreme weather.

The International Federation of Consulting Engineers (FIDIC) produced a report in 2012 (summary available online at http://fidic.org/node/5943) on *Sustainable Infrastructure: Rating and Certification Tools* which summarizes an extensive international survey of these types of tools. The summary table is reproduced hereafter for convenience.

In the Canadian infrastructure context, two rating tools seem to offer the greatest potential: Envision (from the USA) and ISCA (from Australia).

Envision™ Sustainable Infrastructure Rating System

Envision™ (see http://www.sustainableinfrastructure.org/rating/ for details) is the product of a joint collaboration between Harvard University and the US Institute for Sustainable Infrastructure (ISI). It provides a framework for evaluating and rating the community, environmental, and economic benefits of all types and sizes of infrastructure projects. It evaluates, grades, and gives recognition to infrastructure projects that use transformational, collaborative approaches to assess the sustainability indicators over the course of the project's life cycle. Envision™ has assessment tools that can be used for infrastructure projects of all types, sizes, complexities, and locations, such as.

1. Checklist:
    - An educational tool that helps users become familiar with the sustainability aspects of infrastructure project design. It can be used as a stand-alone assessment to quickly compare project alternatives or to prepare for a more detailed assessment.
    - Structured as a series of Yes/No questions based on the Envision™ rating system. It organized into five categories and fourteen subcategories.
2. Rating system:
    - Used by the project team to self-assess the project, or for an third-party, objective review.
    - Includes a guidance manual and scoring system.

At the time of writing this article, an economic optimization tool, construction and O+M phase credits, and other stages of the Envision™ rating system were under development.

Table 2. Summary of sustainability rating and certification tools (After FIDIC – Accessed at http://fidic.org/node/5943)

RATING & CERTIFICATION TOOLS	Key for Rating & Certification tool summaries
	Y Applicable sector
	Y Existing award type
	P Provisional or interim award
	D Award under development

Tool	Countries	Applicable sectors					Award types				
		General civil infrastructure	Transport or hydro only	Buildings	Public Realm	Community / precinct	Design	As built	Operation*	Planning	Other
BCA Green Mark	Singapore	Y		Y	Y	Y		Y	Y		
BEAM	Hong Kong			Y			P	Y	Y		
BERDE	Philippines			Y			P	Y	Y		
BREEAM**	UK developed. Used throughout Europe + other international applications.			Y		Y	Y	Y	Y	Y	
CalGreen	California state only, USA			Y			Y				
CASBEE	Japan			Y		Y	Y	Y	Y	D	Y
CEEQUAL	UK & Ireland version, Hong Kong version, internationally applicable	Y			Y		Y	Y	Y		Y
China Ministry of Construction Green Building System**	China			Y				Y	Y		

Table 2. Summary of sustainability rating and certification tools (After FIDIC – Accessed at http://fidic.org/node/5943) Continued

Tool	Countries	Applicable sectors					Award types				
		General civil infrastructure	Transport or hydro only	Buildings	Public Realm	Community / precinct	Design	As built	Operation*	Planning	Other
DGNB - the German Sustainable Building Certificate	Germany & International			Y		Y	P	Y	Y		
Envision	United States	Y			Y		Y	D	D		
Estidama & the Pearl Rating System	Abu Dhabi			Y		Y	P	Y	D	Y	
Green Building Index	Malaysia			Y		Y	P	Y	Y	Y	
Green Globes	Canada and USA			Y			D	Y	Y		
Green Star (Au)	Australia			Y		Y	Y	Y		D	
Green Star (NZ)	New Zealand			Y			Y	Y	Y		
Green Star (SA)	South Africa			Y			Y	Y	D		
GreenLITES	New York State, US		Y				Y		Y	D	
Greenroads	USA - piloting internationally		Y					Y			
Greenship	Indonesia			Y			P	Y	Y		
GRIHA	India			Y		Y		P	Y		
HQE Amenagement***	France			Y		Y		P	Y	Y	
Hydropower Sustainability Assessment Protocol	Globally applicable		Y				not applicable				
Infrastructure Sustainability	Australia	Y					Y	Y	D		
INVEST	USA		Y				P	P	Y	Y	

Table 2. Summary of sustainability rating and certification tools (After FIDIC – Accessed at http://fidic.org/node/5943) Continued

Tool	Countries	Applicable sectors					Award types				
		General civil infrastructure	Transport or hydro only	Buildings	Public Realm	Community / precinct	Design	As built	Operation*	Planning	Other
LEED	Developed in the US, now international			Y		Y		Y	Y		Y*
NABERS	Australia, expanding to New Zealand			Y					Y		
NatHERS	Australia			Y			not applicable				
SBTool	Europe			Y		D	not applicable				
STAR Community Rating System	USA (primary base) and Canada					Y					Y
STARS	USA		Y				Y			Y	

* Note: The term "operation" is used here in reference to awards that are typically for "existing buildings". An existing building award is for the building, but the assessment is based on aspects of its operation (rather than elements of its construction).

** Summary not reviewed

*** No summary currently available (2012) for this tool

Infrastructure Sustainability Council of Australia (ISCA)

The ISCA rating scheme (see http://www.isca.org.au/ for details) was developed and is administered by the Infrastructure Sustainability Council of Australia (ISCA). It is a rating scheme for evaluating sustainability across design, construction and operation of infrastructure. The ISCA rating scheme can be used to inform and assess most types of infrastructure including:

Transport
Airports
Bike paths and sidewalks
Ports and Harbours
Railways
Roads

Water
Sewerage and Drainage
Storage and Supply

Communications
Communication Networks

Energy
Electricity Trans. & Dist.
Gas Pipelines

2.3 Community Assessment/Climate Change Adaptation Planning

In Canada, municipalities receiving federal Gas Tax funds are required to produce Integrated Community Sustainability Plans (ICSPs) or variations thereof. The level of details about infrastructure condition, needs and long-term plans varies across the country since the requirements were defined under each Federal – Province/Territory agreement. How climate change impacts have been considered in these plans is unknown but should be assessed.

2.3.1 ICLEI: Changing Climate, Changing Communities Framework

The International Council of Local Environment Initiatives (ICLEI) has developed a milestone framework, *Changing Climate – Changing Communities*, to guide local government practitioners through a process of initiation, research, planning, implementation and monitoring for climate adaptation planning. This five step process (Figure 5) is supported by an online interactive tool, the *Building Adaptive and Resilient Communities* (BARC) designed to assist communities in adapting to the impacts of climate change through the development of a municipal climate change adaptation plan and is available through a subscription with ICLEI (see http://www.icleicanada.org/programs/adaptation/barc for details).

The process can be applied at various levels within a community or municipality:

- At the single sector or department level
- For a municipal operations plan covering all departments
- For a community wide plan with multi-stakeholder, community involvement
- Community driven for a vulnerable sector within a municipality (e.g., residents from a flooded area)

2.3.2 7 Steps to Assess Climate Change Vulnerability in Your Community Guide and Worksheets

The Atlantic Climate Adaptation Solutions Association has produced a guidance document and workbook called *7 Steps to Assess Climate Change Vulnerability in Your Community.*

1. Identify the types of climate and weather-related issues that have affected your community;
2. Locate where these issues have occurred or could occur in your community;
3. Assess what infrastructure has been or will be impacted;
4. Identify the residents who have been or will be most affected as well as those who can provide assistance in the community;

5. Assess which economic sectors have been or will be most impacted by the issues;
6. Identify how the natural environment has been or will be affected; and
7. Determine the best ways to address the issues identified.

The workbook produced for Newfoundland for example, includes climate (current, future predictions) information as well as expected trends and impacts from, for example, precipitation (intensity, frequency), temperature (average, extremes) and sea-level rise.

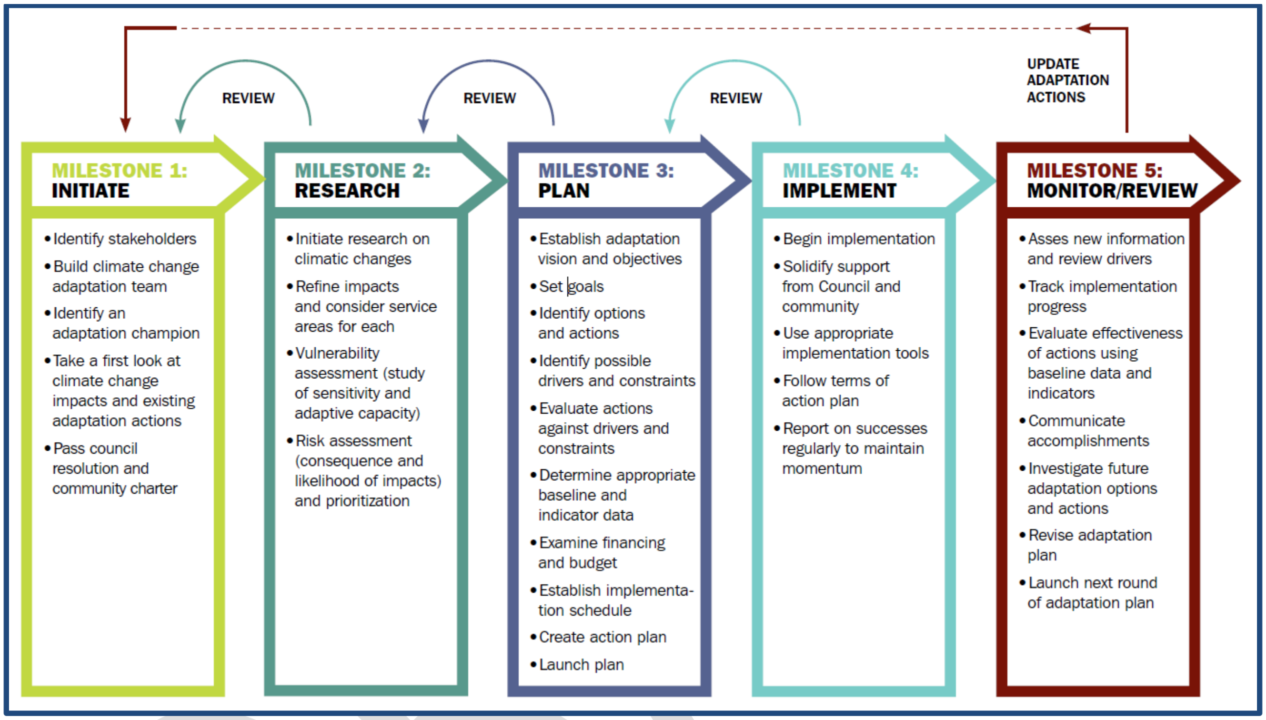


Figure 5. ICLEI's five-step milestone framework (Source: ICLEI).

2.4 Review of Tools for Assessing the Vulnerability of Watersheds

In a report to the Canadian Council of Ministers of the Environment (CCME) Nelitz et al. (2013) provide examples of when vulnerability assessments have been used, which include:

- Providing insight into the actions needed to prevent loss of life, damages, or disasters.
- Understanding vulnerability as a prerequisite for developing adaptation policies that promote equitable and sustainable development.
- Anticipating where impacts may be greatest at a Canada-wide scale, setting priorities for regional assessment of climate change impacts and adaptation strategies, and monitoring climate change effects.
- Understanding the economic costs to communities and infrastructure due to extreme weather events (for example the costs from extreme weather events in Canada from 1996-2006 were greater than for all previous years on record combined).
- Developing policies and adaptation plans for vulnerable areas, sectors, groups, etc. as well as reducing climate change risk.

The authors use the standard definition of risk in describing the vulnerability of watersheds, which comprises, as illustrated in Figure 6

- Potential impact: exposure (to the hazard) and sensitivity (of the element to the hazard)
- Adaptive capacity

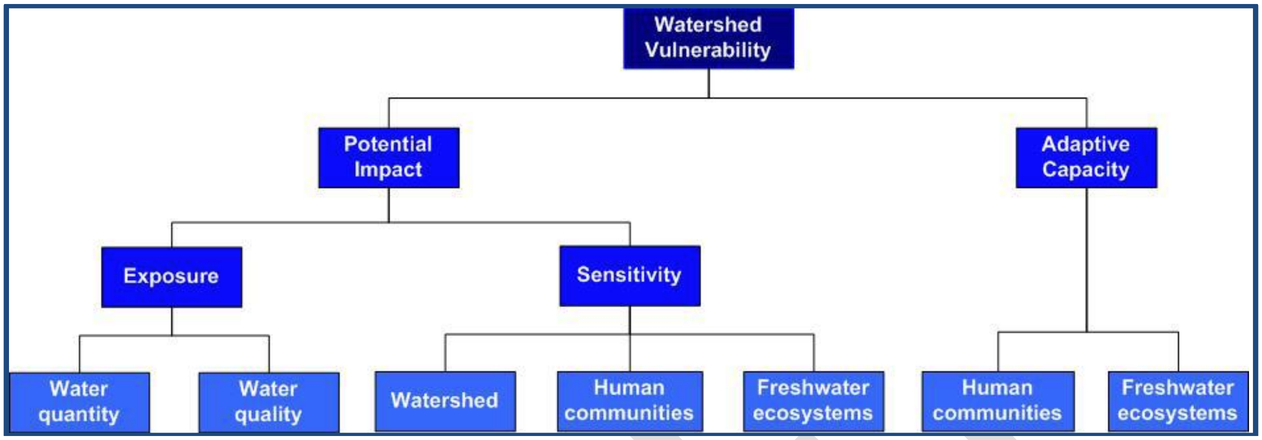


Figure 6. Elements of Watershed Vulnerability Assessments (After Nelitz et al., 2013)

The authors indicate the location and timing of a vulnerability assessment will be affected by the availability of sufficient expertise, time, and financial resources. Furthermore, they found that indicators are used in some form in most vulnerability assessments.

Throughout the literature, indices and indicators are often synonymously called themes, components, or sub-indices (index) and proxies (indicators). In their review, Nelitz et al. (2013) define an indicator as a single measure of a characteristic (e.g., water temperature), the units of which can be described by a particular metric (e.g., annual maximum temperature). An index is defined as a composite, or aggregate, measure of several indicators or indices. These terms are used even though they may not be consistent with the language of the original studies. They provide key considerations when identifying and selecting indicators, which include:

- Appropriateness and relevance to dimension of interest;
- Transparency (not too complicated, should be repeatable);
- Feasibility (considering cost of data collection and time availability); and
- Size and composition of each indicator (absolute vs. relative values, areal measure, etc.).

The tools in the report were selected to be representative of a broad range of water resource issues, data needs, and technical capabilities. They are varied and diverse and range from indicator-based approaches to sophisticated hydrological models that calculate exposure to flood events under future projections of climate change. They also range from qualitative to quantitative approaches that address a broad range of characteristics of social-ecological systems.

Table 2. Overview of tools for assessing vulnerability of watersheds (After Nelitz et. al, 2013)

Dimensions	Components	Tool groupings	Tool sub-groupings / examples
Exposure	Water Quantity / Water Quality	Lumped models	• Canadian Water Evaluation Tool • ForHyM & ForWaDy Hydrologic Evaluation of Landfill Performance • Thornthwaite Monthly Water Balance Model • Water Resources Evaluation of Non-Point • Silvicultural Sources (WinWrnsHyd & ECAAlberta)
		Semi-distributed models	• Hydrological Simulation Program- • FORTRAN Model • Water Evaluation and Planning System
		Fully-distributed models	• MIKE SHE • Variable Infiltration Capacity Model
		Indicators, indices, and statistical models	• Precipitation minus potential evapotranspiration (P-PET) • Isaak et al. 2010 • Swansburg et al. 2004 •
Sensitivity	Watersheds	Indicators of watershed condition or function	• Upslope • Riparian-floodplain • Inchannel
		Biological indicators	• Macro- • invertebrates • Fish
		Coupled or integrated watershed models	• Many possible examples
	Human Communities	Social vulnerability analysis	• Many possible examples
		Engineering vulnerability assessment	• Engineers Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol
		Risk assessment	• Many possible examples

Table 2. Overview of tools for assessing vulnerability of watersheds (After Nelitz et. al, 2013) Continued

Dimensions	Components	Tool groupings	Tool sub-groupings / examples
Sensitivity	Freshwater Ecosystems	Bioclimate envelope models	• Many possible examples
		Species or life history susceptibility	• NatureServe Climate Change Vulnerability Index • System for Assessing Vulnerability of Species
		Habitat or species models	• Conceptual models • Indicator-threshold approaches − Water temperature guidelines − Flow standards • Dynamic systems models
Adaptive Capacity	Human Communities	Determinants of adaptive capacity	• Economic resources • Technology • Information, skills, and management • Infrastructure • Equity • Institutions and networks
		Assets of adaptive capacity	• Human • Social • Natural • Physical • Financial
	Freshwater Ecosystems	Indicators of ecosystem resilience	• Genetic diversity • Integrity of landscape mosaics • Biological diversity

2.5 Residential Basement Flood Vulnerability Assessment Tool - MRAT

In 2013, the Insurance Bureau of Canada (IBC) launched its Municipal Risk Assessment Tool (MRAT) through pilot applications in three cities: Fredericton (NB), Hamilton (ON) and Coquitlam (BC).

MRAT focuses on basement flooding risks, and more particularly on mapping vulnerable areas to flooding within a city. The tool uses data from municipal infrastructure (inventory and condition), land use, current and predicted future climate, and insurance claims. The risk formula considers the probability of climate events occurring (in this case precipitation and resulting floods), the exposure (infrastructure interacting with the particular climate event) and the vulnerability which establishes the susceptibility of the infrastructure to the climate event. Figure 7 illustrates the results expected from the application of MRAT to a municipality.

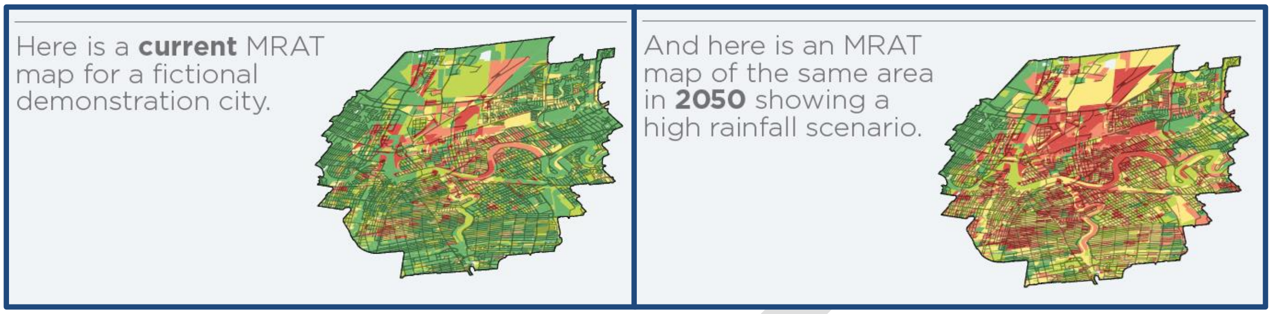


Figure 7. Illustration of MRAT basement flooding risk maps (Source: IBC)

2.6 Engineers Canada – PIEVC Infrastructure Engineering Vulnerability Assessment

Engineers Canada, with support from Natural Resources Canada (NRCan) created the Public Infrastructure Engineering Vulnerability Committee (PIEVC) in 2005 to address engineering concerns with infrastructure risks to climate change impacts. By 2008, the PIEVC had created a tool, the Protocol, to guide engineers working with other professionals in assessing the vulnerability of infrastructure and develop adaptation solutions. An engineering tool, the Protocol helps assess vulnerabilities in several related areas such as planning, operations and maintenance of the infrastructure.

Initially targeted to water resources infrastructure (potable water, wastewater and storm water), roads, bridges, and buildings, the PIEVC Protocol has since its inception been used for a wider spectrum of infrastructure, including dams, coastal structures, airports and electricity transmission grids. In fact, as of November 2014, the Protocol has been or is being used for more than 40 risk evaluations in Canada as shown in Figure 8, and two have been completed abroad. There are no known limitations to the type of infrastructure the Protocol can be applied to. It has been used both by small (e.g., District of Shelburne, NS – population about 3,000) and large (Toronto, ON) municipalities across Canada.

The Protocol is a five-step process that systematically reviews historical climate information and projects the nature, severity and probability of future climate changes and events. It also establishes the adaptive capacity of an individual infrastructure as determined by its design, operation and maintenance. It includes an estimate of the severity of climate impacts on the components of the infrastructure (i.e. deterioration, damage or destruction) to enable the identification of higher risk components and the nature of the threat from the climate change impact. This information can be used to make informed engineering judgments on what components require adaptation as well as how to adapt them e.g. design adjustments, changes to operational or maintenance procedures.

The Protocol provides a screening level profile of high, medium and low risks of climate to infrastructure. It does not require comprehensive and complete data to complete an assessment. Gaps are addressed by professional judgment and experience of the inter-disciplinary team of professionals needed to define the nature and consequence of climate impacts that damage or destroy infrastructure or impede its service to the community it serves. Experience has shown that screening level risk assessment of infrastructure climate risks produces cost-effective and timely evidence at an affordable cost to large and small communities. Recommendations to address the highest risks to improve climate resilience range from collecting more data or more targeted and quantitative engineering analysis to adjustments in operations and maintenance policies and procedures to design improvements that require additional cost information.

Figure 8. Locations and type of Protocol vulnerability assessments completed or in progress as of February 2013

Table 3 lists a number of completed and ongoing PIEVC Protocol application projects in the areas of potable water (intake, treatment and distribution), stormwater management, wastewater systems, and other relevant infrastructure of interest to the water industry.

Engineers Canada has also completed the initial development and testing of a Triple Bottom Line Decision Support Module. This tool evaluates adaptation recommendations from the Protocol using a multi-factor analysis that includes social, environment and economic factors. Engineers Canada offers this additional tool as a complement to the Protocol.

The Appendices hereafter provide summaries of five applications of vulnerability assessments to various types of water infrastructure using the PIEVC Protocol (full reports at www.PIEVC.ca), namely:

- Appendix A: Metro Vancouver (BC) Vancouver sewerage area infrastructure (2008)
- Appendix B: City of Calgary (AB) potable water supply (2011)
- Appendix C: District of Shelburne (NS) vulnerability of Sandy Point STP upgrade (2011)
- Appendix D: City of Welland (ON) stormwater and wastewater infrastructure (2012)
- Appendix E: City of Nelson (BC) stormwater infrastructure (2014)

Table 3. PIEVC Protocol water and related infrastructure climate vulnerability assessments completed and In progress as of January 2015 (source: www.PIEVC.ca)

Host/Partner	**Infrastructure Category**	**Title of Report**
City of Portage la Prairie, MB	Water Resources – Potable water system	City of Portage la Prairie Water Resources Assessment - Phase II Pilot Study (November 2007)
Metro Vancouver, BC	Stormwater/ Wastewater	Vulnerability of Vancouver Sewerage Area Infrastructure to Climate Change (March 2008)
Government of Newfoundland and Labrador – Department of Environment and Conservation, Placentia, NL	Water Resources – coastal structures	Case Study – Placentia Coastal Infrastructure (March 2008)
Metro Vancouver Sewerage and Drainage Division, Vancouver, BC	Stormwater/ Wastewater	Vulnerability of Fraser Sewerage Area Infrastructure to Climate Change (December 2009)
Toronto and Region Conservation Authority Toronto, ON	Water resources - dams	Vulnerability of Claireville and G. Ross Water Control Dams (June 2010)
City of Castlegar, BC	Stormwater	Vulnerability of Stormwater Treatment System (October 2010)
City of Calgary Water Calgary, AB	Water resources	Vulnerability of Calgary's Potable Water Collection, Treatment and Distribution System (May 2011)
Town of Prescott, ON	Stormwater/ Wastewater	Vulnerability of Sanitary Sewer System – Separated Town of Prescott (June 2011)
District of Shelburne, NS	Stormwater/ Wastewater	Vulnerability of Shelburne Sewage Treatment Plant (STP) Upgrade (August 2011)
City of Laval, QC	Stormwater/ Wastewater	Storm water collection system evaluation in the city of Laval – Belgrand overflow structure (September 2011)
City of Toronto Department of Transportation Toronto, ON	Roads and associated structures	Assessment of three road culverts (December 2011)
Town of Welland, ON	Stormwater and Water Resources	Assessment of Town of Welland's Stormwater and Wastewater Systems (February 2012)
City of Trois Rivieres, QC	Stormwater/ Wastewater	Assessment of Stormwater/Wastewater Network (March 2012)

Table 3. Water and Related Infrastructure Climate Vulnerability Assessments Completed and In Progress as of January 2015 (source: www.PIEVC.ca) Continued

Host/Partner	Infrastructure Category	Title of Report
Toronto Hydro Electrical System Limited, Toronto, ON	Electrical distribution	Assessment of Toronto Hydro Electrical Distribution System – A Pilot Study (September 2012)
City of Trois Rivieres, QC	Potable water supply	Study of the potable water supply, treatment and distribution for the City of Trois Rivieres (April 2013)
Leamington/Essex County, ON	Potable water supply	Assessment of the Union Water Supply System (May 2013)
City of Nelson, BC	Stormwater management system	Assessment of City of Nelson Stormwater Management System (February 2014)
Greater Toronto Airport Authority, Toronto, ON	Airport infrastructure	Climate Change Vulnerability Assessment for Selected Stormwater Infrastructure at Toronto Pearson International Airport (August 2014)
Mik'Maq Communities, Cape Breton/Unamaki, NS	Stormwater and Wastewater, Potable Water	Unama'ki Water and Wastewater Vulnerability Assessment and Adaptation (in progress)
Quebec City, QC	Stormwater	Study of a planned (i.e. not yet built) stormwater management system in the d'Estimauville eco-neighbourhood (in progress)
Province of Ontario (Ontario Power Authority), ON	Electrical transmission	Enhancing Resilience to Severe Weather and Climate Change – Transmission Sector (in progress)
Toronto Hydro Electrical System Limited, Toronto, ON	Electrical distribution	Enhancing Resilience to Severe Weather and Climate Change – Distribution Sector (in progress)
Halton Region and Credit Valley Conservation Authority, ON	Stormwater and water resources	Climate risk assessment of wastewater, stormwater and potable water systems (in progress)
City of Mississauga and Credit Valley Conservation Authority	Stormwater and water resources	Climate risk assessment of wastewater, stormwater and potable water systems (in progress)
City of Montréal, QC	Stormwater and wastewater	Climate risk assessment of stormwater and combined sewers systems (in progress)

3 CONCLUSIONS

There are other tools and methodologies not included in this article that have been developed in other countries. For example, several US Federal agencies including the US Environmental Protection Agency have created methodologies for detailed quantitative risk assessments and comprehensive climate change adaptation planning for very large capital-intensive projects. There also exist similar tools developed in Europe and Australia that require quantitative data.

While all the tools reviewed here provide valuable information for engineers, asset managers and decision-makers, the PIEVC Protocol has the engineering depth and breadth of application to help communities large and small adapt to a changing climate. The methodologies developed for risk assessments and climate change adaptation planning in the United States, Europe and Australia are all valuable, but may not be as affordable and timely as the PIEVC Protocol in engaging engineers who must work closely with other professionals to support the planning, operation, maintenance, management and use the infrastructure to benefit society. The results of a PIEVC Protocol assessment inform decision-makers to a level that is adequate to develop cost-effective recommendations that adapt the highest risk components to improve their resilience to climate impacts in ways other assessment tools may not.

The use of the PIEVC Protocol in Canada has provided the opportunity to make recommendations concerning the review of selected infrastructure codes, standards and related instruments (CSRI) in light of the changing climate. The evidence to support these recommendations came from the 22 PIEVC case studies that had been completed in 2012. The report relating to water infrastructure (Felio, 2012) provided the following recommendations:

1. Existing CSRI should clearly provide information on the assumptions and source of climate/weather data used.

2. Weather and climate data needs to be updated on a more regular basis. The frequency of the update will depend on the type of infrastructure (based on its service life) and the type of climate events. CSRI writing organization should establish an appropriate review period for the weather and climate information used in the documents they produce.

3. CSRI should provide guidance on the type and collection frequency of climate data and information required for planning, designing, operating and maintaining water infrastructure. For example, rainfall instruments need to measure intensity in order to generate IDF curves. CSRI should also address the density (number of instruments in a certain area) for meaningful data collection.

4. The evaluation of the risks to the infrastructure requires the evaluation, in the future, of the climate-infrastructure interaction. Both the projections– and uncertainties thereof, of future climate and future infrastructure performance should be addressed in CSRI.

5. CSRI should address incremental options, over the life cycle of the infrastructure, for climate change adaptation.

6. Physical, functional and operational performance considerations should be addressed in CSRI in view of future climate and infrastructure condition.

7. Identifying the risks to infrastructure from future climate events requires engineering, operations, management, planning and climate/weather expertise. Stronger collaboration between these professions, possibly through CSRI, is essential.

8. The design – for new construction, rehabilitation or renewal of existing infrastructure, should provide flexibility for adaptation to climate change. The objective is to design resilient infrastructure (including allowing for "partial failure"), and to establish appropriate emergency response plans to reduce impacts (e.g., downtime) on the service.

9. Risk management is critical to maintaining the performance of infrastructure in light of the uncertainty in future climate. Risk management tools should be included in CSRI.

10. There is a need to share CSRI that include climate change planning developed at local or regional levels within the broad engineering community. This should also include academia.

Finally, it is important to note that most, if not all methodologies for the assessment of infrastructure vulnerability to climate change, including those presented here, fit the general ISO 31000 Risk Management principles and framework. In the medium to long-term, compliance of all these methodologies with ISO 31000 would be a desirable outcome.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

Atlantic Climate Adaptation Solutions Association, *7 Steps to Assess Climate Change Vulnerability in your Community* – website http://atlanticadaptation.ca/ accessed March 2015

Boyle J., Cunningham M. and Dekens J., *Climate Change Adaptation and Canadian Infrastructure - A review of the literature*, International Institute for Sustainable Development, November 2013

Brundtland Commission, *United Nations Report of the World Commission on Environment and Development: Our Common Future*, 1987

Canadian Infrastructure Report Card, Volume 1: 2012 Municipal Roads and Water Systems (2012)

Canadian Infrastructure Report Card - *Asset Management Primer* (2014)

Felio, G., PIEVC Case studies: Codes, standards and related instruments (CSRI) review for water infrastructure and climate change, report to Engineers Canada, October 2012, accessed at http://www.pievc.ca/e/2012_PIEVC_CSRI_Water_Report_Final%20doc.pdf

Engineers Canada, *PIEVC Engineering Protocol - Version 10 Part 1, October 2011* from http://www.pievc.ca/e/index_.cfm accessed March 2015

ICLEI Canada, *Building Adaptive and Resilient Communities*, website http://icleicanada.org/programs/adaptation accessed March 2015

Insurance Bureau of Canada (IBC), *Municipal Risk Assessment Tool (MRAT)*, website http://www.ibc.ca/on/disaster/water/municipal-risk-assessment-tool accessed March 2015

Intergovernmental Panel on Climate Change (IPCC), *Fifth Assessment Report (AR5)*, November 2014

ISO 31000:2009, *Risk management – Principles and guidelines* (2009)

ISO 55000:2014, *Asset management — Overview, principles and terminology* (2014)

McGillivray, G. *The trend to more and larger catastrophic losses in Canada*, Presentation at the June 2014 Engineers Canada workshop for policymakers at the Government of Newfoundland and Labrador, St John's NL (2014)

National Guide to Sustainable Municipal Infrastructure – *InfraGuide: Best Practice for Municipal Infrastructure Asset Management DMIP 7*, an FCM/NRCC publication (2005)

Nelitz M., Boardley S. and Smith R., *Tools for Climate Change Vulnerability Assessments for Watersheds*, report prepared for the Canadian Council of Ministers of the Environment (CCME), August 2013

UN Office for Disaster Risk Reduction, International Strategy for Disaster Risk Reduction, website http://www.unisdr.org/who-we-are/international-strategy-for-disaster-reduction accessed March 2015

US-EPA Water: Sustainable Infrastructure. Website http://water.epa.gov/infrastructure/sustain/localofficials_looks_like.cfm accessed March 2015

Appendix A - Vulnerability of Vancouver Sewerage Area Infrastructure to Climate Change (2008)[1]

Metro Vancouver used the PIEVC Protocol to assess the vulnerability of their infrastructure in the Vancouver Sewerage Area (VSA). The vulnerability assessment included all Metro Vancouver infrastructure and operations within the VSA. This catchment encompasses the City of Vancouver, the University of British Columbia (UBC) campus, UBC Endowment Lands, part of the City of Burnaby and part of the City of Richmond as shown on Figure A-1. The VSA has an approximate area of 13,000 hectares.

Figure A-1. Vancouver Sewerage Area study location map.

Years 2020 and 2050 were selected for analysis of climate change effects. At the time of the study, much of the combined sewer system that makes up the VSA dates to the 1960s or earlier. 2020 represented an early design life boundary for much of the oldest piping and appurtenances. A key operational target was Metro Vancouver's commitment to the elimination of combined sewer overflows (CSOs) in the VSA by 2050. Since the single largest impact of climate change on the VSA was expected to be increased rainfall (and therefore wastewater flow), a 2050 assessment of climate change was considered crucial for Metro Vancouver's sewer separation planning.

In 2008, the VSA was largely a combined sewer system.   Combined sewers are an older type of collection system that carry both wastewater and stormwater in the same pipe. Combined

[1] Reference: *Vulnerability of Vancouver Sewerage Area Infrastructure to Climate Change*, report to Metro Vancouver by Kerr Wood Leidal Associates Limited and Associated Engineering, May 2008. Unless otherwise indicated, the source of figures and tables is the project report.

sewers were less expensive to install and maintain when they were built, generally prior to the 1960's.

During heavy rainfall, combined sewers can overflow directly into a nearby waterway such as the Fraser River or Vancouver Harbour, producing a CSO. This overflow provides a "safety valve" that prevents back-ups of untreated wastewater into homes and businesses, flooding in city streets, or bursting underground pipes. Metro Vancouver's plan is to reduce, then eliminate, CSOs through the process of gradual conversion to a separated sewer system. Metro Vancouver committed to the elimination of CSOs by 2050 in their 2002 Liquid Waste Management Plan (LWMP). The LWMP also commits Metro Vancouver to upgrade the Iona Island Wastewater Treatment Plant (IIWWTP) to full secondary treatment no later than 2020.

The VSA is served by the IIWWTP, the second largest wastewater treatment plant in Metro Vancouver. The design peak wet-weather flow (PWWF) of the IIWWTP is 17 m^3/s. The plant provides primary treatment to wastewater from approximately 600,000 people before discharging it through a 7 km, deep-sea outfall into the Strait of Georgia. The plant opened in 1963 and has been expanded six times for growth and treatment upgrades allowing more than 200 billion litres of wastewater to be treated here in 2001.

Figure A-2. Iona Island WWTP (Photo courtesy of Metro Vancouver)

For this project, climate change modelling was performed by Ouranos (a Montreal-based climate science research consortium) using the Canadian Regional Climate Model to quantify expected changes to various climate factors. In general, all precipitation indices suggested an increase in total rainfall amount, and in the frequency and magnitude of rainfall events. In addition, modelling projected consistently increasing temperature trends at both the 2020 and 2050 horizons, implying that snowfall would decrease.

The estimated global sea level rise was 0.14 m by the 2050s and 0.26 m by the 2080s. Locally, in research conducted by Natural Resources Canada, it was reported that the Fraser River delta areas (Richmond and Delta) were sinking at a rate of 1 mm/yr to 2 mm/yr, while other areas (Vancouver, Burnaby, Surrey, Tsawwassen Heights) were uplifting at a rate of 0 mm/yr to 1 mm/yr. Therefore, for certain areas of the VSA such as Iona Island, global sea level rise would be aggravated by a sinking land surface, increasing the relative sea level rise.

Monthly average minimum and maximum temperatures were predicted to increase by 1.4°C to 2.8°C by the 2050s. A summary of climate events used in the study is outlined in Table A-1.

Table A-1. Summary of Climate events

Climate Event	Expected Change
Intense rain	Increase in 1-day maximum rainfall: 17% by 2050 *
Total annual / seasonal rain	Increase in total annual precipitation: 14% by 2050s
Sea level elevation	Increase in global sea level elevation **: 0.26m by 2080s (Ouranos) to 1.6m by 2080s (Rohling et al., 2007[2])
Storm surge	Not quantified. Likely to increase ***
Floods	Not quantified. Likely to increase
Temperature (extreme high)	Increases in monthly maximum temperature: 1.4°C to 2.8°C by 2050s
Drought	Modeling inconclusive for trend. Average maximum length of dry spell may increase by 0.25 days by 2050s
Wind (extremes, gusts)	Not quantified. Likely to increase.

Notes:
* Estimate is based on total precipitation, which is assumed to be approximately equivalent to rainfall in the VSA.
** Does not include local effects such as subsidence and atmospheric effects
*** Storm surge is a significant contributor to the extreme high water events and therefore lack of quantitative data is a critical information gap.

In general, the study noted that Vancouver rarely experiences extreme or catastrophic weather events such as ice storms, tornadoes, drought or extreme cold. Perhaps the greatest magnitude threat is flooding of the Fraser River, and many predict this risk to decline in response to climate change. A sample of the highest risks identified by the study is shown in Table A-2.

The climate factors identified as threats to infrastructure vulnerability will be evidenced as gradual changes. In fact, the greatest pressure to initiate adaptive action comes not from climate change, but from timing of planned infrastructure improvement plans such as the treatment plant upgrades and combined sewer separation program. So while climate change effects may reveal vulnerabilities, Metro Vancouver is in an ideal position to proactively mitigate and adapt to these challenges.

[2] Rohling E.J., Grant K., Hemleben Ch., Sidda M., Hoogakker B.A., Bolshaw M. and Kucera M., "High rates of sea-level rise during the last interglacial period." Nature Geoscience #16, December 2007

In regards to recommendations, the PIEVC Protocol suggests the following categories:

- Remedial engineering or operations action required
- Management action required
- Additional study or data required
- No further action required.

Table A-2. Climate effect ratings greater or equal to 36

Infrastructure Component	Climate Variable	Priority of Relationship
COLLECTION SYSTEM		
Combined sewer trunks	Intense rain	42
Combined sewer interceptors	Intense rain	42
Sanitary mains	Intense rain	42
TREATMENT (IIWWTP)		
Process		
Effluent disposal	Storm surge	36
Hydraulics		
Effluent disposal	Storm surge	36
Buildings, tankage and housed process equipment	Storm surge	36

Following are some of the conclusions and recommendations from the study.

- The key priorities in the collection system focus on increased rainfall and the associated potential increase in sewer flow, both under combined and separate sewer configurations. Accelerated separation may be necessary to achieve the target of CSO elimination by 2050. The vulnerabilities judged to be of the highest priority at the treatment plant are those associated with the effluent disposal system and the IIWWTP site itself because of the storm surge climate variable.

- While ranked as lower priorities, the potential impacts of an increase in average sea level on the IIWWTP site and associated infrastructure were considered important due to the significant uncertainty and wide range in predicted future increases in mean sea level. The study identified the need for more detailed information and analyses in the context of these potential vulnerabilities.

- The 2008 capacity of standby power available at the IIWWTP was deemed a vulnerability at the time of the study, and was anticipated to be further aggravated by changes in future climate.

- Given the age of the IIWWTP infrastructure, the project team identified the need for additional studies to consider the remaining service life of the components in the context of other potential issues (e.g. seismic). Even if climate change-related vulnerabilities were deemed to exist, they might be overshadowed by other hazards that, when resolved, could simultaneously address climate vulnerabilities.

Appendix B - City of Calgary Potable Water Collection, Treatment and Distribution System (2011)[3]

The City of Calgary, through its Water Resources and Water Services divisions, partnered with Engineers Canada to assess the potential vulnerability of its water supply infrastructure to climate change using the PIEVC Protocol.

The scope of the vulnerability and risk assessment covered the entire water supply infrastructure within the City of Calgary boundaries that is owned and operated by the city. In addition to the physical assets, the study included design processes, construction practices, operations and management of the infrastructure. The study also considered infrastructure not owned or operated by the City in the watersheds but deemed critical in terms of impacts on both the quality and quantity of water available at the intakes.

The City of Calgary has two sources of drinking water:

- The Elbow River, which is 120 kilometers long and passes through four sub-climates before it enters the Glenmore Reservoir, is the source for nearly half of the city's water supply. The Elbow valley watershed covers an area of 1,210 km2.
- The Bow River originates on the Blow Glacier north of Lake Louise and is one of the three main tributaries of the South Saskatchewan River. The Bow River watershed covers an area of 7,770 km2.

The City's water supply infrastructure includes the Bearspaw and Glenmore water treatment plants, the raw water pump stations at Glenmore (Elbow River) and Bearspaw (Bow River), and secondary pump stations and water storage reservoirs around the city. The Glenmore Water Treatment Plant, located on the Elbow River, was constructed in 1933 and expanded in 1957 and 1965. The Bearspaw Treatment Plant, located on the Bow River, was built in 1972 and expanded in 1984.

Following treatment, the potable water flows to high-lift pumps. The pumps push water through transmission mains, which transport large volumes of water to strategically located storage reservoirs and pump stations. In 2011, the city owned 4,678 kilometers of water pipe infrastructure. Additional elements of infrastructure in the water supply system included in the study are:

- Infrastructure elements in the Bow and Elbow River Watersheds
- Raw water sources (Bow River and Elbow River)
- Raw water intakes
- Storage at Glenmore Reservoir
- Water treatment plants (Bearspaw and Glenmore)
- Treated water reservoirs
- Pump stations
- Feedermain network, plus water mains critical to hydraulic conveyance

[3] Reference: *City of Calgary Water Supply Infrastructure: Climate Change Vulnerability Risk Assessment*, report to the City of Calgary by Associated Engineering, May 2011. Unless otherwise indicated, the source of figures and tables is the project report.

At the time of the study, the City was conducting system upgrades to gain sufficient capacity to meet the requirements of projected population growth up to at least 2021. Thus the study addressed the potential impacts of future climate change for the years 2020 and 2050.

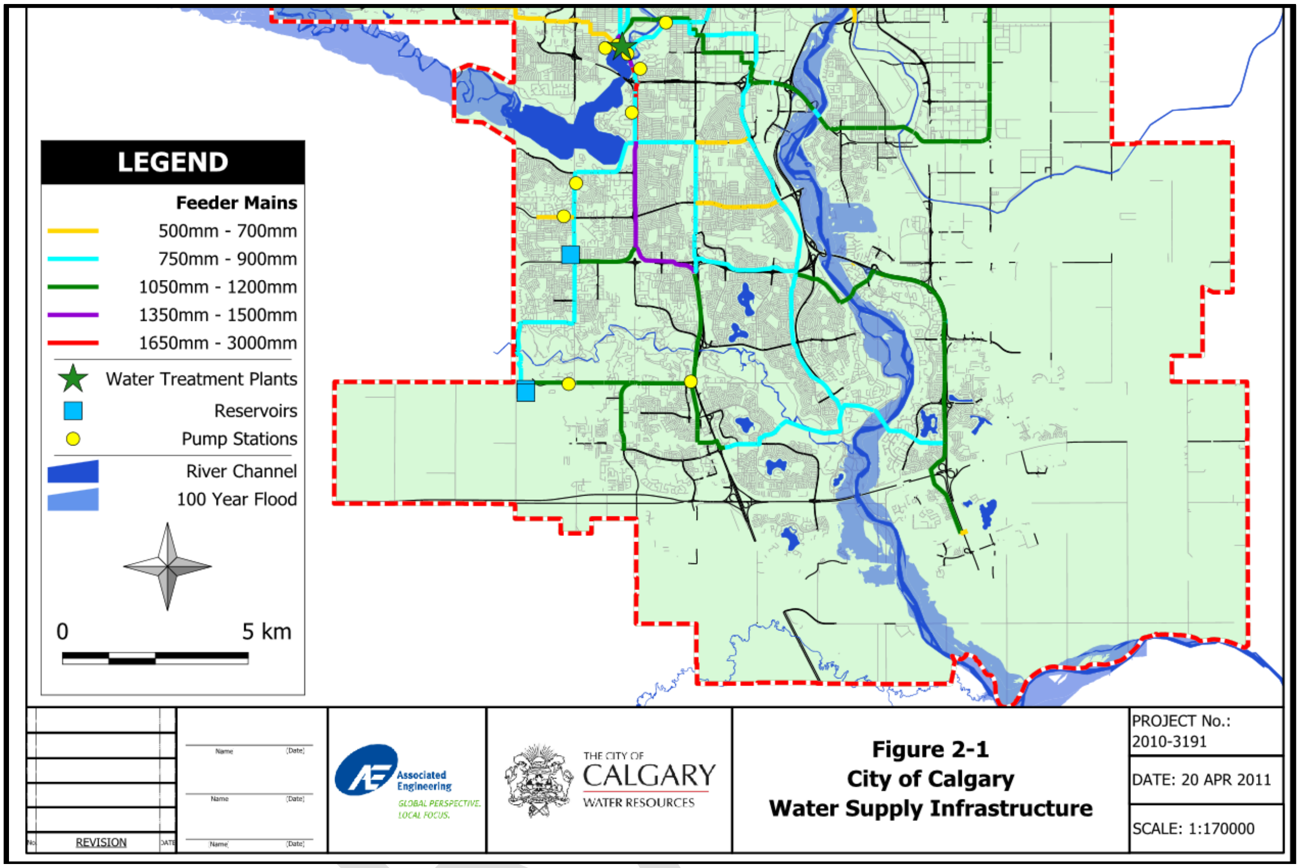

Figure B-1. Illustration of a portion of the water supply infrastructure considered in the study.

Based on available climate projections from various sources, the study identified the expected climate changes for the Calgary area and Bow and Elbow Basins, which included:

- Increased temperatures
- Decreased snowpack
- Earlier melt and earlier onset of spring freshet
- Shorter, warmer winters
- Extended drought conditions
- Changes in precipitation type
- Decreased rain in the summer
- Increased rain in the fall, winter and spring
- Increasing frequency of extreme weather events.

Table B-1 provides a list of the precipitation changes expected for the study area by 2050.

Table B-1. Summary of precipitation (and precipitation derived) Parameters Expected by the 2050s. Changes Shown are the Ranges that were Derived for Calgary Airport and the Basin.

Climate event	Expected Change by 2050
Total precipitation	Increase: year (3%), winter (28 - 31%), spring (4%) and fall (1 - 2%) Decrease: summer (3%)
Total rain and snow	Increase: rain (4%) Decrease: snow (3 - 4%)
Very wet days	Increase of 2 - 16% by 2050
Frequency of precipitation	Increase: year (1 - 4 days), winter (1 - 3 days), spring (2 days) and fall (0 - 1 days) Decrease: summer (2 days)
Frequency of rain	Increase: year (10 - 12 days), winter (3 days), spring (6 - 8 days) and fall (2 - 4 days) Decrease: summer (2 days)
Frequency of snow	Decrease: year (6 - 10 days), winter (0 - 2 days), spring (4 - 6 days) and fall (2 - 3 days)
Consecutive dry days	Increase: year (1 - 2%)
Maximum 5-day precipitation total	Increase: year (5 - 8%)
Precipitation days >10 mm/day	Increase: year (16%)
Simple Daily Intensity Index (SDII)	Increase: year (5%)
Snow depth	Decreasing: year (-2.6 to 0 cm) or up to 25%, winter (-7.4 to 0 cm) and spring (-10.5 to 0 cm)

Some of the conclusions and recommendations from the study are as follows:

- The study found that, in general, the City of Calgary was fortunate to have robust treatment processes in addition to two raw water sources and redundancy within the distribution system. Operation and management plans were in place to reduce both the probability and severity of negative climate-infrastructure interactions occurring. The climate changes identified as having a negative impact to infrastructure will be seen as gradual changes, and ongoing monitoring can identify trending of changes and be incorporated into long-range plans. The vulnerabilities judged as the highest priorities were those associated with extreme events such as flooding (as witness during the 2013 floods), drought, and compounding events.

- As climate change occurs, it is anticipated that the watersheds may change as well, in terms of the quantity of water available and its quality. Changes in temperature and precipitation may both impact the water quality and level of contaminants from forest fires, algae, increased runoff, etc. in the raw water source to the drinking water facilities.

Continued monitoring and studies to address the potential for change was recommended.

- The study noted that the Glenmore Reservoir had limited storage capacity, and limited ability to mitigate potentials for flooding. The reservoir was not designed as a flood control structure. However, as future climate projections predict a potential for increased storm events and increases in the maximum instantaneous flows for the Elbow River, the study team recommended the City should give some consideration to the functionality of the reservoir. During drought conditions The City has water conservation measures in place to reduce demands on the system.

- Recent (as of 2011) and planned upgrades to the treatment facilities provided for robust systems, with adaptive capacities to withstand many of the potential impacts of climate change. The study indicated that increased precipitation and storm events leading to a potential for decrease in water quality (increased turbidity, pathogens from runoff) were expected to be handled adequately by the upgraded pre-treatment systems.

- At the time of the study, pump stations within the distribution system had experienced increased loadings, compounded with increased temperatures, resulting in overloads and tripping of breakers. Increased operator/maintenance attention was required to install temporary fans during high heat periods. The study recommended a review of the HVAC systems of some of the older facilities with remedial actions as required.

- Though some staff had been prevented from accessing facilities in the past due to storm events, the City had reduced the risks of impacts to the water supply system, due to staff being unavailable or unable to get to the facilities through cross training programs. Supporting facilities had also experienced increased loading of the HVAC systems during high temperature periods.

  As climate change models project an increase in the extreme daily temperatures and increased heat wave durations, the study recommended consideration be given to review of HVAC design codes and an assessment of existing facilities to identify remedial actions. An increase in temperature/heat duration presents potential impacts related to HVAC systems/electrical and controls and the availability of standby generation at all facilities including the water treatment plants. For example the Glenmore Water Treatment Plant had limited operational capacity while functioning on standby power.

  A review of standby power capacity at critical facilities was recommended.

Appendix C - District of Shelburne (NS) - Vulnerability of Shelburne STP Upgrade (2011)[4]

The PIEVC Protocol was used to assess the vulnerability of the Sandy Point Sewage Treatment Plant Upgrade to the effects of climate change. The assessment was conducted in response to growing concerns about the vulnerability of public infrastructure located in coastal areas of Atlantic Canada to the expected local impacts of climate change. These potential impacts include: increasing storm frequency and intensity; rising sea levels; storm surges; coastal erosion and flooding.

This case study was the first application of the PIEVC Protocol at the pre-design stage of an infrastructure project, rather than conducting the assessment on existing assets. It is also an application to a small wastewater treatment plant in a rural community, with a view to learn about the scalability of the Protocol and to develop recommendations for how it can best be used to assess other infrastructure of a similar scale.

The Sandy Point STP was originally constructed in 1969 to provide primary wastewater treatment to a small development area that included residential, industrial and institutional development. The facility had a capacity of 30,000 USGPD and had been extensively studied since 2001 when deficiencies in treatment effectiveness were first identified. In response to previous studies and the *Canada-wide Strategy for the Management of Municipal Wastewater Effluent,* endorsed by the Canadian Council of Ministers of the Environment (CCME) in 2009, the decision was taken to replace the existing plant with a new secondary treatment facility which would both expand the capacity of the existing plant, and incorporate a more suitable and sustainable treatment technology.

Part of the study was to assess the adequacy of several potential locations for the new sewage treatment plant. Available records (topographic mapping, property mapping and aerial photography) have been reviewed in conjunction with the Atlantic Canada Wastewater Guideline Manual (ACGWM) separation distance requirements in preparation for locating the proposed STP Upgrade.

In total, three (3) sites were considered as illustrated in Figure C-1.

- Site #1 was located at the south end of the industrial park.
- Site #2 was located east of the Shelburne Industrial Park and Sandy Point Road.
- Site#3 was located east of the old boy’s school.

The initial phases of the STP Upgrade could be accommodated on all three sites without encroachment on neighbours. Future expansion at Site #1 posed some encroachment concerns on neighbours to the south. Site #1 was more susceptible to the effects of climate change (sea level rise, storm surge, erosion, etc.). Site #3 was at a slightly higher elevation than Site #2 which may have affected the sizing of the pumps, length of access road required and further extension of power. Considering the above and other factors, including future climate considerations identified by the PIEVC Protocol application, Site #2 (approximately 1km in direct line from the existing plant) was selected as the preferred option for locating the proposed STP upgrade.

[4] Reference: *Vulnerability of Sandy Point STP Upgrade to Climate Change* report to the Municipality of the District of Shelburne by ABL Environmental Consultants Limited, August 2011. Unless otherwise indicated, the source of figures and tables is the project report.

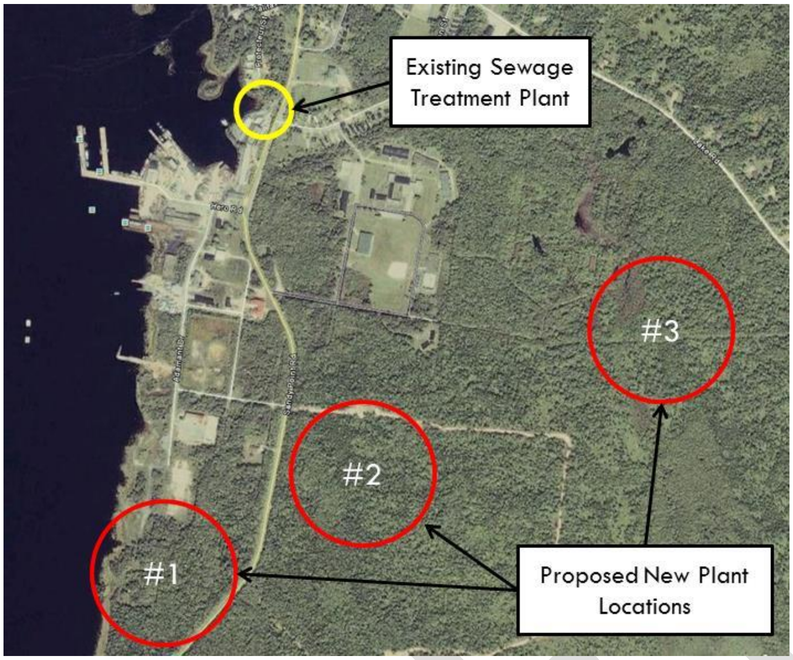

Figure C-1 Location of existing STP and proposed locations for the new plant.

Another innovation realised in this project was the use of the PIEVC Protocol in support of the selection of the technology for the sewage treatment. MDS requested the proposed STP Upgrade be designed to achieve a secondary level of treatment, which could be accomplished by a wide range of technologies available at the time of the study. However, given the design criteria, high rates of extraneous flow and the requirement for modular growth, some of the available options were quickly ruled out due to economic considerations. Based on experience of the team members, the most applicable technologies evaluated included lagoons, Sequencing Batch Reactors (SBRs) and Extended Aeration (EA) plants. The factors considered in the evaluation of alternatives included:

- Ease of operation & maintenance
- Capital & operating costs
- Impact of peak flows (I & I) on process
- Reliability (consistently meet effluent discharge limits)
- Sludge production and management
- Septage handling capability
- Susceptibility to climate impacts (PIEVC)
- Social implications (land, odour, noise)

All treatment processes investigated carried a number of common components, including as a minimum:

- Pumping station (located at existing STP)
- Screening and/or grit removal
- Flow measurement
- Maintenance (blower) building
- Disinfection
- Ocean outfall

The process resulted in the selection of a lagoon (complete with future cell) with ultraviolet treatment as the best suited to the Sandy Point system. Lagoons are typically the preferred treatment option for systems prone to peak (I & I) flows. They often cost less to construct, operate and maintain than other wastewater treatment systems; they are simple to operate/maintain and often only require part-time supervision.

In parallel with the technology and site selection process, the PIEVC Protocol was used to define the categories and components of system for assessment, which included the new treatment facility and the existing collection system. Historical climate data as well as climate change model predictions for 2020, 2050 and 2080 were also gathered with support from Environment Canada. Relevant climate parameters were identified for the region and included:

- Precipitation as rain
- Precipitation as snow
- Sea level elevation
- Wind speed
- Frost
- Fog
- Storm surge
- Ice
- Temperature

The study reports that regional trends in seasonal temperatures for Atlantic Canada show an overall warming of 0.3ºC from 1948 to 2005, with summers showing the greatest increase in temperature (+0.8ºC mean). Warming characterizes springs (+0.4ºC) and autumns (+0.1ºC), whereas winters have become colder (-1.0ºC). Daily minimum temperatures show a slight increase (+0.3ºC), but daily maximums have decreased more (-0.8ºC). Precipitation increased in Atlantic Canada by approximately 10% between 1948 and 1995 a trend that continued through the 1990's.

The projected changes in minimum and maximum temperatures and precipitations for various locations in Nova Scotia are shown in Table C-1.

The vulnerability (risk) assessment was conducted to identify interactions between infrastructure components and climatic events which could lead to vulnerability. The risk assessment included screening of the interactions by the engineering team, as well as a workshop that included participation from the Municipality of Shelburne, Environment Canada, Nova Scotia Environment, Municipality of Yarmouth, Emergency Measures Organization (Eastern Shelburne County) and ABL Environmental Consultants Ltd.

The risk assessment identified a total of eleven (11) interactions which were deemed to be high risk as shown in Table C-2.

Much of the data required for the Engineering Analysis did not exist or was difficult to obtain, but professional judgment and experience was employed where data were not available. For the thirty-five (35) components for which potential vulnerabilities were identified, the analysis resulted in twenty-one (21) remedial engineering actions and four (4) management actions being recommended. Many of the recommendations were combined and are summarized as follows:

- Reduce inflow and infiltration (I&I) into the collection system
- Install backup power supplies at the pumping stations
- Ensure the process building meets code for hurricane resistance
- Install a radio communications system at the pumping stations and process building
- Install high level pump shutoffs at the existing pumping station
- Install a bypass on the grit removal system

- Implement a policy to protect staff from hurricanes, storm surges and ice storms
- Discuss safe conditions for deliveries with septage haulage companies
- Adjust scheduling to accommodate required maintenance

Table C-1. – Annual projected climate change fields (from Lynes et al., 2009[5]) - Yarmouth data selected for the study.

	Minimum Temperature			Maximum Temperature			Precipitation Amount		
Tri-decade	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Units	ΔºC	ΔºC	ΔºC	ΔºC	ΔºC	ΔºC	%	%	%
Greenwood	1.8	2.7	4.1	1.5	2.6	4.1	7.5	7.0	4.5
Kentville	2.2	3.1	4.6	1.6	2.7	4.3	8.0	7.0	4.0
Shearwater	1.9	2.7	4.0	1.2	2.1	3.5	17.0	14.0	11.0
Yarmouth	0.8	1.3	2.0	1.0	1.6	2.3	7.0	6.0	3.0

Table C-2. Interactions with priorities greater than or equal to 36

Infrastructure Component	Climate Variable	Priority of Relationship
Admin / Operations		
Personnel	Hurricane Event	36
Conveyance System		
Existing Gravity Collection		
Sanitary MH	Heavy (Intense) Rain	42
Sanitary Gravity Mains	Heavy (Intense) Rain	42
Pipe Connection & Fittings	Heavy (Intense) Rain	42
Existing Pumping Station		
Power Supply	Hurricane Event	36
	Ice Storm Event	36
New Pumping Station		
Power Supply	Hurricane Event	36
Power Supply	Ice Storm Event	36
Treatment System		
New Treatment System		
Ocean Outfall	Sea Level Elevation	36
Process Building		
Structure	Hurricane Event	36
UV Disinfection	Sea Level Elevation	36
Power Supply	Hurricane Event	36
	Ice Storm Event	36
End Users		
End Users (Res., Ind., Inst.)	Hurricane Event	36

5 Lines, G.S., Pancura, M., Lander, C., Titus, L., *Climate Change Scenarios for Atlantic Canada Utilizing a Statistical Downscaling Model Based on Two Global Climate Models.* Environment Canada, Meteorological Service of Canada, Atlantic Region. Science Report Series No. 2009-01, January 2009.

Appendix D - City of Welland (ON) Stormwater and Wastewater Infrastructure Assessment (2012)[6]

This study included both an application of the PIEVC Protocol and an update of the City of Welland's 1963 Intensity-Duration-Frequency (IDF) rainfall data, as a co-operative initiative between the City of Welland, the Region of Niagara, PIEVC and the Ontario Ministry of Environment. The principal objective was to identify those components of the City of Welland's wastewater and surface drainage collection systems that were at risk of failure, damage and/or deterioration from extreme climatic events or significant changes to baseline climate design values. The approximate study area is shown in Figure D-1.

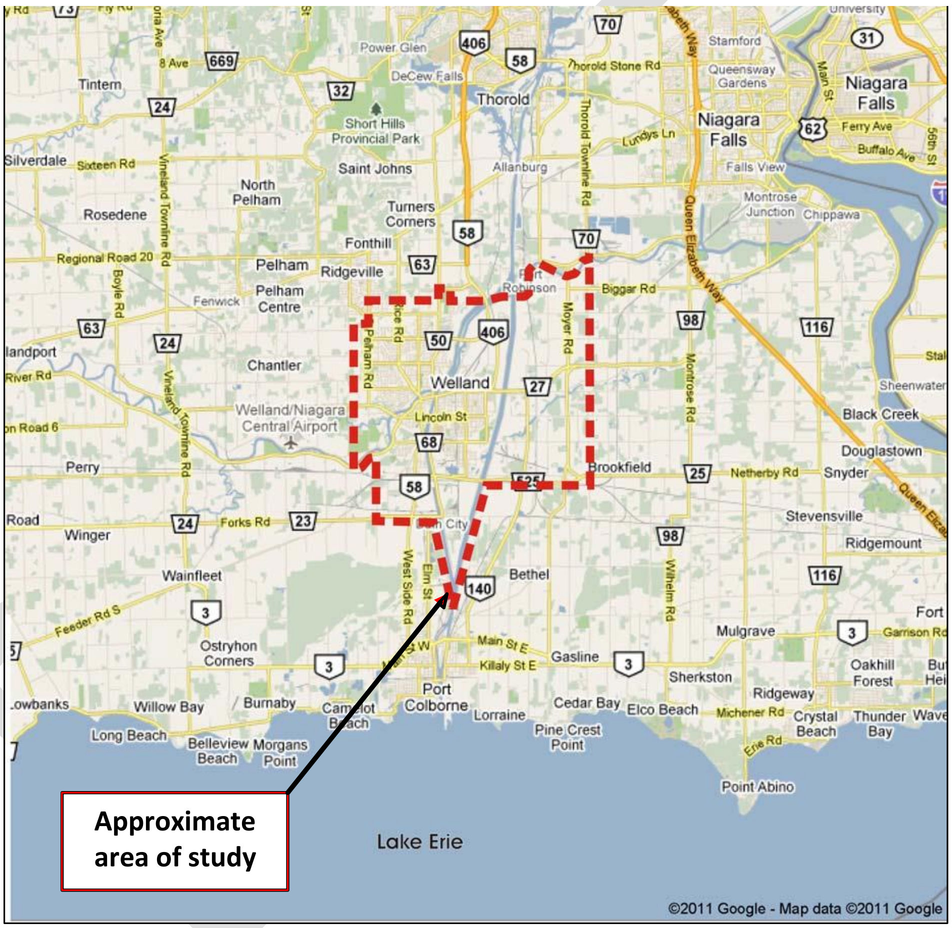

Figure D-1. Location of the City of Welland and approximate study area.

The identification of the infrastructure components considered for evaluation focused on:

- What are the infrastructure components of interest to be evaluated
- Number of physical elements and location(s)

[6] Reference: *City of Welland Stormwater and Wastewater Infrastructure* Assessment, Report to the City of Welland by AMEC Environmental and Infrastructure, February 2012. Unless otherwise indicated, the source of figures and tables is the project report.

- Other potential engineering / technical considerations
- Operations and maintenance practices and performance goals

Table D-1 presents a summary of the storm and sanitary systems information collected for the study. The existing wastewater treatment plant services Welland and the communities of Pelham, Port Robinson, and South Thorold, in addition to a number of non-residential sources. The Welland WWTP consists of a conventional activated sludge plant with effluent filtration, a parallel physical chemical treatment plant to provide treatment of storm flows, effluent disinfection by chlorination followed by de-chlorination, and biosolids stabilization in a two stage mesophilic anaerobic digestion process. Stabilized biosolids are stored on site prior to being hauled to the Region's centralized biosolids processing and storage facility at Garner Road. Treated effluent is discharged to the Welland River, a sensitive receiver tributary to the Niagara River.

Table D-1. Summary information on the storm and wastewater systems in the City of Welland

Descriptor	Storm	Sanitary/Combined
# of Pipes	1717 (Laterals) 2906 (Mains)	17161 (Laterals) 3789 (Mains)
Total Length	186 km	268 km
Maximum Size	3000 mm	2700 mm
Minimum Size	150 mm	125 mm
Average Age of Pipes	30 years	42 years (Sanitary) 66 years (Combined)
Oldest Pipes	106 years	111 years (Sanitary) 110 years (Combined)

In addition to the physical infrastructure, the following operational aspects of the subject infrastructure were considered:

- Administration/Personnel
- Power
- Transportation (primarily related to supplies delivery)
- Communications

In regards to the climate parameters considered, the following were identified:

- High/Low Temperature
- Heat & Cold Waves
- Extreme Diurnal Temperature Variability
- Lightning
- Heavy Rain
- Daily Total Rainfall
- Winter Rain
- Freezing Rain
- Ice Storm
- Snow Accumulation
- Blowing Snow/Blizzard
- Hail Storm
- Freeze Thaw Cycles
- Hurricane/Tropical Storm
- High Winds
- Tornado
- Drought/Dry Period
- Heavy Fog

Additional issues reviewed for this assessment included Lake Erie water levels, local groundwater levels and flooding of the Welland River. Some general outcomes from this assessment included:

- The number of days per year with temperatures exceeding 35^{O}C is expected, on average, to remain unchanged from historic norms through the 2020 period. However, further into the future, through 2050, significant increases of about 4 time's present occurrence are projected.
- The number of days per year with temperatures below -20^{O}C will, on average, be in steady decline through 2050.
- The occurrence of heat waves (three or more consecutive days when the maximum temperature is 32°C or higher) is projected to remain static through 2020 but marginally increase through 2050.
- Days per year experiencing a freeze/thaw cycle (a maximum daily temperature above 0°C and a minimum temperature below 0°C) are in decline.
- Rainfall is expected to increase. This includes postulated increases in the occurrence of winter rain events and increases in the severity of individual rain events.
- An almost doubling of the occurrence of drought/dry periods (defined as 10 or more consecutive days without measurable precipitation) is projected through 2020.

The second objective of this study was the update the City of Welland's 1960's vintage Intensity Duration Frequency (IDF) rainfall curves. This objective was extended to also include development of future IDF data for the project time periods (2020 and 2050). The review of a compendium of past, present and future IDF data would establish appropriate direction for re-definition of rainfall design standards for the City of Welland.

A comparison between the 1963 City of Welland and 2000 Environment Canada IDF data for Port Colborne weather station and the projected future IDF data (for 2020 and 2050) show that (Table D-2) future period maximum IDF values are consistently greater than the corresponding 1963 values with some increases greater than 20%. The comparison of future IDF values with the 2000 Environment Canada IDF data for Port Colborne weather station shows consistent increases for all durations across all scenarios with maximum increases (as much as 54%) associated with shorter duration events.

The following are examples of recommendations made as an outcome of the PIEVC risk assessment of City of Welland infrastructure coupled with the development of current and projected IDF relationships for the Environment Canada weather stations at Port Colborne:

- Projected increases in rainfall could increase the flow, velocities, and head loss in siphons, which has the potential to cause backups in the collection system, resulting in additional volumes of CSO's. An assessment of siphon capacity requirements under projected rainfall conditions should be completed.

- The loss of electricity supply to the pumping stations was identified as a potential impact of severe weather. The City needs to ensure adequate backup power and/or emergency plans for the pumping stations.

- Snow accumulation can be an issue in conjunction with winter rains in regard to performance of, stormwater management facilities and the major overland stormwater conveyance system. The expectation is that even though projected snow accumulation events are decreasing, having significant snow accumulated on the ground, coupled with a winter rain event could have serious results. The potential impact of winter rain coupled with snow accumulation in SWM facilities should be assessed.

In regards to the IDF curves, the study recommended:

- The City of Welland municipal standards outline the design of storm sewers based on IDF curves (Rainfall Intensity Duration Frequency curves). Prior to this study, the City of Welland had used a 1963 based IDF relationship for storm sewer design. The study recommended that the implications (as related to performance and life cycle costing) of the application of the current Environment Canada (i.e., 2000) or the projected (i.e., 2020 and 2050) IDF relationships, developed for this risk assessment, be evaluated to determine long-term applicability for the storm sewer collection system design, operation and maintenance.

- At the time of the study, the City of Welland infrastructure design standards directed the use of the 2 year return period rainfall design event for design of storm sewers in the municipality. The project team recommended that the implications of a change in this design standard to a 5 year or a 10 year design rainfall event should be evaluated in the context of current sewer infrastructure capital plans, performance metrics and long-term sewer objectives.

Table D-2. Comparison of projected rainfall intensities to 2000 values

Duration	2020			2050		
	average	**90^{th} percentile**	**maximum**	**average**	**90^{th} percentile**	**maximum**
5 minute	112%	122%	144%	117%	130%	154%
10 minute	110%	119%	139%	114%	126%	148%
15 minute	111%	118%	137%	114%	125%	146%
30 minute	110%	119%	137%	113%	126%	141%
1 hour	110%	119%	139%	114%	128%	143%
2 hour	110%	120%	139%	114%	128%	143%
6 hour	110%	123%	145%	116%	129%	150%
12 hour	103%	113%	134%	106%	120%	136%
24 hour	110%	118%	138%	110%	124%	142%

Appendix E - City of Nelson (BC) Stormwater Infrastructure Assessment (2014)[7]

Incorporated in 1897, Nelson has a population of 10,230 (2014) and a trading area of over 60,000 people. Within its municipal boundaries, the City's total area is 913.6 ha (2257.53 acres, or 7.2 km^2). It is located in the Southern Interior of British Columbia in a region called the West Kootenay. Nelson is in the Central Kootenay Regional District, one of 27 Regional Districts in the Province of BC and is most closely bordered by RDCK Areas E & F. The regional districts and municipalities function as a partnership to provide and co-ordinate services in both urban and rural areas.

The City of Nelson (BC) recognized the possibility of vulnerabilities to climate change and extreme weather in their stormwater infrastructure and adopted the PIEVC Protocol to identify risks and propose adaptation solutions. The application of the Protocol was limited to specific locations within the City that had exhibited vulnerability in recent high intensity precipitation events and one residential neighbourhood with a history of flooding. The goal of the study was to provide decision-makers with adequate information form stormwater infrastructure upgrades. City of Nelson engineering and public works staff provided specific catch basins location information that historically had been overloaded during intense summer rains. The majority of the infrastructure assessed was located in the downtown area, with one neighbourhood area in Rosemont.

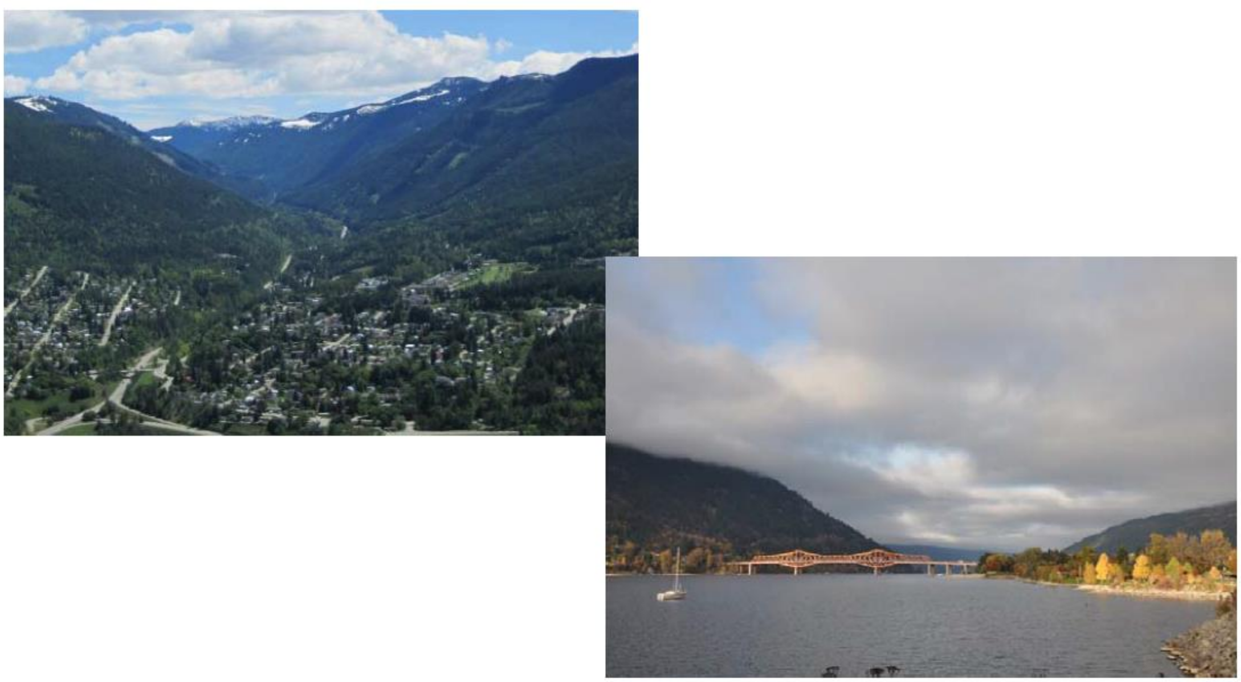

Figure E-1. Photos showing the geography of the City of Nelson

The stormwater management system of the City of Nelson comprises natural drainage channels that transition into a piped network with outlets on Kootenay Lake. The City has two classifications of drainage systems:

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[7] Reference: *City of Nelson Stormwater Infrastructure Assessment*, report prepared for the City of Nelson by Focus Corporation, February 2014. Unless otherwise indicated, the source of figures and tables is the project report.

- Minor system
  Pipes, gutters, catch basins, driveway culverts, open channels, watercourses and stormwater management facilities design to carry flows with a (historical) return period of 1 in 10 years.

- Major system
  Surface flood paths, roadways, roadway culverts, swales, watercourses and stormwater management facilities designed to carry flows with a (historical) return period of 1 in 100 years.

The climate parameters considered in this study was limited to the following:

- Increased intensity of individual storms
- Increase in frequency of high intensity storms
- Seasonal shifts in high intensity storms
- Change in number of ground penetrating frost days

Figure E-2 below illustrates the rainfall of the July 17 2012 storm recorded at one of the weather stations and the impacts on the stormwater infrastructure of that area of town.

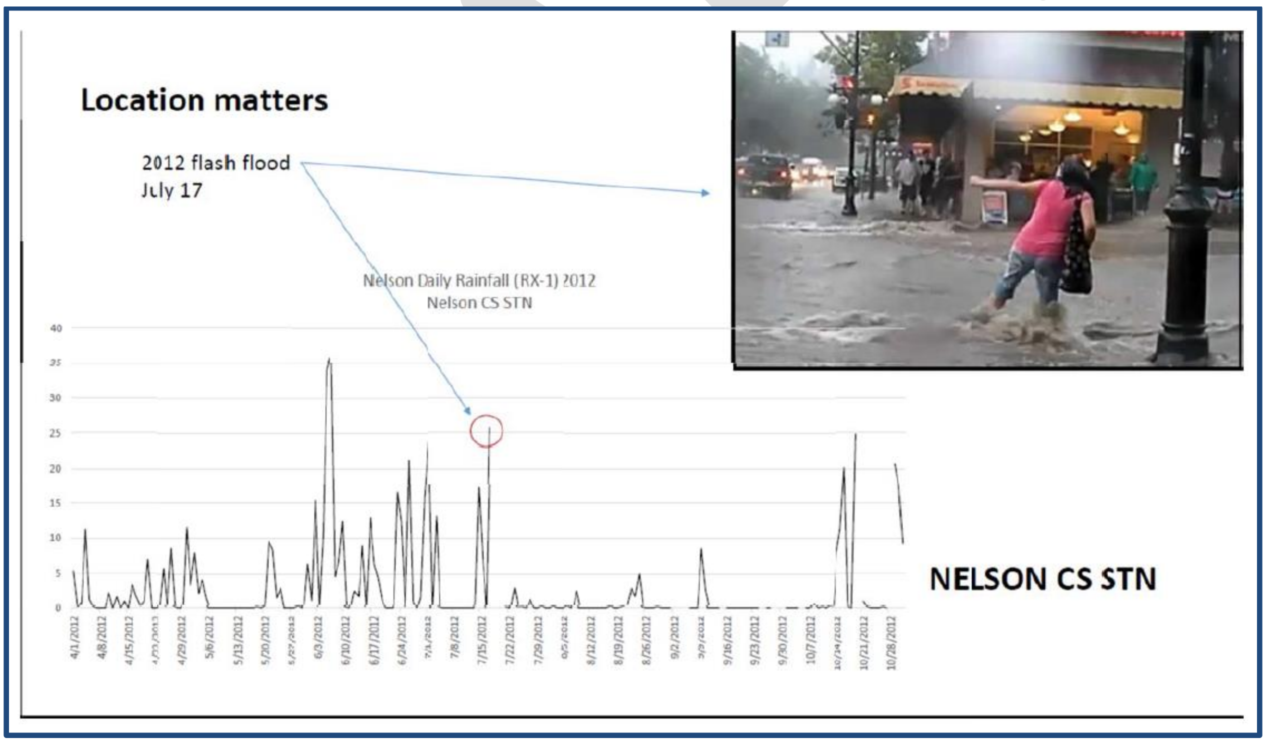

Figure E-2. Precipitation profile for the high intensity rain storm causing flooding at Ward and baker streets on July 17, 2012

The time horizon for the study was 2050. As in most applications of the PIEVC protocol, current (in this project 2013) vulnerabilities are established as the baseline for future risks.

Future climate predictions were made using Pacific Climate Impacts Consortium's (PCIC) Plan2Adapt, a regional climate change tool based on global climate models using projections for

1961-1990 baseline data. The median change in precipitations projections for the Central Kootenay Region (10th and 90th percentiles in brackets) were as follows:

- Annual: +5% (+2% to +12%)
- Summer: -8% (-8% to + 6%)
- Winter: + 7% (-2% to +15%)

The above predictions translate into the following trends that can impact the performance and integrity of the infrastructure:

- Extreme precipitation for one-day and three-hour events (return periods of 5, 10 and 25 years) are projected to increase by a frequency of 2 to 3 times at most locations;
- Mean annual precipitation is projected to increase, except for summers when precipitations is projected to decrease;
- Late spring frosts and ground penetrating frost days can be expected to decrease due to temperature increases; and
- High intensity precipitation is projected to increase.

The PIEVC Protocol directs the practitioner to confirm the infrastructure owner's risk tolerance thresholds prior to conducting the risk assessment. The Protocol suggests High, Medium and Low risk thresholds. Table X outlines the risk thresholds used for this risk assessment.

Table D-1. Risk tolerance thresholds

Risk Range	Threshold	Response
< 12	Low Risk	• No immediate action necessary
12 – 36	Medium Risk	• Action may be required • Engineering analysis may be required
> 36	High Risk	• Immediate action required

The results of the risk assessment showed that flooding due to extreme precipitation events compounded by high lake levels already (in 2014) stressed certain areas of the City's stormwater management system, affecting people and infrastructure. Increased frequency in storm intensity was identified as the main climate parameter of concern. The application of the PIEVC Protocol provided a risk ranking of the five locations studied and therefore allowed to City to prioritize its interventions and investments. These recommendations included:

- Increase the capacity of the catch basins
- Prioritize effective maintenance practices
- Continue to collect and record local weather station data
- Install local weather stations at different elevations/locations within the City
- Update storm hyetograph tables/IDF curves based on climate change data
- Financing of stormwater operations, maintenance and renewal
- Engage property owners to develop effective flood mitigation measures
- Coordination with the BC Ministry of Transportation and Infrastructure (MoTI) and the Canadian pacific Railway (CPR) to develop flood mitigation options
- Explore opportunities for upstream flow diversion in the Wasson Street neighbourhood.