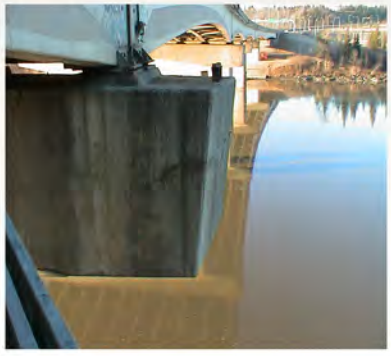

Adapting to Climate Change

Canada's First National Engineering Vulnerability Assessment

of

Public Infrastructure

April 2008

Appendix C
Literature Reviews

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Appendix C

Literature Reviews

Appendix C.1

Water Resources Literature Review

Engineering Literature Review: Water Resources - Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change

Prepared for:

Canadian Council of Professional Engineers

Public Infrastructure Engineering Vulnerability Committee (PIEVC)

Prepared by:

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February 2008

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EXECUTIVE SUMMARY

This report provides a summary of the findings from the literature review, directed at identifying engineering literature that relates to water resources and associated infrastructure vulnerabilities in light of climate change. The review was conducted over the period December 2007 – February 2008. Although many Canadian water related agencies are thinking about the potential vulnerabilities and associated engineering impacts, very few have completed any formal analysis at this time.

Review methodology included broad internet search, followed with the scan of engineering peer reviewed publications and ended with direct communication with various engineering professionals from public, private, and academic sectors including. During the review limited input has been obtained from the some members of the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Water Resources Expert Working Group (RASEWG) group. This report summarizes the information that was located. Although climate change and it's impact on water resources and associated infrastructure is judged to be of high significance for Canada, available information on engineering impacts is limited to non-existent.

This report is divided in five sections. The first section provides a brief introduction. In the second section a summary of ***issues*** related to climate change and water infrastructure are provided. The third section of the report provides ***selected examples*** of specific impacts of climate change on water resources in Canada that are documented in the literature. It is evident that the current publications do not provide comprehensive review of potential impacts of climate change on water resources, nor equitable regional coverage. Section four of the report presents the findings of the ***literature review*** conducted during this study. In the fifth section a summary of issues identified in the literature review is provided together with the discussion and a set of recommendations based on the personal professional experience of the author. Appendices to the report provide bibliography of references and samples of search communications.

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1. INTRODUCTION

The global impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level and precipitation variability (Kundzewicz et al, 2007). More than one-sixth of the world's population live in glacier- or snowmelt-fed river basins and will be affected by the seasonal shift in streamflow, an increase in the ratio of winter to annual flows, and possibly the reduction in low flows caused by decreased glacier extent or snow water storage. Sea-level rise will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas. Increased precipitation intensity and variability is projected to increase the risks of flooding and drought in many areas. Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, water system reliability and operating costs. These pollutants include sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt, and thermal pollution.

Climate change affects the function and operation of existing water infrastructure as well as water management practices. Functioning of the existing facilities that are not design to accommodate climate change impacts (different temperature, precipitation and flow patterns for example) may increase chances of infrastructure failure, insufficient supply, inadequate protection from floods and unacceptable water quality conditions. Water management practices under climate change will need to address: (a) the different needs for operating storage facilities; (b) temporal and spatial water allocation patterns; and (c) change in operating municipal, industrial and agricultural water supply infrastructure. Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change, and urbanization. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate change are likely (Kundzewicz et al, 2007). Current water management practices are inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems. Incorporation of current climate variability into water-related management is required to make adaptation to future climate change easier.

Adaptation procedures and risk management practices for the water sector are slowly being developed in Canada. It has been determined that the negative impacts of climate change on freshwater systems outweigh its benefits. In the fourth IPCC Assessment Report (IPCC, 2007) North American Region (including Canada) shows an overall net negative impact of climate change on water resources and freshwater ecosystems. Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources. The beneficial impacts of increased annual runoff in other areas will be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risks.

This report reviews the engineering literature in professional Journals on climate change impacts, vulnerability and design considerations for water resources infrastructure in

Canada. It also provides findings from direct communications with a number of institutions that may have internal documentation on climate change impacts and engineering adaptation strategies.

In the second section a summary of ***issues*** related to climate change and water infrastructure are provided. The third section of the report provides ***selected examples*** of specific impacts of climate change on water resources in Canada that are documented in the literature. It is evident that the current publications do not provide comprehensive review of potential impacts of climate change on water resources, nor equitable regional coverage. Section four of the report presents the findings of the ***literature review*** conducted during this study. In the fifth section a summary of issues identified in the literature review is provided together with the discussion based on the personal professional experience of the author. Appendices to the report provide bibliography of references and samples of search communications.

2. WATER INFRASTRUCTURE AND CLIMATE CHANGE

In general, there are very few examples of engineering reports, both in Canada and elsewhere which discuss climate change impacts on water infrastructure and specifically how they can be addressed in engineering design, construction, operation and maintenance. This section provides *more insight* into the link between the climate change impacts and water resources infrastructure. In the following Section a selected set of *illustrative examples* are presented. Both sections provide a background for the literature review that follows in Section 4 of the report.

2.1 Water diversions

The use or allocation of water in eastern Canada is governed by the law of riparian rights - those who own property adjoining lakes or streams are allowed to use their waters, as long as they do not interfere with the rights of other riparians. In the western provinces, because of water scarcity the allocation is governed by prior appropriation - licensing of water uses by the Crown on a first-in-time, first-in-right basis; and apportionment - the negotiated division of transboundary river flows between or among jurisdictions.

The existing allocation mechanisms did demonstrate over time many dificiencis that will be exaggerated with further change of climatic conditions. Early water uses, like agriculture, which consume large volumes of water, leaves little or nothing for later, especially urban and instream, uses. Existing licensees have no incentive to conserve water that could benefit other uses. Some streams have even been licensed beyond what is available in flow. Inevitably, this system leads to regional water shortages, and to engineering investigations to import from more distant unappropriated water sources. These issues have become especially controversial in southern Alberta where water shortages are common and competition is increasing.

Infrastructure needs for water diversions will increase with further deepening of existing, and formation of new conflicts. Dams and diversions normally go together: water is stored behind a dam, then withdrawn from its natural course for transfer elsewhere in the same or to another drainage basin. Pressure for more water transfers over larger distances will increase with time. Water transfer schemes between the drainage basins will become

a necessity and additional storage facilities (reservoirs) will be required together with the diversion structures to carry water from far a way sources to the users. So, one of the direct climate change impacts on the water diversions will be the need for capital investment in new infrastructure.

2.2 Dams and reservoirs

In Canada dams have been constructed to reduce risks associated with flood hazards, to harness energy for industry and commerce, and to help secure a reliable source of water for domestic, industrial and/or agricultural use. Dams are also structures that transform river ecosystems over a range of spatial and temporal scales. The Canadian Dam Association (CDA: http://www.cda.ca) assessed in the year 2000 that Canada had 849 large dams (≥10 m in height) in operation or under construction (Canadian Dam Association, 2003). The majority (70%) of large dams in Canada were constructed solely for hydroelectric production. Canada also has ten of the world's largest 40 dams as measured by gross reservoir capacity. The storage capacity of the 849 largest reservoirs is sufficient to hold the equivalent of two years' runoff from all of Canada, or approximately one quarter the volume of the five Great Lakes. Although storage of water in reservoirs increases evaporation, the total effect cannot be estimated because information about reservoir areas and water depths is lacking. Greatest losses occur in shallow reservoirs and where dams have been constructed in hydro-climatic zones characterized by naturally high rates of lake evaporation, such as Lake Diefenbaker in the central Prairies.

Most of the assessments of climate change impacts on dams and reservoirs are focusing on questions of long term water supply, and variability of supply, erosion impacts and water quality upstream and downstream (Manitoba Hydro and Quebec Hydro, personal communications). However, dam and reservoir infrastructure issues are related to the prediction of floods from extreme precipitation as it relates to dam safety. Government of Ontario (Ministry of Environment Ontario, personal communications) is in the process of revising the methodology for developing Dam Safety Management Plans. Additional issues raised by the climate change include the application of design codes and standards; risk assessment and risk management as it relates to engineering design, public safety, economic impacts, serviceability, environmental impacts, etc. Process of reservoir operations will be affected too and will include implementation of contingency planning principles and best practices to prevent dam infrastructure failures and the use of climate scenario planning as it relates to engineering decisions.

2.3 Extremes: droughts and floods

Droughts

Droughts present a serious national threat to Canada. Large-area droughts have major impacts on a wide range of water-sensitive sectors including agriculture, industry, municipalities, recreation, and aquatic ecosystems. They often stress water supplies by depleting soil moisture reserves, reducing streamflows, lowering lake and reservoir levels, and diminishing groundwater supplies. This in turn affects several economic activities: for example, decreased agricultural production, less hydroelectric power generation, and increased marine transportation costs. During the past two centuries, at

least 40 long duration droughts have occurred in western Canada (Environment Canada, 2004). In southern regions of Alberta, Saskatchewan, and Manitoba, multi-year droughts were observed in the 1890s, 1930s, and 1980s. Droughts in eastern Canada are usually shorter, smaller in area, less frequent, and less intense; nonetheless, some major droughts have occurred during the 20th century. In 1963/64 in southern Ontario, for instance, several wells ran dry, necessitating shipping of water from other areas. Great Lakes' water levels also fell to extreme lows with major losses incurred by the shipping industry. Droughts in the Atlantic Provinces occur even less frequently, but reduced occurrence results in lower adaptive capacity, making the region more susceptible to drought impacts.

Adaptation involves adjusting to climate change, variability, and extremes to avoid or alleviate negative impacts and benefit from opportunities. Canadians have a great deal of experience in adapting to droughts. The adaptation strategies vary by sector and location. Adaptive drought measures include soil and water conservation, improved irrigation, and construction of infrastructure, including wells, pipelines, dugouts and reservoirs, and exploration of groundwater supplies. Better management responses may be made with improved drought and drought impacts monitoring and advanced prediction.

Floods

Flooding in Canada is primarily but not exclusively caused by hydro-meteorological conditions, which can occur in the form of excess snowmelt-runoff, rain, rain on snow, ice-jams, or natural dams. Anthropogenic causes of flooding include changes in drainage patterns resulting from urbanization and flooding due to dam-breaks. Over the last century, flood damages in Canada have exceeded $2 billion with over 198 lives lost. The recent devastating floods on the Saguenay River during the summer of 1996 and the Red River in the spring of 1997 have brought the reality of natural hazards home to Canadians. The Saguenay flood occurred due to an unprecedented precipitation event over a 24-hour period and resulted in more than $1 billion in damages and loss of 10 lives. The "flood of the century" in southern Manitoba was caused by a combination of hydro-meteorological factors, beginning with high antecedent soil moisture, heavy winter snowfall, and a rapid spring melt. Although there was no direct loss of life, damages (including flood-fighting costs) were estimated at $500 million in Canada and over $2 billion in total (IJC, 2000).

As encroachment into the natural floodplain has increased with population growth, so has the damage caused by flooding. Structural measures such as dams, dykes and diversions have been engineered to mitigate flood risks, giving residents a sometimes false sense of security. Non-structural approaches to reducing flood damages, including floodplain regulation and flood forecasting, are being combined with structural options to provide an integrated mitigation strategy for reducing damages. Structural approaches to flood mitigation usually include multi-purpose structures such as large dams. Design of these structures requires analysis of potential large flows for adequate spillage and dam safety requirements. The Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) are criteria commonly used in design and safety analysis and will need revision to include the impact of climate change. Any engineered flood control structure such as a dam, diversion or dyke must not only be designed appropriately, but must also be operated and maintained effectively.

2.4 Municipal water supply

This topic is addressed with another literature review and will not be treated here in details. However, the impacts of climate change on water supply and treatment infrastructure are so significant that the following potential needs are included in this review too.

Water distribution systems

Ability to address the climate change impacts on water distribution systems requires development of a better knowledge of demand variation, peak and base uses. From the infrastructure point of view it is needed to undertake an inventory of the condition/capacity of the existing distribution and treatment systems and develop financial approaches ensuring a timely replacement of the ageing water supply infrastructure.

Water treatment systems

The most important consequence of climate change on water treatment systems is additional demand for the development and implementation of new processes for reclamation and/or recycling of wastewater, greywater, rainwater, stormwater and process waters.

Municipal water supply sources

To insure the safe supply of water under the changing climatic conditions one of the most important tasks is the development and implementation of integrated water management plans to ensure the protection of drinking water sources.

2.5 Hydropower

Canada is the world leader of hydroelectricity production, followed by the United States and Brazil. Installed generating capacity totaled 67,121 megawatts (MW) in 2002. A high electrical energy production rate of 59% was achievable due to the use of large reservoirs. About half of the Canadian provinces are responsible for the majority of hydroelectric energy production in Canada, with Quebec being a market leader. The largest producers are provincially-owned electric utilities such as: Hydro-Quebec; BC Hydro; Manitoba Hydro; Ontario Power Generation; and Newfoundland and Labrador Hydro. These utilities have developed a series of large-scale hydro sites across the country. One of the largest hydroelectric development in the world is La Grande complex on the Quebec side of James Bay. It has a capacity of over 15,000 Megawatts. Some of the other large-scale hydro sites in Canada include: Churchill Falls station in Labrador; Manicouagan-Outardes complex on the Quebec North Shore; Sir Adam Beck station on the Niagara River in Ontario; Nelson River development in Manitoba; Gordon Shrum station in Northern British Columbia; and Columbia River complex in the southern part of British Columbia.

Climate change impacts on hydropower sector are multiple and the main issues are (personal communications with Hydro Quebec and Manitoba Hydro, 2008): *Infrastructure Priority Impacts*

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Energy Infrastructure - Generation

Highest - The expected local impact of climate change on long term water supply, and variability of supply, as it relates to hydroelectric dams.

Other - Approaches for the prediction of floods from extreme precipitation as it relates to hydroelectric dam safety.
- The effect of climate change on the magnitude of peak energy demand.
- The effect of climate change on the timing and seasonality of peak energy demand.
- The implications of a change in the energy supply mix if hydroelectric capacity is reduced because of changes to dam water supply.

Energy Infrastructure - Transmission

Highest - The impact of climate change on localized climatic loads, particularly ice and wind, as it relates to transmission wires and transmission towers.

Other - Adaptations for transmission system components that are sensitive to higher temperatures.
- Expectations for changes in system demands, particularly due to increasing summer heat, and its effect on transmission system design.

General Engineering

- Using climate change models and climate change model experts to integrate modeling into design at the local project level.
- The application of design codes and standards, and the adaptation of codes and standards, in the face of climate change impacts.
- Potential opportunities for adaptive infrastructure that can be modified as conditions change.
- Concepts, options, and technology for reducing greenhouse gas emissions

Non-technical and Broader Priority Impacts

High - Risk assessment and risk management as it relates to engineering decisions about the effects of climate change on public infrastructure, including public safety risks, economic risks, serviceability risks, environmental risks, etc.

High - The financial elements of infrastructure decision making that are necessary to properly support infrastructure decision-makers.

Other - Understanding and coping with the lack of clear cut solutions to engineering problems and seeing solutions more as a range of possibilities.
- The science behind climate change and the broad impacts of climate change on the physical environment.
- The legal and ethical responsibilities for engineers concerning climate change and the implications to negligence and due diligence if climate change is ignored in engineering decisions.
- Contingency planning principles and best practices for engineers relating to infrastructure failures.

- Implementing climate change infrastructure solutions as part of a multidiscipline, multifunction, integrated plan.
- The principles of scenario planning as it relates to engineering decisions.
- Frameworks for looking at climate change and infrastructure issues to ensure problems are framed optimally.
- The financial and social implications of different infrastructure adaptation decisions on business and the public.
- The relationship of climate change to the principles of sustainability.
- The effect of changes to supply routes, like shorter ice road seasons and longer shipping seasons, on Northern communities.
- Barriers to acceptance of available technology solutions for reducing greenhouse gas emissions
- The effect on public health of climate change and the role of engineering infrastructure decisions on public health.

2.6 Industrial water supply

Water is important to the manufacturing process. Without water to use in processing, to serve in cooling, condensing and steam generation, and to convey waste material, industry would be unable to function; consequently, manufacturers in Canada use large quantities of water resource. In terms of total withdrawals, thermal power generation dominates, extracting some 28,750 million cubic metres (MCM) per year in 1996—the last year for which national estimates are available (Environment Canada, 2004). Canadian manufacturing industries are next, withdrawing just over 6000 MCM/year in 1996.

Little research and literature exist on effects of climate change on industry and consequences for water use. Higher temperatures imply greater cooling requirements at industrial plants, and, accordingly, increased water demands, particularly during the summer season. Predicting impacts on this sector is extremely difficult because climate change itself will alter the demand for some products, which changes the water needs of the individual manufacturer. What is known is that climate change will affect both the supply and demand for water. Industries located in water-short regions face periodic, largely seasonal constraints on their water supplies. In the short term, this may translate into reduced production although there is widespread evidence that industries adapt to water shortages quickly through technological substitution, such as adoption of water recirculation and other measures aimed toward conservation. In Canada, industry groups and governments at all levels have fostered water conservation typically through pollution prevention programs. In summary, although the thermal power generation and manufacturing sectors withdraw large amounts of freshwater in Canada, they consume (water that is not returned to its original source) relatively less than other sectors. Large industrial withdrawals from small rivers and streams are likely to be the greatest immediate threat to water availability. Consequences on water related infrastructure are not investigated.

2.7 Irrigation and drainage

Irrigation

Agriculture accounts for 3% of Canada's gross domestic product, making it one of the largest sectors in the country. Approximately 7% of Canada's land base is used for agriculture, amounting to 67.5 million ha. Prairie Provinces account for 82% of this total, while Ontario and Quebec contribute only 13%. Although agriculture is not Canada's largest user of water, it is the largest net consumer - agriculture consumes 71% of the water it diverts. About 85% of agricultural withdrawals (surface and ground water) are used for irrigation (primarily in the West) and 15% is used for watering livestock (Environment Canada, 2004). Much of the water required for irrigation throughout the growing season must be captured during spring snowmelt and stored behind dams or in reservoirs for later use. This storage promotes significant evaporative losses throughout the year. In addition, the diverted water that is ultimately used in crop production results in gaseous losses through evapotranspiration, which will generally exceed those losses found under natural vegetation cover. Alberta has approximately 630,000 ha of irrigated land, or about 60% of the total irrigated cropland in Canada. In the South Saskatchewan River basin of Alberta, irrigation consumes about 2.2 billion m^3 of water each year from the river system, equivalent to 28% of the total annual river flow. As a result of increased water demands from all sectors, some Alberta watersheds are near or at full allocation and under water diversion moratoriums. The majority of irrigation in Canada is through sprinkler systems. This type of irrigation has significantly less impact on surface hydrology than traditional flood irrigation. Flood irrigation often results in surface water losses of up to 50%. The present focus is to improve irrigation effectiveness through higher efficiency irrigation systems, improved water management, scheduling irrigation to meet crop water demands, suppression in evaporation losses and production of higher value crops.

One of the major infrastructure related consequence of climate change is an increasing demand for more dams, reservoirs, and diversions to meet increased demand for irrigation. Many watersheds in Canada now have their water resources fully allocated and greater irrigation efficiencies will be required if irrigation acreage is to expand, while maintaining acceptable streamflows for other uses.

Drainage

The beneficial effects of land drainage for crop production are well understood. Surface drainage systems include shallow ditches designed to drain surface depressions in fields, and deeper ditches designed to intercept overland flow and seepage, and to prevent water from re-entering agricultural land. Such systems eventually drain into natural waterways.

Under the climate change, surface drainage systems may increase runoff, which may be of poor quality and contain high quantities of nutrients, agri-chemicals and sediment. Awareness is increasing as to the potential impact that drainage systems have on soil moisture relationships, and on both surface and ground water volumes and quality. Drainage system design will increasingly take these factors into account. Other infrastructure impacts are not investigated.

2.8 Navigation

Inland water navigation in Canada is mostly focusing on the St. Lawrence waterway as one of the world's greatest inland water navigation systems. The main route canals of Canada are those of the St. Lawrence River and the Great Lakes. The others are subsidiary canals: Welland Canal; Soo Locks; Trent-Severn Waterway; and Rideau Canal. In spite of the very detailed action plan (available on line, last accessed Feb 10, 2008 - http://www.slv2000.qc.ca/plan_action/phase3/navigation/SND/synthese_a.htm) the St. Lawrence navigation system is not documenting any issues related to climate change.

However, navigation in general will require iimproved water level forecasting and daily predictions to address the problems of low water levels that may occur under changing conditions. Fluctuating lake levels creates uncertain conditions for the navigation sector in terms of cargo transport. Reduced water levels in the St. Lawrence - Great Lakes can translate into millions of dollars of lost cargo carrying capacity. Information is equally needed on cost benefit analysis of different adaptations - dredging or redesigning ships. If some ports are deemed inaccessible due to climate change, the environmental impacts of alternative modes of transport (such as rail, freight, etc.) should be evaluated in terms of their climate change impacts. Safety issues are of concern to the industry with the potential for more extreme events, ice storms, storm surges, etc., therefore the relationships among extreme events, navigation and safety issues in terms of emergency preparedness must be thoroughly examined.

2.9 Coastal water issues

By the end of this century, the global mean sea-level rise could amount to 0.09 to 0.88 metres (IPCC, 2007). In Canada, where the total coastline exceeds 203,000 kilometres, sea level rise is a significant issue. Two major regions of high sensitivity are identified: Atlantic Canada (much of the coasts of Nova Scotia, Prince Edward Island, and New Brunswick); and parts of the Beaufort Sea coast. Small areas of high sensitivity occur in Quebec, Newfoundland and Labrador, and British Columbia (NRCAN, 2008 - http://atlas.nrcan.gc.ca/site/english/maps/climatechange).

Climate change impacts the coastal zone primarily through changes in water levels. Other impacts on the coastal zone would result from changes in wave patterns, storm surges, and the duration and thickness of seasonal ice cover. As sea level rises, storm surges will inflict greater damage on communities located close to the level of the ocean. A reminder of this was the flooding of Charlottetown, Prince Edward Island by a storm surge in January 2000. Other communities at risk include Placentia in Newfoundland and Labrador, and even downtown Halifax. The lowlands at the head of the Bay of Fundy are also at risk from storm surges. This area was devastated in the great storm surge of 1869, the so-called 'Saxby Tide'. With accelerated sea-level rise, the dykes will be breached by some of the high tides by the middle of the century.

The other large area of high sensitivity is the Beaufort Sea, where some of the most rapid coastal erosion rates in Canada are found. The problem is exacerbated by the thawing of permafrost in beach sediments. Storm surges commonly cause flooding in this region.

Settlements such as Tuktoyaktuk will undoubtedly experience further difficulties in the coming years. An additional concern in this region is that the extent and duration of sea ice will be reduced as the climate warms, thus allowing storms to flood and erode the coast more frequently. Note that coastal erosion is restricted to summer months, and cannot occur in winter when the ocean is frozen.

The main adaptation strategies to climate change will be similar to existing strategies used to deal with past changes in water level - protect (attempt to prevent the sea from impacting the land), accommodate (adjust human activities and/or infrastructure to accommodate sea level changes) and retreat (do not attempt to protect the land from the sea). Adaptation plans would generally involve a combination of these strategies. Some specific adaptation strategies recommended for sensitive regions of Canada include dune rehabilitation in Prince Edward Island, extending and upgrading the dyke system in the Fraser Delta, and adjusting shoreline management plans and polices in the Great Lakes region (NRCAN, 2004).

Rising sea level on the coasts will have potential consequences for causeways, bridges, marine facilities and municipal infrastructure. No documented initiatives are available in the literature.

3. SELECTED IMPACTS OF CLIMATE CHANGE ON CANADIAN WATER RESOURCES

This section of the report provides a selected (documented) summary of the impacts of climate change on the Canadian water resources. There are many impacts that are not documented and therefore are not included in this selected summary. Terms of reference for the literature search did not require identification of these impacts. However, it is the opinion of the author that the insights in general climate change impacts on water resources will provide better understanding of how the water resources infrastructure may be affected and what is the required scope for infrastructure adaptation.

3.1 Selected documented current impacts

In Canada, warming from 1900 to 2003 led to a decrease in total precipitation (Figure 1) as snowfall in the west and Prairies (Vincent and Mekis, 2006). Since 1950 for example, stream discharge in Columbia river basin has decreased, at the same time annual evapotranspiration (ET) increased by 55 mm (Walter et al., 2004). Fernandes at al., (2007) conducted assessment of annual trends in actual evapotranspiration (AET) at 101 locations across Canada. Increases in annual AET, of up to 0.73% yr^{-1}, were identified at 81 locations, and decreases, of up to 0.25% yr^{-1}, were found at the remaining 20 stations. Statistically significant increasing trends were detected in 35% of the locations with the majority corresponding to Atlantic and Pacific coastal regions. Increasing trends were generally related to increasing temperature and total downwelling surface radiation trends in eastern Canada and increasing temperature, surface radiation, and precipitation trends in western Canada. AET trends in the prairie climate zone were mixed in terms of increases and decreases. In regions with winter snow, warming has shifted the magnitude and timing of hydrologic events. Whitfield and Cannon (2000) and Zhang et al. (2001) reported earlier spring runoff across Canada. Summer (May to August) flows of the

Athabasca River have declined 20% since 1958 (Schindler and Donahue, 2006). Break up of river and lake ice across North America has advanced by 0.2 to 12.9 days over the last 100 years (Magnuson et al., 2000). Vulnerability to extended drought is increasing across North America as population growth and economic development create more demands from agricultural, municipal and industrial uses, resulting in frequent over-allocation of water resources (Alberta Environment, 2002; Morehouse et al., 2002; Postel and Richter, 2003; Pulwarty et al., 2005). Although drought has been more frequent and intense in the western part of Canada, the east is not immune from droughts and reductions in water supply, changes in water quality and ecosystem function, and challenges in allocation (Dupigny- Giroux, 2001; Bonsal et al., 2004; Wheaton et al., 2005).

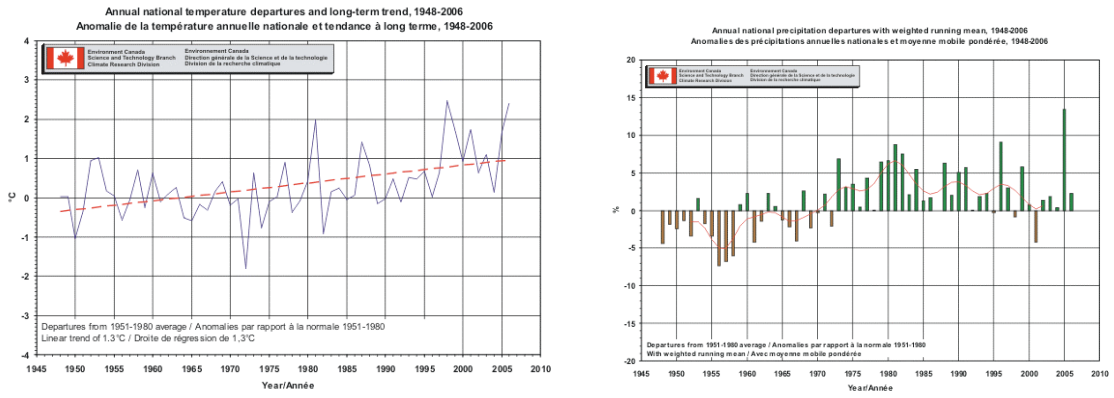

Figure 1. Annual national (a) temperature and (b) precipitation departures and long term trends, 1948-2006 (source Environment Canada, 2006)

3.2 Selected documented future impacts

Freshwater resources will be affected by climate change across Canada, but the nature of the vulnerabilities varies from region to region (Field et al, 2007). In many regions of Canada, surface and/or groundwater resources are intensively used for often competing agricultural, municipal, industrial and ecological needs, increasing potential vulnerability to future changes in timing and availability of water.

Surface water

Simulated annual water yield in basins varies by region, General Circulation Model (GCM) or Regional Climate Model (RCM) scenario, and the resolution of the climate model. Higher evaporation related to warming tends to offset the effects of more precipitation, while magnifying the effects of less precipitation. Warming, and changes in the form, timing and amount of precipitation, will lead to earlier melting and significant reductions in snowpack in the western mountains by the middle of the 21st century (Field et al, 2007). In projections for mountain snowmelt-dominated watersheds, snowmelt runoff advances, winter and early spring flows increase (raising flooding potential), and summer flows decrease substantially. Over-allocated water systems of the western Canada, such as the Columbia River, that rely on capturing snowmelt runoff, will be especially vulnerable (see section 2.3). Lower water levels in the Great Lakes are likely to influence many sectors, with multi-dimensional, interacting impacts shown in Figure 2.

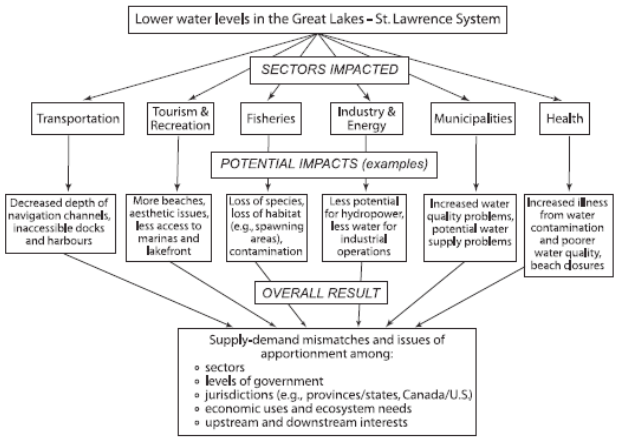

Figure 2. Interconnected impacts of lower water levels in the Great Lakes - St Lawrence system (after Lemmen and Warren, 2004).

Many, but not all, assessments project lower net basin supplies and water levels for the Great Lakes – St. Lawrence Basin (Mortsch et al., 2000; Quinn and Lofgren, 2000; Lofgren et al., 2002; Croley, 2003; Kutzbach et al., 2005). Adapting infrastructure and dredging to cope with altered water levels would entail a range of costs (Schwartz et al., 2004b). Adaptations sufficient to maintain commercial navigation on the St. Lawrence River could range from minimal adjustments to costly, extensive structural changes (St. Lawrence River-Lake Ontario Plan of Study Team, 1999; D'Arcy et al., 2005). There have been controversies in the Great Lakes region over diversions of water, particularly at Chicago, to address water quality, navigation, water demand and drought mitigation outside the region. Climate change will exacerbate these issues and create new challenges for bi-national cooperation (Koshida et al., 2005).

Groundwater

With climate change, availability of groundwater is likely to be influenced by withdrawals (reflecting development, demand and availability of other sources) and recharge (determined by temperature, timing and amount of precipitation, and surface water interactions) (Field et al., 2007). Simulated annual groundwater base flows and aquifer levels respond to temperature, precipitation and pumping – decreasing in scenarios that are drier or have higher pumping and increasing in a wetter scenario. In some cases there are base flow shifts - increasing in winter and decreasing in spring and early summer. For aquifers in alluvial valleys of south-central British Columbia, temperature and precipitation scenarios have less impact on groundwater recharge and levels than do projected changes in river stage (Allen et al., 2004).

Water quality

Simulated future surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries throughout NorthAmerica consistently increase from 2 to 7°C (based on various climate change scenarios) (Filed et al, 2007). Warming is likely to extend and intensify summer thermal stratification, contributing to oxygen depletion. Climate change is going to make it more difficult to achieve existing water quality goals. Restoration of

beneficial uses (e.g., to address habitat loss, eutrophication, beach closures) under the Great Lakes Water Quality agreement will likely be vulnerable to declines in water levels, warmer water temperatures, and more intense precipitation (Mortsch et al., 2003). Based on simulations, phosphorus remediation targets for the Bay of Quinte (Lake Ontario) and surrounding watershed could be compromised as 3 to 4°C warmer water temperatures contribute to 77 to 98% increases in summer phosphorus concentrations in the bay. Decreases in snow cover and more winter rain on bare soil are likely to lengthen the erosion season and enhance erosion, increasing the potential for water quality impacts in agricultural areas.

3.3 Examples

The following set of examples are selected as illustrative of climate change impacts on Canadian water resources.

Climate change and management of the Columbia River system

Current management of water in the Columbia River basin involves balancing complex and competing, demands for hydropower, navigation, flood control, irrigation, municipal uses, and maintenance of several populations of threatened and endangered species (e.g., salmon). Current and projected needs for these uses over-commit existing supplies. Water management in the basin operates in a complex institutional setting, involving two sovereign nations of Canada and the USA (Columbia River Treaty, ratified in 1964), aboriginal populations with defined treaty rights, and numerous federal, state, provincial and local government agencies. Pollution (mainly non-point source) is an important issue in many tributaries. The first-in-time first-in-right provisions of western water law in the U.S. portion of the basin complicate management and reduce water available to junior water users. Complexities extend to different jurisdictional responsibilities when flows are high and when they are low, or when protected species are in tributaries, the main stem or ocean.

With climate change, projected annual Columbia River flow changes relatively little, but seasonal flows shift significantly toward larger winter and spring flows and smaller summer and autumn flows. These changes in flows will coincide with increased water demand from regional growth. Loss of water availability in summer would exacerbate conflicts, already apparent in low-flow years, over water. Climate change is also projected to impact urban water supplies within the basin. Long-lead climate forecasts are increasingly considered in the management of the river but in a limited way. Each of 43 sub-basins of the system has its own sub-basin management plan for fish and wildlife, none of which comprehensively addresses reduced summertime flows under climate change.

The challenges of managing water in the Columbia River basin will expand with climate change due to changes in snowpack and seasonal flows. The ability of managers to meet operating goals (reliability) will drop substantially under climate change. Reliability losses are projected to reach 25% by the end of the 21st century and interact with operational rule requirements. For example, ‘fishfirst’ rules would reduce firm power reliability by 10% under present climate and 17% under changed climate. Adaptive

measures have the potential to moderate the impact of the decrease in April snowpack, but lead to 10 to 20% losses of firm hydropower and lower than current summer flows for fish. Integration of climate change adaptation into regional planning processes is in the early stages of development.

Costs of climate change in Okanagan

The Okanagan region in British Columbia, is a semi-arid watershed of 8,200 km^2 area. The region's water resources will be unable to support an increase in demand due to projected climate change and population growth, so a broad portfolio of adaptive measures will be needed. Irrigation accounts for 78% of the total basin licensed water allocation. Figure 3 illustrates, from a suite of six GCM scenarios, the worst-case and least-impact scenario changes in annual water supply and crop water demand for Trout Creek compared with a drought supply threshold of 30 million m^3/yr and observed maximum demand of 10 million m^3/yr (Neilsen et al., 2004).

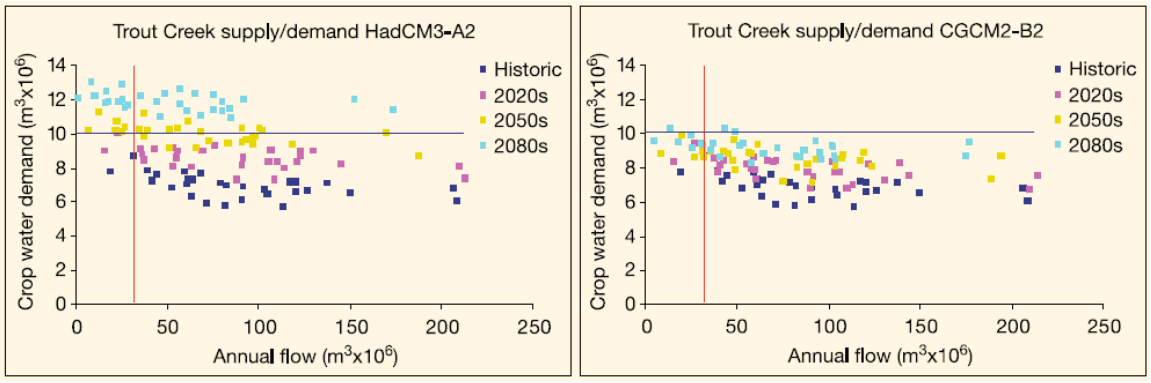

Figure 3. Annual crop water demand and water supply for Trout Creek, Okanagan region, Canada, modelled for 1961 to 1990 (historic) and three 30-year time slices in the future. Each dot represents one year. Drought supply threshold is represented by the vertical line, maximum observed demand is shown as the horizontal line (after Neilsen et al., 2004).

For flows below the drought threshold, local water authorities currently restrict water use. High-risk outcomes are defined as years in which water supply is below the drought threshold and water demand above the demand threshold.

Table 1. Relative costs per unit of water saved or supplied in the Okanagan region, British Columbia (after Hrasko and McNeill, 2006).

Adaptation option	Application	Relative unit cost	Water saved or supplied in % of the current supply
Irrigation scheduling	Large holdings to small holdings	1.0 to 1.7	10%
Public education	Large and medium communities	1.7	10%
Storage	Low to high cost	1.2 to 3.0	Limited (most sites already developed)
Lake pumping	Low (no balancing reservoirs) to high cost (with balancing reservoirs)	1.3 to 5.4	0 to 100%
Trickle irrigation	High to medium demand areas	3.0 to 3.3	30%
Leak detection	Average cost	3.1	10 to 15%
Metering	Low to high cost	3.8 to 5.4	20 to 30%

For all six scenarios, demand is expected to increase and supply is projected to decline. Table 1 illustrates the range of costs of adaptive measures currently available in the region, that could either decrease water demand or increase water supply. These costs are expressed by comparison with the least-cost option, irrigation scheduling on large holdings, which is equivalent to US$0.35/$m^3$ (at 2006 prices) of supplied water. The most expensive options per unit of water saved or stored are metering and lake pumping to higher elevations. However, water treatment requirements will lead to additional costs for new supply options (Hrasko and McNeill, 2006). No single option is expected to be sufficient on its own.

Climate change and management of floods in the Red River basin

Situated in the geographic center of North America, the Red River originates in Minnesota and flows north (one of the eight rivers in the world that do so). The Red River basin covers 116,500 km^2, of which nearly 103,600 km^2 are in the United States. The basin is remarkably flat. When the conditions are right and the river floods, nothing holds it back. During major floods, the entire valley becomes the floodplain. The 1950 flood on the Red River prompted the construction of the Red River Floodway (completed in 1966), the Portage Diversion (completed in 1970), and the Shellmouth Reservoir (completed in 1972) as a complex flood protection system for the City of Winnipeg. All the decisions regarding the capacity of flood control works were based primarily on economic efficiency, getting the largest return for the investment. Existing facilities effectively protected the city from the floods in last decades, but uncertainty still exists about their ability to protect the city from floods under future climate change.

An original modeling framework for assessment of climate variation and change impacts on the performance of complex flood protection system has been developed for the Red River basin, Manitoba by Simonovic (2001) and Simonovic and Li (2003). Modeling framework allows for evaluation of different climate change scenarios generated by the global climate models. Temperature and precipitation are used as the main factors affecting flood flow generation. System dynamics modeling approach proved to be of great value in the development of system performance assessment model.

The use of three different GCMs results in different patterns of temperature and precipitation in the Red River basin. Considerable research is still required to bring GCMs to the level of being of real value in predicting future hydrological conditions on the watershed scale. Despite the differences between the models and the scenarios, the application of DYHAM revealed with consensus that the annual precipitation and annual streamflow volume in the Red River basin will increase under future climate change scenarios. Flood starting time and peak time will also shift earlier. The results of this study indicate that the capacity of the existing Red River flood protection system is sufficient to accommodate future climate variability and change if the low-reliability criteria shown in Table 2 are used. In the case of application of the high-reliability criteria, future increase of flood protection capacity is warranted. Current expansion of the Red River Floodway follows the latter recommendation.

Table 2. Flood Protection System Reliability—ECHAM4 and CGCM1 Models (after Simonovic and Li, 2003)

	ECHAM4 S1			CGCM1 S2		
River and location	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Assiniboine River						
Shellmouth Reservoir	0.7972	0.9861	0.9754	0.7014	0.9836	0.9599
Channel capacity	0.8000	0.9944	0.9774	0.7479	0.9945	0.9650
Russell	0.8000	0.9917	0.9776	0.7507	0.9945	0.9653
St. Lazare	0.8000	0.9944	0.9774	0.7479	0.9945	0.9650
Miniota	0.9417	0.9806	0.9982	0.9151	0.9918	0.9938
Griswold	0.9417	0.9806	0.9982	0.9151	0.9918	0.9938
Brandon	0.9472	0.9917	0.9984	0.9178	0.9781	0.9944
Holland	0.9472	0.9889	0.9984	0.9205	0.9753	0.9944
Portage	0.9694	0.9806	0.9989	0.9205	0.9863	0.9951
Red River						
Ste. Agathe	0.8889	0.9944	0.9949	0.8795	0.9945	0.9865
Winnipeg	—	—	1.0000	—	—	1.0000

Increased risk of flooding in the Upper Thames watershed

One of the most significant anticipated consequences of global climate change is the increased frequency of hydrologic extremes. Predictions of climate change impacts on the regime of hydrologic extremes have traditionally been conducted using a top-down approach. The top-down approach involves a high degree of uncertainty associated with global circulation model (GCM) outputs and the choice of downscaling technique. Cunderlik and Simonovic (2007) introduced an inverse approach to the modelling of hydrologic risk and vulnerability to changing climatic conditions. With a focus targeted at end-users, the approach first identifies critical hydrologic exposures that may lead to local failures of existing water resources systems. A hydrologic model is used to transform inversely the main hydrologic exposures, such as floods and droughts, into corresponding meteorological conditions. The frequency of critical meteorological situations is investigated under present and future climatic scenarios by means of a generic weather generator. The weather generator, linked with GCMs at the last step of the proposed methodology, allows the creation of an ensemble of different scenarios, as well as an easy updating, when new and improved GCM outputs become available.

The upper Thames River basin (UTRB) is located in southwestern Ontario, Canada. The UTRB has a drainage area of 3450 km2 and outlets to the Lower Thames Valley segment of the Thames River, which is a tributary to Lake St Clair. The population of the UTRB is 460 000. The main urban centre in the UTRB is the city of London, which was designated a growth centre in the province of Ontario. Other urban centres in the UTRB have also expanded boundaries significantly in recent years. Much of the present urban growth either is centred along the Thames River corridors or is expanding along tributaries, vulnerable both from a flood perspective and also increasingly from an ecologic perspective (Nirupama and Simonovic, 2007). Floods and droughts represent the main hydrologic hazards in the UTRB. Snowmelt is the major floodproducing factor in the UTRB, generating flood events most frequently in March. Intensive flood-producing storms are most frequent in August (Cunderlik and Simonovic, 2007). Three main reservoirs in the UTRB, i.e. Fanshawe, Wildwood, and Pittock, assist in flood management efforts.

The results show that the critical rainfall events may occur less frequently than they do under present conditions under the increased temperature scenario (named dry) and more frequently than they occur under present conditions under the increased precipitation scenario (named wet). The increased precipitation scenario is identified as the critical scenario for the assessment of risks associated with the occurrence of floods in the basin (Figure 4).

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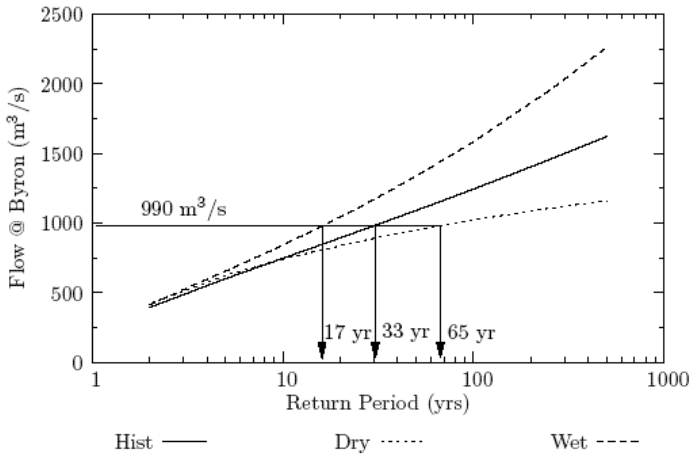

Figure 4. Probability of critical rainfall events for different climate change scenarios (after Prodanovic and Simonovic, 2007)

The outcomes of the study are being translated into new hazard mitigation guidelines and vulnerability reduction strategies for improved flood prevention and robust water management under changing climatic conditions (Prodanovic and Simonovic, 2007).

4. LITERATURE REVIEW

In terms of climate change adaptation, water resources are frequently cited as one of the highest priority issues in Canada. Water infrastructure is perhaps the most vulnerable of all types of infrastructure to climate change, and the importance of water to human health, the economy and the environment also make it one of the most critical types of infrastructure. This type of infrastructure has the potential to suffer the greatest damages or losses associated with climate change unless proactive adaptation actions are taken. The impacts of climate change on water infrastructure could result in a numerous problems, presented in Section 2 of the report, such as increased water demand, water apportionment issues, loss of potable water, increased water quality problems, increased risk of flooding, sewer overflows, and dam failures among others.

The vulnerability of water resources infrastructure to climate change and the potential impacts that new engineering requirements, codes and standards will have on climate change vulnerability are largely unknown. The engineering community in Canada is beginning to work on climate change adaptation options for water resources infrastructure and very few agencies have completed any formal analysis at this time.

4.1 The review methodology

A generic web search yields over several hundred thousand hits. It is observed that there is only a very small fraction of the literature related to the water resources infrastructure vulnerability focusing on the engineering issues related to climate change.

The second step of the literature search involved the review of engineering technical journals. Since this review follows the PIEVC study completed in 2005, only a very few additional publications has been identified.

The third step of the review included direct communications with various institutions across the country in search for internal documentation on climate change impacts water resources infrastructure and engineering adaptation strategies for mitigating potential impacts. In this step, the government websites of all ten provinces (Alberta; British Columbia; Manitoba; New Brunswick; Newfoundland and Labrador; Nova Scotia; Ontario; Prince Edward Island; Québec and Saskatchewan) and ten largest Canadian cities based on population as per Canada 2006 census (Toronto, Montreal, Vancouver, Ottawa, Calgary, Edmonton, Québec City, Winnipeg, Hamilton and London) were reviewed for publications and reports, including engineering consultant reports. A priority in the review was given to the water and environment departments. A direct communication has been established with these departments in search for internal documentation (communication details are in the Appendix B of this report). The following three sections summarize the results of the review.

Due to the major limitations in available documentation it was impossible to organize the literature review (a) according to different impacts on water resources infrastructure, or (b) according to regional issues. Presentation of the available literature is organized in the following sections according to literature review methodology steps.

4.2 A generic search

A generic web search for “climate change + infrastructure vulnerability + water resources + Canada” and similar combinations of related words yields over several hundred thousand hits. Although selected words are appearing in various reports and documents across Canada, available detailed information on engineering impacts was limited to non-existent. The relevant findings are briefed below.

Natural Resources Canada

The Earth Sciences Sector (ESS) of Natural Resources Canada has listed the priorities during 2006 to 2009 that improve the life quality of Canadians. One of the national initiatives managed by ESS on behalf of the Government is “Climate Change Impacts and Adaptation Program” (online – last accessed on January 2, 2008 - **http://adaptation.nrcan.gc.ca/index_e.php**). A report on Climate Change Impacts and Adaptation: A Canadian Perspective (Water Resources) briefs the future changes in climate projected by most global climate models and the problems that are most likely to arise where the resource is already under stress. The extreme events, like droughts and floods, are projected to become more frequent and of greater magnitude in many parts of the country. A relatively high degree of uncertainty will likely always exist regarding projections of climate and hydrological change at the local management scale. Focus must therefore be placed on climate change in the context of water engineering risk management and vulnerability assessment. The complex interactions between the numerous factors that influence water supply and demand, as well as the many activities dependent upon water resources, highlight the need for integrative approach that will

involve all relevant stakeholders in the development of appropriate and sustainable adaptation strategies.

Infrastructure Canada
The research study by Infrastructure Canada (2007) entitled "Adapting Infrastructure to Climate Change in Canada's Cities and Communities: A Literature Review" (available online – last accessed on January 2, 2008 - **http://www.infrastructure.gc.ca/research-recherche/result/studies-rapports/rs14_e.shtml**) suggests the following inferences:

- Adaptation measures for water infrastructure are controversial because of the uncertainties surrounding climate change impacts and the significant environmental, economic and social costs associated with building new infrastructure. Many experts recommend avoiding or postponing the construction of large-scale water infrastructure until there is greater certainty regarding the magnitude of expected hydrological changes.
- The vulnerability approach, which is based on the concepts of vulnerability and adaptive capacity, is the best method for determining and choosing adaptation options. This approach is used and promoted by Natural Resources Canada and many international organizations. There isn't a good understanding of the vulnerability of different types of infrastructure, nor do we know what potential impacts new engineering requirements and codes and standards will have on climate change vulnerability.
- It is for sure that the infrastructure design must change and engineers need new and updated climatic design values, revised codes and standards, and new methodologies to incorporate potential climate changes into engineering procedures.
- The federal role in areas such as monitoring and reporting is essential. There is a need for more communication (information sharing and training) between climate change researchers, policy makers, engineers, architects, operators or asset managers in order to mainstream climate change adaptation into design, maintenance and restoration of infrastructure.

The Infrastructure Canada research study (2007) finds that much of the literature on water infrastructure adaptation stresses the importance of implementing "no-regrets" measures. A "no-regrets" climate change adaptation provides benefits to the community whether anticipated climate changes materialize or not (examples include water conservation and demand management measures, education and awareness to change attitudes about climate change, long-term planning and preparedness for droughts and severe flooding, enhanced water quality protection, renewal of water monitoring efforts, and improved procedures for equitable allocation of water).

However, in addition to "no-regrets" measures, there are opportunities for direct incorporation of climate change into infrastructure planning processes. One example is the Ontario Government's *Clean Water Act, 2006.* The Act requires municipalities, conservation authorities and other local stakeholders to develop source protection plans at the watershed scale. Source protection plans involve, among other things, the development of a water budget, which requires a water manager to answer questions such

as: How much water is available within this watershed, and how much is being used? **(**for example see: Conservation Ontario, 2006; **)** Including climate change considerations into these practices would mainstream climate change into water management, and, consequently, water infrastructure planning, in Ontario (de Loe and Berg, 2006).

Canadian Standards Association

Study by the Canadian Standards Association – CSA – (Girard and Mortimer, 2006) investigates the role of standards in Adapting Canada's Infrastructure to the Impacts of Climate Change. Study findings include:

1. A more comprehensive understanding and overall mapping of the codes and regulatory landscape for infrastructure would be helpful.
2. Opportunities for enhanced adaptation and capacity building are created as standards are reviewed and updated. A multitude of CSA infrastructure standards have review cycles of between two and five years. This enables new research, technology and practices to be incorporated into mainstream practice on a continual basis. The cross-functional, multi-disciplinary and balanced nature of the CSA technical committee system provides effective and accessible forums for tackling complex issues.
3. Further evaluation of the needs related to the development of new national standards could enhance adaptive capacity-building. Examples of high priority issues already identified are, storm-water management, rehabilitation of existing infrastructure systems, and acute vulnerabilities in Northern infrastructure and coastal regions. National standards do not presently exist in these areas.
4. Climatic load data that is referenced and/or used by codes and standards is critical to infrastructure designers and operators. As climate continues to change, predictive models with sufficient detail and resolution to be useful at the local community level are required. Presently, the climatic loads used by designers are sometimes based on historical data that is no longer representative of future conditions. This is of great concern to infrastructure designers since many infrastructure works are intended for extremely long service life – up to 100 years in some cases. Canada's infrastructure designers rely on a strong climatic observation network, its coordination across jurisdictions and world-class analytical expertise. Access to high quality, reliable climatic load data is an essential element of designing resilient infrastructure.
5. Canada's codes and standards network is omnipresent and influential. However, awareness of the implications of climate change impacts and adaptation varies amongst its stakeholders. Implementation of coordinated outreach efforts will help to ensure that the full potential of the codes and standards network is harnessed toward improving the resilience of Canada's infrastructure.

The Canadian Climate Impacts and Adaptation Research Network

The Canadian Climate Impacts and Adaptation Research Network (C-CIARN) emphasizes the need to adapt to climate change as well as to mitigate emissions of greenhouse gases. The C-CIARN was created to foster scooperation between stakeholder and researchers, to identify the potential impacts of climate change and to increase stakeholder participation in the development of adaptation strategies. The network

promotes new climate change research techniques and methodologies, disseminates information on impacts and adaptation, and determines knowledge gaps in the adaptation community that need addressing. Very limited effort of the network is aimed towards the engineering issues in adaptation to climate change. Funding for the network has been cancelled since July of 2007.

4.3 A review of publications in the professional engineering journals

This section summarizes a very limited literature related to the potential impacts of climate change on the water resources infrastructure published in the professional engineering journals.

Qin *et. al*. (2008) developed an MCDM expert system MAEAC (MCDM-based expert system for adaptation analysis under changing climate) to tackle the interrelationships between the climate change and the adaptation policies in terms of water resources management in the Georgia Basin, Canada. MAEAC was developed based on system configuration, knowledge acquisition, survey analysis and MCDM-based policy analysis. A number of processes that were vulnerable to climate change were examined and pre-screened through extensive literature review, expert consultation and statistical analysis. Adaptation policies to impacts of temperature increase, precipitation-pattern variation and sea-level rise were comprehensively explicated and incorporated within the developed system. The MAEAC could be used for both acquiring knowledge of climate-change impacts on water resources in the Georgia Basin and supporting formulation of the relevant adaptation policies. It can also be applied to other watersheds to facilitate assessment of climate-change impacts on socio-economic and environmental sectors, as well as formulation of relevant adaptation policies.

Jyrkama and Sykes (2007) presented a methodology that can be used to characterize both the temporal and spatial effect of climate change on groundwater recharge. The method, based on the hydrologic model HELP3, can be used to estimate potential groundwater recharge at the regional scale with high spatial and temporal resolution. In this study, the method is used to simulate the past conditions, with 40 years of actual weather data, and future changes in the hydrologic cycle of the Grand River watershed. The impact of climate change is modeled by perturbing the model input parameters using predicted changes in the regions climate. The results of the study indicate that the overall rate of groundwater recharge is predicted to increase as a result of climate change. The higher intensity and frequency of precipitation will also contribute significantly to surface runoff, while global warming may result in increased evapotranspiration rates. Warmer winter temperatures will reduce the extent of ground frost and shift the spring melt from spring toward winter, allowing more water to infiltrate into the ground. While many previous climate change impact studies have focused on the temporal changes in groundwater recharge, results suggest that the impacts can also have high spatial variability.

Cunderlik and Simonovic (2007) explored an inverse approach to the modeling of hydrologic risk and vulnerability to changing climatic conditions. With a focus targeted at end-users, the proposed approach first identifies critical hydrologic exposures that may

lead to local failures of existing water resources systems. A hydrologic model is used to transform inversely the main hydrologic exposures, such as floods and droughts, into corresponding meteorological conditions. The frequency of critical meteorological situations is investigated under present and future climatic scenarios by means of a generic weather generator. The weather generator, linked with GCMs at the last step of the proposed methodology, allows the creation of an ensemble of different scenarios, as well as an easy updating, when new and improved GCM outputs become available. The technique has been applied to the Upper Thames River in Ontario, Canada. The results show significant changes in the frequency of hydro-climatic extremes under future climate scenarios in the study area.

Prodanovic and Simonovic (2007a) present the application of the inverse approach in the study of high and low flows due to changing climatic conditions in the Upper Thames River basin, southwestern Ontario. The inverse approach is an alternative to statistical downscaling of global circulation model outputs, typically used in climate change studies. At the core of the inverse approach is a weather generator model that uses locally observed climate data, together with outputs from global circulation models, to generate an arbitrary long record of regional climatic conditions. A base case and two climate scenarios are produced by a weather generator, whose output is used as input into: (a) an event hydrologic model (for high flows); and (b) a continuous hydrologic model (for low flows). Changing hydrologic conditions are identified through frequency analysis for both flood and low flow hydrographs (obtained as outputs from hydrologic models). Changes in local water resources management practices, guidelines and design standards are recommended on the basis of the analysis of altered climates and their impacts on the hydrologic flow regime.

Larrivee and Simonet (2007) opined that assessing the vulnerability of infrastructure requires both a good knowledge of the infrastructure itself as well as how climate conditions affect it. Determining the climate parameters to which the infrastructure is sensitive helps protect how the infrastructure might be affected in a changing climate. Depending on the parameter, scenarios of future climate change can be generated to predict what changes are expected and how this may affect the structure. Climate changes and other factors that may contribute to vulnerability vary from place to place, making infrastructure in certain areas more vulnerable than in other areas. Not all infrastructure is directly sensitive to weather conditions. But, infrastructure may be indirectly sensitive due to reliance on other infrastructure that may be impacted by weather and climate. Other factors that relate to the vulnerability of infrastructure include the length of its life cycle, the type of risk it poses, the community adaptation, changes to land use and land cover in the area. Adaptations can occur at each phase of the infrastructure life cycle like gathering knowledge to inform decision making; building awareness and modifying behavior; interventions through regulations, codes and standards; apply new techniques and technologies; and recommend best practices. Several standards' association like the Canadian Standards Association have recognized the need to re-evaluate building and construction code criteria and are now examining how to adapt the codes and standards. This is important for making communities more resilient and better able to adapt with the unprecedented changes by the changing climate.

4.4 A search of internal publications

The federal, provincial and municipal governments have reacted proactively to the issue of climate change and have recognized that in addition to mitigating greenhouse gases and reducing emissions, it is essential to evaluate the infrastructure vulnerability and adapt accordingly. Various personal contacts among governmental officials (at provincial and municipal levels) and professionals working on climate change have been attempted in this search for internal documentation related to water resources infrastructure vulnerability. The communication details are provided in Appendix B and related findings follow.

City of Calgary

The City of Calgary prepared a Climate change action plan target 2050 in July 2006 which proposed the various water conservation community-oriented programs in Calgary with focus on the water metering, residential water conservation, ICI water conservation, limit of the tap water use for non-consumptive use and limit of the storm water runoff through storm water system.

City of Edmonton

City of Edmonton did some cursory review of climate change in terms of the change in Edmonton's design storms. The study shows that the 1:5 year storm 24 hour volume has been moving up by about 1 mm per 10 years. Similarly the 1:100 year value is going up at about 2 mm per 10 years. The single point statistics used in traditional hydrologic analysis are a concern as they ignore big storms that happen in other parts of the City. Currently the city of Edmonton is doing some research and analysis of radar data on a regional basis to see if there is a better way of assessing storm risk. The most recent storm related disaster occurred in 2004. The details of the storm are as follows: (a) July 2/3 – 136 mm in west & south Edmonton (1:200 year return frequency, 76 mm in 1 hour); (b) July 6/7 – Large event focused in north (30mm, 1:5), only ~ 5 mm in west; (c) July 11 – 64 mm in west and south (1:200 year event, 57 mm in 1 hour); and (d) 4,113 Basements Flooded – double the previous worst year.

It is evident from the statistics that it is difficult to forecast the flooding by a second 1:200 year storm. City of Edmonton is trying to develop a different storm rating system than return period for public understanding/consumption. The 2004 storms dramatically highlighted the vulnerability of older Edmonton neighborhoods to storms. City of Edmonton is striving hard to improve the older areas' ability to cope with large storms and keep continuing to improve these areas as need arises and funds become available. In general, it is felt that new systems are robust and can handle major storms (Lodewyk, 2007).

City of London

Prodanovic and Simonovic (2007b) analyzed the short duration high intensity rainfall for London, Ontario under the changing climate conditions. Predicted future climate change impacts for Southwestern Ontario include higher temperatures and increase in precipitation. They assessed the change in IDF curves for use by the City of London

under changing climatic conditions. The methodology implemented to assess changes in rainfall magnitude includes the following components: (a) Development and use of a daily weather generator model for synthetic generation of rainfall under current and future climates; (b) Disaggregation of daily rainfall into hourly; (c) Statistical analysis of rainfall of various durations and development of IDF curves under changed climatic conditions; (d) Comparative analysis of IDF curves; and (e) Recommendation for possible modification of municipal infrastructure design standards. The results of simulations in this study indicate that rainfall magnitude (and intensity) would be different than historically observed. The climate change scenario recommended for use in the evaluation of storm water management design standards reveals a significant increase in rainfall magnitude (and intensity) for a range of durations and return periods. This increase has major implications on the ways in which current (and future) municipal water management infrastructure is designed, operated, and maintained. They recommended the revision of the design standards and guidelines currently employed by the City of London.

This study was completed in December of 2007 and after review the London City Council passed two resolutions: (i) to develop a transitional strategy that will review and update the IDF curves currently used by the City for design of municipal infrastructure, replace the IDF curves developed in the 1960's, and investigate increasing the level of service of municipal infrastructure by approximately 15-20% to account for climate change; and (ii) undertake a city wide risk assessment regarding the potential impact of increased extreme rainfall characteristics expected in the future.

City of Toronto

The City of Toronto is focusing their effort on (a) drafting the Climate Adaptation Framework document; and (b) dealing with water quality implications of climate change.

Climate adaptation framework. The development of a climate change adaptation strategy is a key component of the City's "Climate Change, Clean Air and Sustainable Energy Action Plan", (Toronto Environment Office, 2007) which was unanimously adopted by Council in July, 2007. Work on the strategy is in progress. Some of the key issues related to infrastructure under consideration include: (a) more extreme weather events - e.g.: heavy rain, flash floods, high wind, freezing rain, hail, tornadoes, etc.; and (b) damage to buildings, water, sewer & transportation infrastructure and electrical systems causing blackouts. Key issues under consideration related to water include: (a) more frequent flooding from intense rainfall events; (b) water quality impacts from stormwater runoff, warmer lake water and lower lake levels that will affect shipping and deep lake cooling system; and (b) more frequent heat waves and droughts that will increase water demand. From the mitigation measures being considered it is important to mention expansion of deep lake water cooling and from the adaptation measures infrastructure upgrades (sewers and culverts) and residential programs of sewer backflow and downspout disconnection (D. MacLeod, personal communication, 2008)

Water quality. Toronto's water pollution solution is a long-term plan to protect the environment and sustain healthy rivers, streams and other water bodies. It is about reducing the adverse effects of wet weather flow, which is runoff generated when it rains or snows. In a natural setting where there's a lot of grass or vegetation, storm water isn't

usually a problem because the rain filters into the ground. But, due to modernization the city has a lot of impervious surfaces with lots of concrete, asphalt, brick, and these changes the way water travels and percolates along the way to the sewer. City of Toronto has a lot of storm water runs off roofs, roads and parking lots. It trickles down through drain pipes and empties into storm water grates. Once it enters the grate (having collected dirt, oil, grease and a lot of other pollutants along the way), it travels through the extensive storm sewer system - 4,500 km in all - to some 2,600 outfalls or outlet pipes. In some cases, storm water mixes with wastewater in the combined sewers or infiltrates into sanitary sewers. This causes the wastewater system and the City's sewage treatment plants to be overloaded and untreated water enters the rivers, streams and Lake Ontario which result in degraded water quality conditions from an environmental and physical perspective.

Toronto's plan to handle storm water pollution by setting to achieve 13 objectives under four categories:

Water quality

1. meet guidelines for water and sediment quality
2. virtually eliminate toxics through pollution prevention
3. improve water quality in rivers and the lake for beaches that are healthy for swimming
4. improve aesthetics

Water quantity

5. preserve and re-establish a natural hydrologic cycle
6. reduce erosion impacts on habitats and property
7. eliminate or minimize threats to life and property from flooding

Natural areas and wildlife

8. protect, enhance and restore natural features (eg., wetlands) and functions
9. achieve healthy aquatic communities
10. reduce fish contamination

Sewer system

11. eliminate discharges of sanitary sewage
12. reduce infiltration and inflow to sanitary sewers
13. reduce basement flooding.

To achieve these objectives, City of Toronto developed a 25-Year Plan which outlines programs and projects that, together, provide a solution for storm water pollution. A key component is raising public awareness about the issue and raising awareness means encouraging participation by Toronto's residents in some of the community-based programs which will help deal with storm water pollution. The total capital cost for the 25-year plan is approximately $1.047 billion or $42 million per year. Operational and maintenance cost to implement the capital projects is an estimated $16 million annually (information available online – last accessed January 2, 2008 - **http://www.toronto.ca/water/protecting_quality/wwfmmp/index.htm**).

Toronto and Region Conservation Authority

Extreme rainfall under current and future climate conditions will continue to affect all components of drainage infrastructure such as storm sewers within all urban centers and rural regions of Ontario. On August 19, 2005, significant rainfalls impacted the municipalities of southern York Region and the City of Toronto, clearly demonstrating the potential for major damages to both municipal infrastructure, transportation and to the public when the design capacity of our water management systems is exceeded. Other high impact rainfall events have been documented and studied by the Conservation Authorities and Environment Canada for 2000, 2002, 2004 and 2005.

Population data prepared by Statistics Canada indicate an ever increasing percentage of the population of Ontario residing within urban areas (Nirupama and Simonovic, 2007). As of 2001, 85% of Ontario's population resided within urban areas, and recent planning documents such as the Provinces Places to Grow plan clearly show an increase in urban growth through intensification.

With increasing population in urban areas will come increasing vulnerabilities to climate extremes and the changes in climate projected for the future, reflecting a need for new drainage design standards. The current level of science is defining atmospheric conditions which are projected to result in more intense rainfalls in future, similar to that experienced on August 19, 2005, when rainfall intensities and amounts exceeded the current design capacities of both the minor (piped) and major drainage (roads) systems through municipalities in and near Toronto. The current practice of using historical extremes to estimate future extremes and risks will become increasingly invalid.

At present, the design capacity of the municipal storm drainage systems is determined either through manual calculations or through use of computer modeling, with design rainfall amounts determined using statistical approaches to develop Intensity Duration Frequency Curve (IDF) values. This process analyses the historical high intensity rainfalls at specific precipitation gauges, typically resulting from heavy rainfall events such as thunderstorms. These methodologies and statistical approaches have assumed that the historical data represent homogeneous conditions and that the longer the historical data record available, the better the statistical analysis and accuracy. The validity of this premise is becoming questionable, considering regionally changing climate conditions and questions on the homogeneity of the data base. At the same time, reductions in the original number of MSC reference stations used for historical calculations of IDF curves has created challenges for the updating of values, with the implication that many locally intense storms now have an even greater chance of being missed or not occurring directly at a reference station gauge, resulting in locally misleading temporal trends in intense rainfall events.

Toronto region Conservation Authority and Environment Canada are involved with the collaborative pilot study for the central portion of southern Ontario that will investigate and recommend various approaches to deal with data coverage, IDF calculations, the changing climate and drainage infrastructure design issues for a region defined by the areas of responsibilities for the partners (personal communication with D.Haley, 2007). The study area encompasses the watersheds of the following Conservation Authorities:

Toronto and Region CA; Nottawasaga Valley CA; Otonabee Region CA; Credit Valley CA; Kawartha CA; Halton CA; Grand River CA; Central Lake Ontario CA; Lake Simcoe Region CA; and Ganaraska CA.

This pilot study proposes to assess the standard methodologies used in creating "Regional IDF curves" and to recommend appropriate regional approaches for south-central Ontario. These methodologies will be used to generate a preliminary “Regional IDF curve” for the pilot region, subject to additional peer review/assessment beyond the pilot study period. The analysis will utilize rainfall data from a number of sources, incorporating additional municipal, provincial and Conservation Authority rainfall databases along with data traditionally archived by Environment Canada. By utilizing a dense network of precipitation data, it is hoped that the uncertainties in estimating risks from high intensity localized storms can be improved, that issues of declining reference stations can be better dealt with (i.e. regional approaches for handling intense rainfall events that miss historical IDF stations and gauges) and that regional precipitation databases can be developed for the pilot region. The study will assess approaches and methodologies to deal with regional estimation of IDF values, review trends in increased precipitation intensities and amounts, recommend statistical methodologies and procedures needed to deal with the ever changing weather and climate patterns, and aim to develop a preliminary regional IDF curve/value for the pilot region that can be used for updating both the regional and local IDF information.

Given that the above work identifies a significant upward trend in the rainfall intensity and frequency data and a shift in the subsequent curve, it will also include an economic assessment of impacts on a typical drainage system.

Metro Vancouver
The Greater Vancouver Regional District (GVRD)mow operating under the business name of Metro Vancouver commissioned the Pacific Climate Impacts Consortium (PCIC) to update the analysis and focus on rainfall intensity and frequency of occurrence of large rainfall events in the Vancouver region. Future precipitation projections derived from 29 experiments with 7 global climate models show a considerable range in projections for the GVRD region. A large range indicates considerable uncertainty. However, models consistently project a 14% to 33% decrease in summer precipitation by the middle of the century. In addition, most models project small increases in precipitation during all other seasons, particularly in winter (4% to 14% increase by the middle of the century). The projected net annual increase in precipitation of 1% to 5% by the middle of the century is too small (and uncertain) to be used for planning purposes. The small range indicates that neither very large decreases nor increases in the annual average are to be expected. However, important seasonal changes are projected despite the small annual average change: large winter precipitation increases (4% to 14%) and summer decreases (-33% to -14%) by the middle of the century. Furthermore, consistent projections for warming in the region by mid-century (2.1°C to 2.6°C) will cause increased winter and spring rainfall due to a larger fraction of total precipitation falling as rain rather than snow (Murdock *et. al.*, 2007).

Burton (2007) recommended the Environment Committee, Metro Vancouver that there is considerable uncertainty in estimating the magnitude and timing of the changes due to climate at any particular location. The related regional effects include the sea level rise, aggravated in some low lying areas by ground subsidence; shifts in seasonality and form of precipitation (i.e. more precipitation in winter, less in summer and more as rain rather than snow); increasing frequency of extreme weather events, including precipitation and earlier spring runoff, higher temperatures and higher flood flows in river systems dominated by snowmelt like the Fraser River. He also stressed on the effect of climate change on regional role that the exclusive use of historic data for design and planning purposes will not be enough. The impact of climate change needs to be considered so that the existing infrastructure is designed with appropriate capacity. Climate change imposes a new level of uncertainty on regional planning and utility management, leading to a need for policy responses that are both flexible and reasonable. The drinking water management plan outlines actions to improve system resiliency in the face of a number of uncertainties, including climate change. Policy response that assists in coping with climate change impacts on both regional infrastructure and environment are being developed in the revised liquid waste management plan. Similarly, factors affecting regional growth management, such as issues of development on floodplains that could be at increasing risk from sea level rise and storm surge are being considered as the new growth management strategy is developed.

Fraser Basin Council managed a project in 2006 to update design flood levels for the lower Fraser River. The project looked at river flooding during the spring snowmelt, as well as ocean flooding from a winter storm surge. Although climate change is not accounted for in the final results, the influence of climate change was considered within the sensitivity analysis of the hydraulic model by varying the sea level and river flows. Basically, sea level rise had a direct influence on flood levels associated with the winter storm surge, but relatively little effect on river flood levels. Conversely increased river flows had a direct influence on river flood levels, but little or no impact on winter storm surge flood levels (Northwest Hydraulic Consultants, 2006). In terms of infrastructure vulnerability, the hydraulic modeling study was somewhat limited. They did review current dike elevations relative to predicted flood levels and found that most of the dikes were vulnerable to failure from one or both flood events. However, this report did not consider other infrastructure that may be vulnerable due to its location within the floodplain such as transportation infrastructure, energy utilities, water and sewer, etc. There is a very significant amount of infrastructure located within different parts of the lower Fraser River floodplain; however, there is no comprehensive inventory, nor an analysis of vulnerability (Litke, 2007).

Province of Ontario

In recent years, Ontario has been experiencing an increase in frequency and intensity of flood events. Recent examples in the urban water infrastructure failure include:

- Stratford, Ontario, where the sewer system failed after an intense rainfall event in 2001. Local residents' basements flooded after that storm and again in 2002 after another intense storm. The municipality is now spending $70 million to retrofit

its infrastructure with a 250-year storm design and facing a $250 million class action lawsuit from local residents who experienced basement flooding (Rickett et al, 2006).

- Peterborough, Ontario, was hit by a severe rainfall, that was well beyond typical urban drainage design thresholds, event that caused significant flood damage July 2004. Flood damage was reportedly in excess of $100 million in direct physical damages to private and public property. UMA (2005) analysis identified the following causes for the flood damage: (a) Unprecedented heavy rainfall of an intensity of more than twice the current design standard used by most municipalities, centred on the largely impervious downtown core, resulting in high runoff; (b) Insufficient storm sewer capacity caused primarily by ineffective water collection and undersized pipes. Approximately 80% of the City's storm trunk sewers analysed do not meet current 5-year design standards; (c) Poorly defined overland flow routes caused primarily by filling in of natural waterways over time without accommodating the water elsewhere. Over 225 properties in the City are vulnerable to overland flow damage from a 100-year storm event; and (d) Unwanted water getting into the sanitary sewer system leading to system overflow. It is believed to be primarily a result of foundation drain and illegal roof leader connections and inflow through aging pipes and manholes. To improve the operation of the City's drainage and sanitary systems, a "toolbox" of potential solutions is identified and the overall action plan, called the Master Plan, to determine which solutions to apply, to which systems, and in which parts of the City. The priorities are set on preventing basement flooding from sanitary sewage and urgent drainage system improvements in four catchments: Jackson, Curtis, Beyersville/Harper, and Riverview (UMA, 2005).
- Toronto, Ontario was hit with extremely heavy thunderstorm event, with rainfall intensity greater than that experienced during Hurricane Hazel, (TRCA, 2005) on August 19, 2005, resulting in the failure of a culvert under Finch Avenue. "As a result, the entire roadbed of Finch Avenue West at Black Creek was washed downstream, affecting all of the City and utility infrastructure within the road allowance." The storm has cost approximately $500 million in insured losses due to flooding, collapsed roadways, and lost "buried" infrastructure, plus the extreme traffic disruptions caused by the loss of a section of the entire roadbed on Finch Avenue West.

Losses from flooding, drought and other recent disasters has resulted in the province of Ontario passing its Emergency Management and Civil Protection legislation requiring that all municipalities, regional governments and provincial Ministries assess their hazards, including floods, prioritize their risks, and develop emergency and disaster management plans to reduce risks from the most significant hazards. Environment Canada (2007) recently completed a study funded by the Climate Change Impacts and Adaptation Program - the full report was submitted to the CCIAP in July and it is not yet available to the public. This study estimates possible changes in future rainfall-related flooding risks using a modeling exercise and existing data from reliable sources for four selected river basins in Ontario. This study spans only the warm season (April–November) and identifies the critical rainfall thresholds that have triggered, in the past

decades, high numbers of rainfall-related insurance claims and economic costs in the four selected cities (i.e., London, Ottawa, Toronto, Kitchener-Waterloo). It also quantitatively estimates the impacts of future climate change on the frequency and magnitude of rainfall, streamflow, and rainfall-related flooding risks in Ontario for three windows of time (2016–2035, 2046–65, and 2081–2100).

The modeled results show that, averaged over the five Global Circulation Model scenarios and across the study area, both the monthly total number of rainfall-related water damage insurance claims and incurred loss could increase by about 13%, 20% and 30% for the periods 2016–2035, 2046–2065, and 2081–2100. Based on the results of the study the following key recommendations are that: (i) the results and rainfall/streamflow simulation models from this study be incorporated into municipal/community emergency response plans ; (ii) the rainfall simulation model developed from this study be integrated into an operational forecast model and used to assist forecasters in predicting daily rainfall occurrence and amount during the warm season; and (iii) the rainfall and streamflow simulation models derived from the study be used in an advance warning system for Ontario municipalities.

Province of Saskatchewan

Saskatchewan is currently developing an Integrated Water Management Framework and governance model that will bring federal and provincial agencies with significant roles in water management together to address issues and challenges at the provincial level. While the precise solutions to the challenges posed by climate change for water management are not yet clear, it is clear that the chances of success will be greater if the regulating bodies address the challenge together, rather than taking a fragmented approach. Development of the integrated water management model for Saskatchewan will prepare the province to deal with the effects of climate change on water. The integrated water management model identifies the watershed as the logical level for most decision making. Work is already underway to develop and implement watershed plans to protect water supplies. A variety of measures being undertaken through this process will leave the watersheds healthier and better prepared to deal with challenges created by climate change. The watershed planning processes also create groups of concerned citizens working to protect their watersheds, providing capacity for collaboration and support in dealing with new challenges. As knowledge allows, these groups will bring adaptation measures to deal with climate change directly into their watershed planning processes (The Saskatchewan Energy and Climate Change Plan, 2007).

4.5 Selected presentations - Workshop on stormwater management in a changing climate

The Ontario Public Works Association organized on December 5, 2007 in Mississauga one day workshop on “Stormwater Management in a Changing Climate”. Two relevant presentations from the workshop are reviewed in the following section.

Watt *et. al.* (2007) presented the potential impacts of climate change on stormwater management emphasizing the potential implications, key climate parameters, and planning and design strategies to mitigate the adverse impacts. They stressed the temperature and precipitation projections from IPCC (2007), and suggested two emerging approaches (a) preservation of the predevelopment water balance and (b) stormwater reuse for an efficient stormwater management. The scope of almost all elements of any stormwater management system should expand with a changing climatic condition. However, even with certain knowledge about increased rainfall, there can be no guarantee that this knowledge will be incorporated into stormwater management or storm sewer guidelines issued by provincial or municipal government agencies. There has been and continues to be a great deal of inertia in urban stormwater policy and design. It remains a challenge to encourage all Canadian provinces and municipalities to use the existing historical rainfall database in their design guidelines, let alone accommodate potential shifts in climate.

The following are the implications of climate change for the new stormwater management infrastructure: (a) Design pipe diameter will increase with increased design rainfall; (b) Required live storage of quantity control structures will increase; (c) Required storage volume of quality control structures will increase, but design value may not increase (provincial guidelines); and (d) Size of combined sewer overflow abatement structures will increase.

Additional maintenance of existing infrastructure may be necessary should the rainfall regime over the service life of the structure become more severe than that for which the structure was designed. But, maintenance may be relatively insensitive to modest impacts of climate change.

They also suggested that the key climate change variables for SWM (rainfall IDF data, rainfall temporal distribution, antecedent conditions, critical rain plus snowmelt sequences, critical temperature sequences) should be developed from the best possible estimates of recent climate. While planning and designing approaches to mitigate the adverse impacts, they recommended to view climate change as an additional uncertainty.

Boyd (2007) suggests the following ways of mitigating the consequences of climate change: (a) Making the landscape more resilient (by implementing tried and true conservation practices; by implementing risk management programs and policies; by continuing to provide long term monitoring to help adapt existing programs; and by having a watershed plan to provide an overall framework to deal with a range of watershed management issues, one of which is climate change and climate variability); (b) Putting more storage back on the landscape; (c) Implementing riparian buffers and natural channels; (d) Wetlands enhancement and restoration; (e) Reforestation; (f) Implementing good risk management policies, floodplain management, subwatershed planning, and storm water management; (g) Having a current watershed plan; and (h) Maintaining flood mitigation structures and testing them against new design standards.

5. SUMMARY, DISCUSSION AND RECOMMENDATIONS

5.1 Review summary

The literature shows that the planning, design, operations and maintenance phases of water infrastructure needs to change to accommodate climate changes. Vulnerability and risk assessments should replace the current dependence on historical climate data. Regularly updated climate input values that reflect the latest changes in regional climate, including precipitation variables, are required for (a) the water infrastructure development plans; (b) the updating of design codes and standards; (c) the adaptation of the water infrastructure operations strategies; and (d) the development of maintenance procedures. In spite of the high level of significance given to water resources infrastructure vulnerability to climate change in Canada, documented engineering work is non-existent.

Currently, water engineers use historical climate records when dealing with most water infrastructure systems. If precipitation patterns change, water systems could fail, causing problems such as sewer backups, basement flooding, dam failures, dikes overtopping, among other impacts. Recent examples in the urban water infrastructure failure, presented in Section 4, include: Stratford in 2001 and 2002, Peterborough in 2004 and Toronto in 2005.

The expense of adapting water infrastructure is the major issue. Infrastructure Canada (2007) estimates the cost for wastewater treatment infrastructure adaptation in Canada and found that Niagara region's costs may range from $8 to $24 million, while Toronto's costs may range from $633 million to $9 billion. In some cases modifications such as increases in storage capacity may be sufficient and replace costly adaptation options such as changes to pipe size. A study in North Vancouver (Lemmen and Warren, 2004) found that drainage infrastructure could be "adapted to more intense rainfall events by gradually upgrading key sections of pipe during routine, scheduled infrastructure maintenance." When changes to infrastructure such as pipe size *are* necessary, it is predicted to be less costly than the possible losses due to failed infrastructure. Uncertainty and cost should not be barriers to implementing adaptation options. "No regrets" adaptation options provide cost effective benefits regardless of future climate changes.

5.2 Discussion

Climate change is now recognized in the water engineering community as a risk that needs to be addressed through adaptation as well as through mitigation. Changes of the magnitude projected by the Intergovernmental Panel on Climate Change (IPPC, 2007) for the current century would have significant impacts on Canada. Different regions will have differing vulnerabilities, which are a function of the nature of climate change, the sensitivity of the region and its adaptive capacity. Although both positive and negative impacts are expected to result from future climate change, it is clearly evident from the review of literature that in Canada negative impacts will prevail (IPCC, 2007).

Effective adaptation strategies should consider current and future vulnerabilities and aim to incorporate climate change into existing risk management frameworks. Quite comprehensive effort is required to make the adaptation to climate change an inherent part of the water infrastructure planning, design, operations and maintenance processes.

A very close coordination of regulatory, engineering and budgetary activities is necessary in order to move the water infrastructure adaptation forward.

An *example of local recommendations* for adapting flood management in the Upper Thames River watershed to climate change impacts illustrates the necessary coordination (Prodanovic and Simonovic, 2007a):
(1) Regulatory. Changing hydro-climatic characteristics imply that rules and regulations currently employed by the Upper Thames River Conservation Authority may need revision. This recommendation is supported by the analysis showing that floods of all magnitude will increase in frequency of occurrence. Possible revisions of existing regulation include those pertaining to: (i) use of river and its adjacent park land for recreation; (ii) removal of pumping stations near area rivers during the course of a flood; (iii) patrolling of river banks during periods of high water levels and monitoring performance of critical infrastructure (such as roads, bridges, culverts, drains, sewer systems); (iv) issuing of permits for floodplain development; and (v) revision of reservoir operating procedures (including smaller dams, weirs, outflows, etc.).
(2) Budgetary. This set of guidelines looks at possible changes in allocation of budget for safe operation of existing flood management infrastructure, as well as required investment into future infrastructure. Since floods will occur more frequently (as the wetter climate suggests), so will the maintenance, retrofitting and upgrading of existing flood management infrastructure. For example, the over-topping of dykes in London is expected to occur more often than in the past and dykes will hold higher water levels more often thus requiring increasing maintenance levels leading to higher costs. An evaluation of current structural and non-structural measures used to reduce flood damage (such as reservoirs, dykes, floodwalls or implementation of land use zoning practices, flood warning systems, waterproofing, etc.) will need to take place. As flood frequency increases basin-wide, so do budgets allocated to maintenance of flood protection measures. A need will also arise for investment in additional infrastructure to bring the flood protection to regulatory levels and meet the needs of the population. As this new infrastructure comes on line, existing budget allocation rules for maintenance may also need modifications.
(3) Engineering. Changes in this set of regulations aim to look at possible changes in design standards for municipal infrastructure (such as roads, buildings, bridges, culverts, drains, sewer systems, treatment plants, etc.). Changes will be necessary as climate change is expected to bring about changes in hydroclimatic characteristics. Since current hydroclimatic characteristics were used to formulate today's design standards, it only follows that under changing conditions different standards should be set.

5.3 Recommendations

In conclusion, although some initial activities at various levels are indicating the beginning of the implementation of adaptation measures for water infrastructure:

(i) *More data needs to be collected.* Canadian water resources monitoring networks are inadequately resourced and poorly coordinated (Environment Canada, 2004). Therefore, targeted expansion of baseline monitoring for key

components of the hydrologic cycle, representative water demand and usage parameters, and effluent quality and aquatic impacts is required. In view of this recommendation, it would seem urgent to undertake a coordinated national review of freshwater monitoring programs to identify specific deficiencies and develop prioritized proposals for corrective actions. Innovations in monitoring techniques such as satellite remote sensing should be more aggressively and systematically implemented. A valuable supporting initiative might be to develop and regularly disseminate easily understood indicators of the status of water resources and their socio-economic importance, in order to enhance and sustain public awareness of water issues and their relationship to changing climate.

(ii) *More research needs to be conducted*. An improved knowledge base is clearly essential for prediction of future threats to the available freshwater resource, and for development of more effective water management policies and practices. Responding to this challenge requires improved simulations of future climate and more useful seasonal climate forecasts. Climate models (global and regional) combined with better downscaling techniques should continue to improve in spatial and temporal resolutions. Additional research efforts are required with focus on improved understanding and modelling of hydrological processes and systems. Issues related to water quality also need to be addressed: for example, new chemicals of concern and their human and ecosystem health implications; drainage chemistry from industrial and mine wastes; and enhanced processes for water treatment, reclamation and recycling. Understanding must be improved of the social and economic factors underlying demands for water or posing impediments to innovation, conservation and recycling, and socio-economic models developed for various water uses and the forces driving demand patterns and recirculation decisions.

(iii) *Engineering designs need to change and climatic design inputs need regular updates*. Climatic load data that is referenced and/or used by infrastructure codes and standards is critical to infrastructure designers and operators. Presently, the climatic loads used by designers are mostly based on historical data that is no longer representative of future conditions. This is of great concern to infrastructure designers since many infrastructure works are intended for extremely long service life – up to 100 years in some cases. Climatic load data must be updated with every new observation available. In addition, predictive models with sufficient detail and resolution to be useful at the local community level are required.

(iv) *Risk based water infrastructure planning, design, operations and maintenance.* The concepts of risk and risk approach are key to understanding climate change adaptation. “Risk” is a probabilistic term used to denote the possibility of negative consequences resulting from decisions or processes. “Risk approach” denotes the process of planning, design, operations and maintenance associated with risk. Based on the considered risks of various actions or non-actions, better decisions may be possible and can be taken in

accordance with the risk approach. If it is not possible, then decisions can deal with the consequences.

(v) *Actions need to take place to mainstream climate change adaptation*. Decision-makers will have to consider the effects of climate change over the full lifetime of their projects when they develop infrastructure, place major industrial facilities and new dams, and improve infrastructure stock. They must then include features that will accommodate these changes into the design and operation of these facilities.

(vi) *Much more coordinated effort of all stakeholders should lead the water infrastructure impacts mitigation and adaptation process*. Responses to climate change tend to have two aspects: mitigation and adaptation. Water engineering community in Canada ought to pursue both options. Sea levels will rise while the Great Lakes and the Prairies will have to deal with lower water levels resulting from a warmer environment. Water infrastructure planning, design, operations and maintenance suffer from fragmented responsibilities, from one level of government to another (local, to provincial, national, or international). So the first task is to provide for *vertical integration* of various levels of government in consideration of climate change in relationship to water resources infrastructure problems. In addition the problem of horizontal fragmentation among different agencies of a government, such as agriculture, energy, industry, mining, municipal affairs, or economic development has to be addressed too. Climate change requires a strong support for *horizontal integration* as a way to reach solutions through coordination and collaboration. In the domain of water resources systems integration should be based on integration of freshwater management and coastal zone management; integration of land and water management; integration of surface water and ground water management; integration of quantity and quality in water resources management; and integration of upstream and downstream water interests. Climate change mitigation and adaptation requires use of the engineering, social, natural, ecological, and economic sciences in real *partnership*. Water is a subject in which everyone is a stakeholder. Real *participation* only takes place when stakeholders are part of the decision-making process. Participation requires that stakeholders at all levels of the social structure have an impact on decisions at different levels of water management.

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Appendix B – Communication documentation

Subject	RE: Request for Information
From	**"Water, Water" <water@gov.nl.ca>**
Date	Monday, November 19, 2007 12:27 pm
To	**Vasan Arunachalam <varunach@uwo.ca>**

Dear Dr. Vasan:
The Department of Environment and Conservation is also involved with a PIEVC project so I am somewhat familiar with it. Unfortunately, I do not have any titles related to what you are looking for.
Regards, Martin

Martin G. Goebel, P.Eng
Director
Water Resources Management Division
Department of Environment and Conservation
4th Floor Confederation Bldg W
PO Box 8700
St. John's NL A1B 4J6

Tel: (709) 729-2563
Fax (709) 729-0320
Email: **MGoebel@gov.nl.ca**
Web: **www.env.gov.nl.ca/Env/water**

Subject	RE: Request for Information
From	mailto:"Crowe, Brian" <brian.crowe@vancouver.ca>
Date	Wednesday, November 21, 2007 7:02 pm
To	Vasan Arunachalam <varunach@uwo.ca>
Cc	Brent Burton <Brent.Burton@metrovancouver.org> , Steve Litke <slitke@fraserbasin.bc.ca>

Dear Vasan,

Our work at the City of Vancouver on vulnerability of infrastructure to climate change impacts is in its infancy. We have recently struck a Climate Change Adaptation working group among Engineering and Parks staff, which I lead. We are presently in the scoping and information gathering phase. Our medium term goal is to incorporate Adaptation Planning into our infrastructure capital planning programs.

The City of Vancouver has done extensive work on Climate Change Mitigation, but we are just beginning to work on Adaptation. I have surveyed staff and we are not aware of any internal reports or studies on engineering vulnerabilities and impacts. We have made reference to these issues in a few recent reports (such as a April, 2007 Council Report on
Flood Proofing Policy), but these are brief references that I don't believe would be informative to your research. Most of our adaptation discussions to date have been internal staff meetings and verbally answering questions from City Council.

Two other groups you may want to contact are Metro Vancourver (Brent Berton) and the Fraser Basin Council (Steve Litke). Metro recently briefed their Board on adaptation, and is working with Engineers Canada on a Metro Vancouver pilot study titled: Local Pilot Study of Regional Wastewater Infrastructure: Evaluation of Vulnerability to Climate Change.
The Fraser Basin Council produced a 2007 report titled "Lower Fraser River Hydraulic Report" with some preliminary work on adaptation. I believe both groups are undertaking additional work, and may have some relevant "grey literature".

We look forward to seeing the outputs from the Engineers Canada vulnerability project. We hope it will help Vancouver and other Canadian municipalities plan for climate change adaptation.

Sincerely,

Brian Crowe, P.Eng.
Assistant City Engineer
Water & Sewers

Subject	RE: Request for Information
From	**Brent Burton <Brent.Burton@metrovancouver.org>**
Date	Tuesday, November 27, 2007 7:47 pm
To	**Vasan Arunachalam <varunach@uwo.ca>**
Cc	**Steve Litke <slitke@fraserbasin.bc.ca>**

Hello Dr. Vasan:

Sorry, I'm going through my backlog of emails and am just getting to this now.

FYI, I am a water resources engineer employed with Metro Vancouver and I am a member of PIEVC's expert working group. We are currently working through Engineers Canada on a pilot study of the vulnerability of our regional wastewater infrastructure.

I don't think that we will have a lot of information for you, but please take a look at our website at: **http://www.gvrd.bc.ca/air/climate_change.htm** (right side). In particular, I draw your attention to the 2002 and 2007 precipitation / climate change reports that have been completed for us. I believe that both reports may have some useful information for you. Also, perhaps take a look at this short report to our Environment Committee (political) which summarizes some potential vulnerabilities on a regional basis: **http://www.gvrd.bc.ca/board/comagendas/Environment/September/5.8.pdf**. More work needs to be done on addressing these vulnerabilities.

Steve at the FBC has been involved with some very regionally-significant work on updating design flood levels along the Fraser River and there was some sensitivity analysis done around adaptation (sea level rise and hydrologic change in the basin). I believe that there is more work yet to be done and Steve may wish to comment more on that.

Best of luck,

Brent
604-451-6572

Subject	RE: Request for Information
From	**Kim Peters <kpeters@toronto.ca>**
Date	Wednesday, November 28, 2007 11:39 am
To	**Vasan Arunachalam <varunach@uwo.ca>**
Cc	**askwater@toronto.ca**

Dear Dr. Vasan,

Thanks for your inquiry regarding engineering studies on the impacts of climate change on the City's infrastructure. The City of Toronto has only just recently established a working group on climate change adaptation, and it intends to look at the risk management aspects of climate change, including infrastructure. However, there are a few recent studies that may be of interest to you:

Climate Change Adaptation Impacts for Toronto's Urban Forest
http://www.cleanairpartnership.org/pdf/climate_change_adaptation.pdf

Time to Tackle Toronto's warming: Climate Change Adaptation Options to Deal with Heat in Toronto
http://www.cleanairpartnership.org/pdf/time_to_tackle_toronto_warming.pdf

Cities Preparing for Climate Change: A Study of Six Urban Regions
http://www.cleanairpartnership.org/pdf/cities_climate_change.pdf

Skills for Energy Efficient Construction: A REport on Trades Training for Energy Efficient Construction in the Greater Toronto Area
http://www.cleanairpartnership.org/pdf/skills_05_2007.pdf

A Scan of Climate Change Impacts on Toronto
http://www.cleanairpartnership.org/pdf/climate_change_scan.pdf

Decision Makers Workshop
http://www.cleanairpartnership.org/climate_change.php?p=cc_impacts06

All of these initiatives have been undertaken by the Clean Air Partnership, which is partially funded by the City of Toronto through the Toronto Atmospheric Fund.

Best regards,
Kim Peters
Senior Environmental Planner, Toronto Environment Office, City of Toronto
Tel (416) 392-1848 email: **kpeters@toronto.ca**
www.toronto.ca/teo

Subject	Your Request for information on Infrastructure vulnerability to climate change
From	**Sid Lodewyk <Sid.Lodewyk@edmonton.ca>**
Date	Wednesday, November 28, 2007 12:36 pm
To	**Vasan Arunachalam <varunach@uwo.ca>**
Cc	**John Hodgson <John.Hodgson@edmonton.ca>** , **James Tan <James.Tan@edmonton.ca>** , **Steven Chan <Steven.Chan@edmonton.ca>**

Dear Dr. A. Vasan,

We have done some cursory review of climate change in terms of the change in Edmonton's design storms. The attached PowerPoint shows that the 1:5 year storm 24 hour volume has been moving up by about 1 mm per 10 years. Similarly the 1:100 year value is going up at about 2 mm per 10 years.

The single point statistics used in traditional hydrologic analysis are a concern to us as they ignore big storms that happen in other parts of the City. We are currently doing some research and analysis on radar data on a regional basis to see if there is a better way of assessing storm risk.

Our most recent storm related disaster occurred in 2004. Here is a summary:

- July 2/3 – 136 mm in west & south Edmonton (1:200 year return frequency, 76 mm in 1 hour)
- July 6/7 – Large event focused in north (30mm, 1:5); only ~ 5 mm in west
- July 11 – 64 mm in west and south (1:200 year event, 57 mm in 1 hour)
- 4,113 Basements Flooded – double the previous worst year.

It is difficult to tell people that they have been flooded by a second 1:200 year storm, as they expect to be safe for 200 years after the first one (i.e. they do not understand the statistics). We are trying to develop a different storm rating system than return period for public understanding / consumption.

The 2004 storms dramatically highlighted the vulnerability of older Edmonton Neighbourhoods to storms. The attached reports show our response to these storms – a similar response to major flooding as in years before. Through these construction programs we are working to improve our older areas' ability to cope with large storms. We continue to improve these areas as need arises and funds become available.

In general, we feel that our new systems are robust and can handle major storms:
Storm: we use a major minor concept, with the minor system handling the 1:5 year value, and the major, overland system, handling flows above that.
Sanitary: We rely on the tightness (i.e. pvc or concrete with gaskets) of new sewers to prevent large responses to rainfall.

If you have any more questions, please contact me.
Sid Lodewyk, M.Sc., P.Eng.
General Supervisor of Environmental Monitoring,
Drainage Services, City of Edmonton
5th Floor, Century Place, 9803-102A Avenue,
Edmonton, Alberta T5J 3A3
Ph.(780) 496-5582
email: **sid.lodewyk@edmonton.ca**

Subject	Re: Request for Information
From	**Steve Litke <slitke@fraserbasin.bc.ca>**
Date	Wednesday, November 28, 2007 1:43 pm
To	**Brent Burton <Brent.Burton@metrovancouver.org>** , **Vasan Arunachalam <varunach@uwo.ca>**

Hello,

As Brent has mentioned, the Fraser Basin Council managed a project in 2006 to update design flood levels for the lower Fraser River. This looked at river flooding during the spring snowmelt, as well as ocean flooding from a winter storm surge. Although climate change is not accounted for in the final results, the influence of climate change was considered within the sensitivity analysis of the hydraulic model by varying the sea level and river flows. Basically, sea level rise had a direct influence on flood levels associated with the winter storm surge, but relatively little effect on river flood levels. Conversely increased river flows had a direct influence on river flood levels, but little or no impact on winter storm surge flood levels. The full technical report can be downloaded at: **http://www.env.gov.bc.ca/wsd/public_safety/flood/structural.html#hydraulic**

In terms of infrastructure vulnerability, the hydraulic modeling study was somewhat limited. We did review current dike elevations relative to predicted flood levels and found that most of the dikes were vulnerable to failure from one or both flood events. However, this report did not consider other infrastructure that may be vulnerable due to its location within the floodplain such as transportation infrastructure, energy utilities, water and sewer, etc. There is a very significant amount of infrastructure located within different parts of the lower Fraser River floodplain; however, I am not aware of any comprehensive inventory, nor an analysis of vulnerability.

I hope this information is helpful.

Regards,

Steve Litke
Program Manager
Fraser Basin Council
1st Floor - 470 Granville St.
Vancouver, BC, Canada V6C 1V5
Tel: (604) 488-5358
Fax: (604) 488-5351
www.fraserbasin.bc.ca

Subject	Fwd: Re: Request for Information
From	**Ted Bowering <tbowerin@toronto.ca>**
Date	Thursday, November 29, 2007 10:04 am
To	**Vasan Arunachalam <varunach@uwo.ca>**
Cc	**Chessie, Patrick D." <PChessie@toronto.ca>** , **Ilze Andzans <iandzan@toronto.ca>** , **"P'ng, Jonathan" <jpng@toronto.ca>** , **"Snodgrass, William" <wsnodgr@toronto.ca>**

I have to try again, email was too big for our gateway.

I have replaced the attachments with links to the City Web site:

Please check out:
http://www.toronto.ca/water/protecting_quality/wwfmmp/index.htm
http://www.toronto.ca/involved/projects/archived/wwfmmp_archive/index.htm
http://www.toronto.ca/water/protecting_quality/stormwater_management/watershed.htm

Policy and Guidelines Documents
http://www.toronto.ca/involved/projects/archived/wwfmmp_archive/pdf/wwfmmp_policy.pdf
http://www.toronto.ca/water/protecting_quality/wwfmmp/pdf/wwfm_guidelines_2006-11.pdf

I have also copied your letter of introduction for the benefit of those copied on this.

Ted Bowering >>> Ted Bowering 29/11/2007 9:42 AM >>>

Hello Dr. Vasan:

I am forwarding your request for information to Patrick Chessie, Manager of Sewer Asset Planning and Jonathan P'ng, Manager, Stormwater Management. I expect that most of the reports or studies that we have are of more interest to the stormwater and wastewater systems group.

In the past ten years, we have focused a lot of effort on the management of storm water. Some documents that have come out of that process are attached. Although these do not address the issue of Climate Change directly, they should provide us with a more flexible, adaptable and hopefully sustainable approach to managing wet weather flow in the City of Toronto.

Ted Bowering
Manager, Policy and Program Development
Water Infrastructure Management, Toronto Water
Metro Hall, 18th Floor, 55 John Street, 416-338-5473

Subject	Re: Request for Information
From	**"Cunningham, Neil (STEM)" <Neil.Cunningham@gov.mb.ca>**
Date	Monday, December 3, 2007 12:12 pm
To	**Vasan Arunachalam <varunach@uwo.ca>**
Cc	**Marcoux, Denise (STEM)" <Denise.Marcoux@gov.mb.ca>**

Hello Mr. Arunachalam:

I have attached information from Municipal World Magazine for your review as requested below.

I suggest that you contact the following individuals for additional information:
- David Noble (2degreesC) consults with municipalities on adaptation issues (writes for Municipal World) his email address is: **noble@2degreesC.com**
- Jenny Fraser, Province of BC: **Jenny.Fraser@gov.bc.ca**
- Dr. David Sauchin, University of Regina: **sauchyn@uregina.ca**

We look forward to receiving your final reports.

Many thanks,
Neil Cunningham

Neil R. Cunningham, M.L. Arch.
Policy and Program Analyst
Climate & Green Initiatives Branch
Manitoba Science, Technology, Energy and Mines
1202 - 155 Carlton Street
Winnipeg, Manitoba, Canada R3C 3H8

Phone: 204-945-8793
Fax: 204-948-3739
Email: **neil.cunningham@gov.mb.ca**
Please note my new email address.

Subject	Re: Request for Information
From	**WWD-Division-Response <Water-Division-Response@winnipeg.ca>**
Date	Wednesday, December 5, 2007 3:04 pm
To	**Vasan Arunachalam <varunach@uwo.ca>**

Hello,

I apologize for the delay in responding to your email. I'm sorry but we do not have any reports on climate change.

Thank you
Sherri Adamson
City of Winnipeg
Water and Waste Department

Slobodan P. SIMONOVIC
Consulting Engineer, Ltd.

From: Cheng,Shouquan [Ontario] [Shouquan.Cheng@ec.gc.ca]
Sent: Monday, February 11, 2008 11:32 AM
To: Simonovic, Slobodan; Klaassen,Joan [Ontario]
Cc: simonovic@uwo.ca
Subject: RE: Request for the report documentation
Dear Dr. Simonovic,

Thank you very much for your interest in our climate change and rainfall-related flooding risk study. The full report was submitted to the CCIAP (Climate Change Impacts and Adaptation Program) in summer 2007 and has not yet released by the CCIAP. At this stage, I would like to provide you the Executive Summary instead of the full report. Hopefully, it covers enough detailed information for your literature review.

Best regards,
Chad

From: David MacLeod [dmacleo2@toronto.ca]
Sent: Monday, February 11, 2008 11:46 AM
To: Simonovic, Slobodan
Cc: Frank Duerden; jpenney@cleanairpartnership.org; Joan [Ontario] Klaassen; dsandink@iclr.org; sramroop@ryerson.ca; Don Altman; Ilze Andzans; Ted Bowering
Subject: Request for the documentation
Hello Dr. Slobodan Simonivic at the University of Western Ontario and ICLR;

Thanks for your interest about climate adaptation at the City of Toronto. I am generally aware of your work, and in particular your contact with Toronto Water. I think that for specific information on what Toronto Water (TW) is doing, you are best to contact Ilze Andzans ph. 416 338-2847. She is the TW rep on Toronto's Climate Adaptation Steering Committee. I believe that in the recent past you have also had some contact with Ted Bowering.

I can tell you more generally what is happening on climate adaptation at the City of Toronto. I am working on this almost full time now, as a staff member in the Toronto Environment Office.

http://www.toronto.ca/teo/adaptation.htm

The above website has a quick presentation in Powerpoint with information on the process we are going through on climate adaptation. It also has Powerpoints from six experts who participated in a recent large meeting at Council Chambers on climate adaptation.

We are just drafting our Climate Adaptation Framework document now, and it will be ready for public release in few weeks for public comment. I will send you a presentation that I prepared last week summarizing the status of work on climate adaptation in Toronto. I just need to get it compressed as it is too large to send.

Please note that ICLR's Dan Sandink is working to help develop a web based Climate Adaptation Reference Collection. We now have 320 docs and counting, relating to adaptation, as relevant to municipalities. Hope to have this up and running in month or so. We would be happy to have Dan share that with you. I recommend that he mail the disk, as it is very large.

I organized a special meeting for David Lapp to come meet some of our key Engineers at the City of Toronto, so thinking on vulnerability to climate change has been on our agenda. Also, I arranged for Darrel Danyluk to be on the expert panel. This occured Jan. 22.

I would be happy to speak over the phone. Today is not so good though, as we have a key deadline for our Adaptation Framework Doc today.

On a separate, but related matter, a class of 4th year Ryerson Students is working on a literature review of "What we know and what we don't know about climate change in Toronto" . I would be grateful if their group spokes person, Sasha Ramroop, could be in touch with you or one of your researchers, to find out what literature collections you can direct them to. I am copying their professor, Frank Duerden, as he would probably be interested to know about your work as well. I am also copying some of the people on the Climate Adaptation Steering Group so that they will be aware of your work.

Best regards,

David MacLeod
Sr. Environmental Specialist
Toronto Environment Office
City of Toronto
City Hall, East Tower 21st floor
100 Queen Street West
Toronto, ON M5H 2N2
Phone: 416 - 392-4340
Fax: 416 - 338-0808
dmacleo2@toronto.ca
www.toronto.ca/teo

Slobodan P. SIMONOVIC
Consulting Engineer, Ltd.

From: Brent Burton [Brent.Burton@metrovancouver.org]
Sent: Tuesday, February 05, 2008 8:35 PM
To: Simonovic, Slobodan
Subject: RE: Water Resources Literature Review

Hi Slobodan,

The only documents that I had to provide were already considered in your report, so I don't have anything further to add at this point.

Thanks for asking though,

Brent

Appendix C.2

Stormwater and Wastewater Literature Review

Literature Review

Stormwater and Wastewater – Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change

Public Infrastructure Engineering Vulnerability Committee (PIEVC)

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1. INTRODUCTION

Engineers Canada, in partnership with Natural Resources Canada through a Contribution Agreement, supervises the Public Infrastructure Engineering Vulnerability Committee (PIEVC). The PIEVC is supported with contributions and inputs from a large array of organizations from different parts of the country and its main objective is to conduct an engineering assessment of the vulnerability of public infrastructure to climate change in Canada and recommend/facilitate a review of infrastructure codes, standards and practices to account for vulnerabilities.

Four categories of infrastructure are being assessed through specific expert working groups (EWGs):

- Buildings
- Roads and associated structures i.e. bridges
- Stormwater and wastewater systems
- Water resource systems

In March 2007, PIEVC completed a general scan of the climate change literature for a review of relevant information and previous work on assessing infrastructure vulnerabilities. Based on that general review, a draft protocol was thereafter developed and applied in a pilot study for the Portage-la-Prairie water works system.

Following this pilot project, a need was identified to produce a more specific scan of the technical literature, with more emphasis on the engineering aspects. Through a service agreement, Aquapraxis inc. was in that context given a mandate to conduct this literature review for the EWG for Stormwater and Wastewater Sytems. The objective was to review and summarize in a report the main findings from engineering, municipal and provincial literature on climate change impacts, vulnerabilities and design considerations for stormwater and wastewater system infrastructure in Canada.

This report provides the summary of the main findings, which will be discussed from different perspectives. After a general overview of the background and the context on climate change in section 2, section 3 discusses different aspects of vulnerability as related to climate change impacts, first in a broad context and also more specifically for stormwater and wastewater systems. Approaches for adaptation responses to climate change that have been proposed and analyzed in the literature are also discussed in section 3. Section 4 provides a review based on the type of infrastructures, discussing separately the literature relating either to wastewater systems or to stormwater systems. A review by region is thereafter given in section 5, highlighting what has been reported not only for different Canadian provinces but also for different parts of the world (Australia, U.K. and Europe. Section 6 gives the review on engineering design and standards whereas section 7 provides a discussion of identified knowledge and research needs.

2. BACKGROUND AND CONTEXT

2.1 Climate change – trends for Canada

The Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC, 2007) asserts that there is "very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming". It is impossible to outline the exact shifts that will occur as a result of climate change but the general consensus suggests that changes in temperature (or, more appropriately, increases in air temperature and changes in precipitation patterns) will alter water quantity and quality around the world and in many cases for worse rather than for better.

For Canada, the IPCC Fourth Assessment Report (Field et al., (IPCC), 2007) outlines the following potential climate changes :

- Warming that is likely to exceed global mean warming
- Warming is likely to be largest in winter and in northern regions
- Annual mean precipitation is very likely to increase but may come in the form of increased extreme events such as heavy rainstorms
- Precipitation in the Prairies and Southern Ontario is likely to increase in winter and spring but decrease in summer
- Length and depth of the snow season is very likely to decrease except in the northern-most regions where snow depth may increase
- Warming is likely to contribute to earlier snowmelts
- Decrease in sea-ice extent and thickness is very likely
- Coastal regions will be exposed to sea level rise

Increases in precipitation in Canada are projected to be in the range of +20% for the annual mean and +30% for the winter (Field et al., (IPCC), 2007). Some studies project widespread increases in extreme precipitation (Christensen et al., (IPCC), 2007: Section 11.5.3.3), with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation. In general, projected changes in precipitation extremes are larger than changes in mean precipitation (Meehl et al., (IPCC), 2007).

Key points from the recent IPCC report for North America (Field et al., (IPCC), 2007) are as follows:

- North America has experienced substantial social, cultural, economic and ecological disruption from recent climate related extremes, especially storms, heat waves and wildfires.

- Continuing infrastructure development, especially in vulnerable zones, will likely lead to continuing increases in economic damage from extreme weather.

- The vulnerability of North America depends on the effectiveness of adaptation and the distribution of coping capacity, both of which are currently uneven and have not always protected vulnerable groups from adverse impacts of climate variability and extreme weather events.

- A key prerequisite for sustainability is 'mainstreaming' climate issues into decision making.

Table 2.1. Recent trends, assessment of human influence on the trend, and projections for extreme weather events for which there is an observed late 20th century trend (Christensen et al. (IPCC), 2007).

Phenomenon and direction of trend	Likelihood[a] that trend occurred in late 20th century (typically post-1960)	Likelihood[a] of a human contribution to observed trend	Likelihood[a] of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	Very likely[b]	Likely[c]	Virtually certain[c]
Warmer and more frequent hot days and nights over most land areas	Very likely[d]	Likely (nights)[c]	Virtually certain[c]
Warm spells/heatwaves. Frequency increases over most land areas	Likely	More likely than not[e]	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	More likely than not[e]	Very likely
Area affected by droughts increases	Likely in many regions since 1970s	More likely than not	Likely
Intense tropical cyclone activity increases	Likely in some regions since 1970	More likely than not[e]	Likely
Increased incidence of extreme high sea level (excludes tsunamis)[f]	Likely	More likely than not[e,g]	Likely[h]

These anticipated changes are expected to directly impact Canada's water resources in several ways, affecting populations across the country. Looking more specifically at stormwater and wastewater systems, increases in temperatures and severity and frequency of extreme rainfall events could have various impacts on the infrastructure and the ecosystems (IC, 2006; Noble et al., 2005; Kling et al., 2003; Lemmen and Warren, 2004):

- Increased rainfall quantity and intensity from extreme events could cause flooding and overtaxing of drainage facilities.
- High volumes of rain will flow quickly across the ground, eroding land along the way and transporting contaminants from roads and agricultural fields to surface and ground waters.
- Increased rainfall quantity and intensity from extreme events could increase overflows from sanitary and combined sewer systems.
- Flooding and sewer overflows could have far-reaching impacts on health and water supply systems as untreated wastewater discharges into lakes and streams, further compromising water quality and possibly tainting both surface and ground water drinking water supplies (Mehdi, B., 2007).
- Treatment plant capacities could be exceeded with higher frequency, with also a modification of the inflows due to the change in the hydrological regime.
- A warmer climate will result in greater evaporation from surface waters and thus reduced base flows, and therefore less assimilative capacity for discharges ,
- Thawing of the permafrost in northern Canada could cause rupture of sewage lines, ruptures of sewage storage tanks, seepage from sewage storage lagoons

and also reduced land stability and increased erosion (Lemmen and Warren, 2004).
- Modifications to the ice regime could produce more frequently ice jams in rivers, which could in turn have an impact on the drainage systems (Mehdi, B, 2007).
- Coastal regions are also at risk from increased erosion due to a decrease in sea ice that usually protects shorelines from winter storms (Mehdi, B., 2006).

These impacts will of course vary with the regions and specific geographic areas. Other general elements that could have an influence on the adaptation measures are given in the recent IPCC report (Parry et al., 2007):

- Higher water temperatures, increased precipitation intensity and longer periods of low flows are likely to exacerbate many forms of water pollution, with impacts on ecosystems, human health, and water system reliability and operating costs (high confidence).

- Climate change affects the function and operation of existing water infrastructure as well as water management practices (very high confidence).

- The negative impacts of climate change on freshwater systems outweigh its benefits (high confidence).

- The resilience of many ecosystems (their ability to adapt naturally) is likely to be exceeded by 2100 by an unprecedented combination of change in climate, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other global change drivers (e.g., land-use change, pollution, over-exploitation of resources) (high confidence).

Zharin et al. (2007) give an up-to-date summary of the performance of global coupled climate models that participated in the IPCC diagnostic for the Fourth Assessment Report. The key elements that are particularly relevant for Canada and urban drainage infrastructures are:

- Cold extremes warm faster than warm extremes by about 30%–40% over the globe, on average, or about 25% over landmasses. Most of this excessive warming is confined to regions where snow and sea ice retreat under the global warming. For example, the magnitude of the warming in cold extremes in the Arctic regions north of 65° N is more than a factor of 2 greater than the corresponding warming in warm extremes. Cold extremes warm faster than warm extremes by about 30% in the European region and up to 50% in the North American region.

- Fractional increases in the intensity of precipitation extremes generally exceed those for mean precipitation. Figure 2.1 shows that the change in mean precipitation is small or negative in the 45^{o} – 10^{o} S and 10^{o} – 40^{o} N zonal bands, whereas the magnitude of extreme precipitation increases by up to 15-20 % in these regions, on average. Figure 2.2 shows the relative changes (%) in globally averaged 20-yr return values of annual 24-h precipitation extremes as a function of the averaged changes in mean temperature, according to different models.

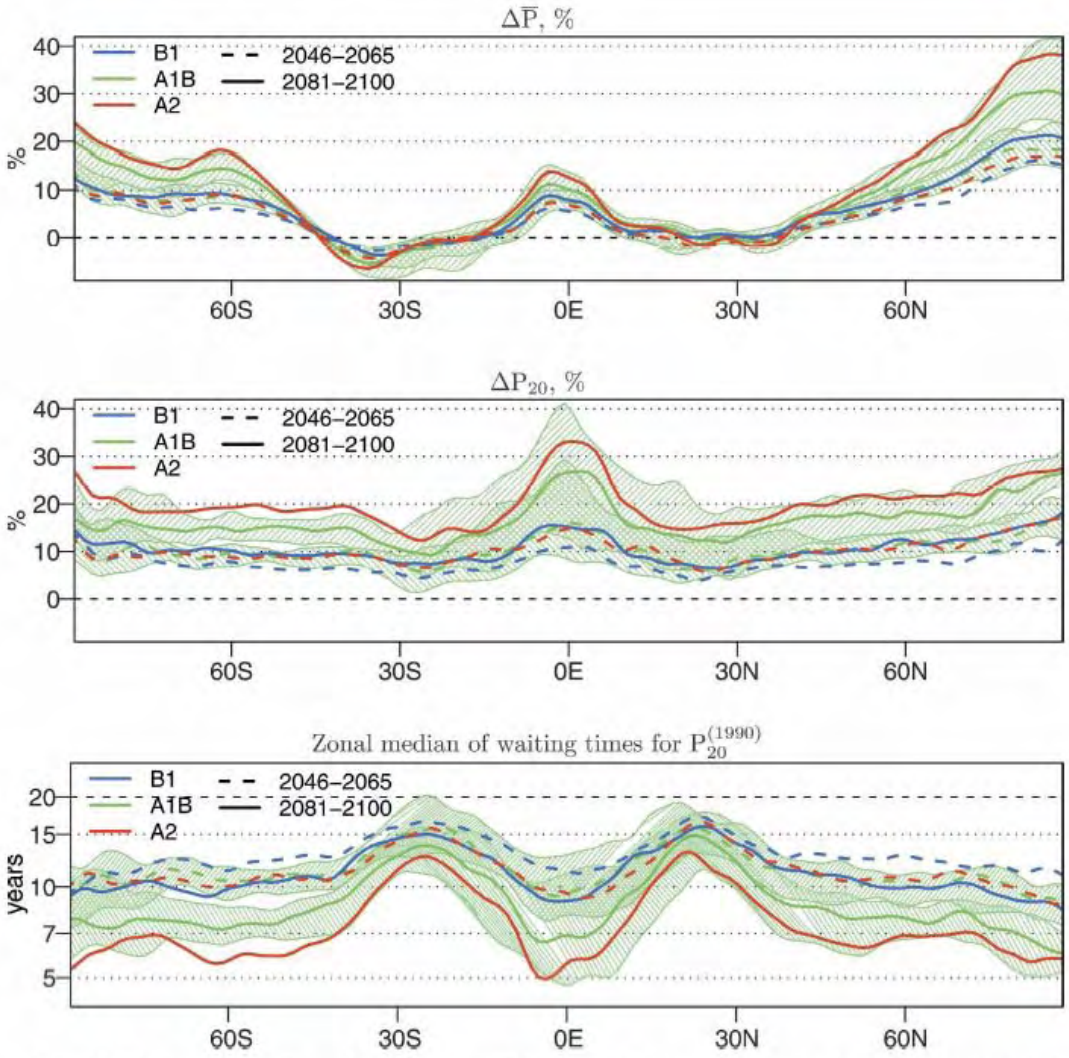


FIG. 14. Multimodel median relative change (%) in (top) the zonally averaged annual mean precipitation rate, (middle) 20-yr return values of annual extremes of 24-h precipitation rates, and (bottom) the zonal median of the waiting times for present-day P_{20} (yr) as simulated by 14 IPCC AR4 models in 2046–65 (dashed lines) and 2081–2100 (solid lines) relative to 1981–2000 in the SRES B1 (blue), A1B (green), and A2 (red) experiments. Light green hatching indicates the central 50% intermodel range for the A1B scenario in the two time periods.

Figure 2.1. Comparison of relative change (%) for zonally averaged annual precipitation and annual extremes (24-h precipitation rates) (Zharin et al., 2007).

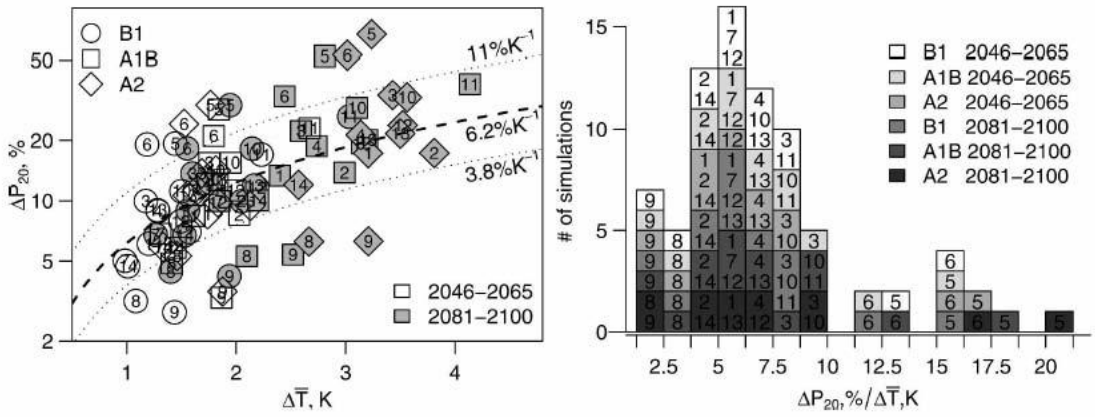


FIG. 16. (left) Relative changes (%) in globally averaged 20-yr return values of annual 24-h precipitation extremes (ΔP_{20}) plotted on a log scale as a function of globally averaged changes in mean surface temperature $\Delta\overline{T}$ (K) simulated by the IPCC AR4 models in the SRES B1 (circles), A1B (squares), and A2 (diamonds) experiments in 2046–65 (empty symbols) and 2081–2100 (gray symbols). The median slope of 6.2% K^{-1} and the 15th and 85th percentiles are indicated by the bold dashed and dotted lines, respectively. (right) Histogram of $\Delta P_{20}/\Delta\overline{T}$ (% K^{-1}) simulated by the IPCC AR4 models in the three scenarios and two time periods. The models are indicated by numbers in both panels as 1: CCCMA CGCM3.1(T47), 2: CCCMA CGCM3.1(T63), 3: CNRM CM3, 4: ECHO G, 5: GFDL CM2.0, 6: GFDL CM2.1, 7: GISS AOM, 8: GISS ER, 9: INM CM3.0, 10: IPSL CM4, 11: MIROC3.2(hires), 12: MIROC3.2(medres), 13: MPI ECHAM5, and 14: MRI CGCM2.3.2.

Figure 2.2. Relative changes (%) as a function of the averaged changes in mean temperature, according to different models. (Zharin et al., 2007).

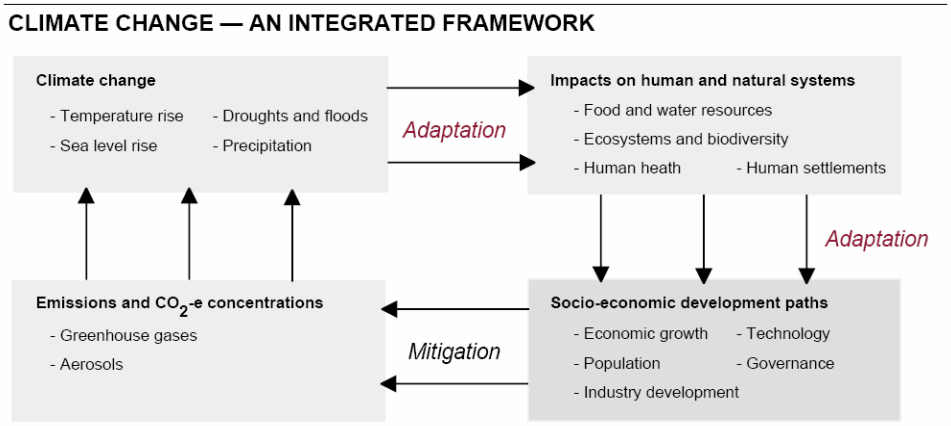
2.2. Climate change assessment

Assessments of climate change impacts, adaptation and vulnerability (CCIAV) are undertaken to inform decision making in an environment of uncertainty. In the recent IPCC report (Carter et al., 2007), five approaches to CCIAV are identified. Four are conventional research approaches: impact assessment, adaptation assessment, vulnerability assessment, and integrated assessment. The fifth approach, risk management, has emerged as CCIAV studies have begun to be taken up in mainstream policy-making. Table 2.1 presents different characteristics of each of the four approaches.

Table 2.2. Some characteristics of different approaches to CCIAV assessment. Note that vulnerability and adaptation-based approaches are highly complementary (Carter et al., (IPCC), (2007).

	Approach			
	Impact	**Vulnerability**	**Adaptation**	**Integrated**
Scientific objectives	Impacts and risks under future climate	Processes affecting vulnerability to climate change	Processes affecting adaptation and adaptive capacity	Interactions and feedbacks between multiple drivers and impacts
Practical aims	Actions to reduce risks	Actions to reduce vulnerability	Actions to improve adaptation	Global policy options and costs
Research methods	Standard approach to CCIAV Drivers-pressure-state-impact-response (DPSIR) methods Hazard-driven risk assessment	Vulnerability indicators and profiles Past and present climate risks Livelihood analysis Agent-based methods Narrative methods Risk perception including critical thresholds Development/sustainability policy performance Relationship of adaptive capacity to sustainable development		Integrated assessment modelling Cross-sectoral interactions Integration of climate with other drivers Stakeholder discussions Linking models across types and scales Combining assessment approaches/methods
Spatial domains	Top-down Global → Local	Bottom-up Local → Regional (macro-economic approaches are top-down)		Linking scales Commonly global/regional Often grid-based
Scenario types	Exploratory scenarios of climate and other factors (e.g., SRES) Normative scenarios (e.g., stabilisation)	Socio-economic conditions Scenarios or inverse methods	Baseline adaptation Adaptation analogues from history, other locations, other activities	Exploratory scenarios: exogenous and often endogenous (including feedbacks) Normative pathways
Motivation	Research-driven	Research-/stakeholder-driven	Stakeholder-/research-driven	Research-/stakeholder-driven

A report from Infrastructure Canada (IC, 2006) provides an overview of the research and concern regarding climate change in Canada and elsewhere. In recent years, it has become obvious that adaptation measures had to be developed because it was realized that mitigation, though necessary for reducing impacts, would not prevent climate change from occurring (Lemmen and Warren, 2004). In contrast to mitigation, which involves addressing the causes of climate change, adaptation refers to activities "that minimize the negative impacts of climate change, and/or position us to take advantage of new opportunities that may be presented." Figure 2.3 provides an integrated framework to respond to climate change (Allen Consulting Group, 2004).



Source: Adapted from L. Srivastava and T. Heller, 2003, *Integrating Sustainable Development and Climate Change in AR4*, p. 3.

Figure 2.3. Integrated framework for climate change (Allen Consulting Group, 2004)

Apart from mitigation and adaptation, resiliency could be added as a third component (Sheltair Group, 2003) : to assume that the future will include a major element of surprise, and that urban systems must be designed and operated in ways that accommodate sudden and unexpected changes in climate. A prudent approach is to assume that some of the predictions will be wrong, and that the system may react in surprising ways. Resiliency is “a concept that embraces two characteristics: the robustness or strength of a system when subjected to stress, and the adaptability of a system in response to changing conditions and objectives. The term can be applied both to governance systems and to the many elements and features of the built environment. Resiliency implies responsive governance systems - decision-making processes that can quickly identify and respond to new priorities or new threats.

Incorporating resiliency into our urban systems means that the region must enhance the personal and collective capacity of individuals and institutions to respond to unexpected economic, social, and environmental change. Self-organization is a feature of resilient systems, since self-organized systems respond more quickly to changing circumstances, allowing for more innovative solutions.

Adaptability is another key aspect of resiliency, and can be broken down into a number of simple elements such as:

- Flexibility, or enabling minor shifts in how systems function or spaces are used;
- Convertibility, or allowing for changes in use for parcels of land or buildings, or changes in inputs for infrastructure systems; and
- Expandability, or facilitating additions (or deletions) to the quantity of land or space dedicated to particular uses.

Compartmentalization, modularization and ‘clustering’ are design concepts that help to reduce the vulnerability of systems to the failure of any single part. When such concepts are applied to urban systems, the result is sometimes referred to as ‘distributed infrastructure’. Redundancy and self-reliance are design strategies that also reduce vulnerability for urban systems. Redundancy compensates for weak links in the system as a whole. Self-reliance provides a contingency plan, to ensure that critical goods and services can be provided should all the links be compromised.

All these characteristics – such as robustness, adaptability, durability, redundancy, and self-reliance - contribute to resilient systems, and in so doing, may reduce the region’s vulnerability to climate change and other shocks to the urban system.

The Infrastructure Canada report (IC, 2006) highlights the fact that there are challenges at the federal level and also at the provincial and municipal levels. In Canada, due to budget cuts and shifting priorities, responsibility for water management has been passed from one-level of government to the next, such that resource management regularly falls on the shoulders of municipalities (Thirlwell et al., 2007). According to a report produced by Natural Resources Canada in 2006, Canadian municipalities have demonstrated leadership in their mitigation efforts but have given far less attention to adaptation (Mehdi, B., ed. (2006). Other published reports (Australian Government, 2007) also emphasizes the fact that many adaptation actions are to be taken at the local government level.

National climate change reports are prepared by Environment Canada and gives a good overview of the general relevant activities and programs related to climate change (Environment Canada, 2006). The third report was released in 2001 and the fourth in 2007.

Much work is needed on climate change adaptation in Canada, and particularly adaptation for infrastructure (IC, 2006).

3. VULNERABILITY AND ADAPTATION RESPONSES

Adaptation to climate change is a challenge that is complex and involves increasing risk. Efforts to manage these risks can involve many decision-makers, conflicting values, competing objectives and methodologies, multiple options, uncertain outcomes and debatable probabilities (Noble et al., 2005). Adaptation occurs at multiple levels in a complex decision environment, and is generally evaluated as better-worse, not right-wrong, based on multiple criteria. Identifying the best adaptation response is difficult, and as a result, people may deny, delay or defer important actions. Risk management techniques and vulnerability assessment help to overcome these problems.

3.1. General vulnerability and risks concepts

Many recent publications have discussed the risk management approach to adaptation to climate change (IC, 2006; Noble et al., 2005; Lemmen and Warren, 2004; IPCC, 2007; Allen Group, 2005; Olmos, 2001). Noble et al. (2005) discusses general risk management approaches that have been developed, notably the CSA Guideline CAN/CSA-Q850-97, *Risk Management: Guideline for Decision-Makers.* Figure 3.1 shows the general steps of the risk management process for the identification, analysis, evaluation and control of risks and potential risks, including risks to health and safety. Figure 3.2 provides an application of the approach to climate change. As shown in Table 3.1, different definitions exist and could be discussed in a context of climate change (Brooks, 2003).

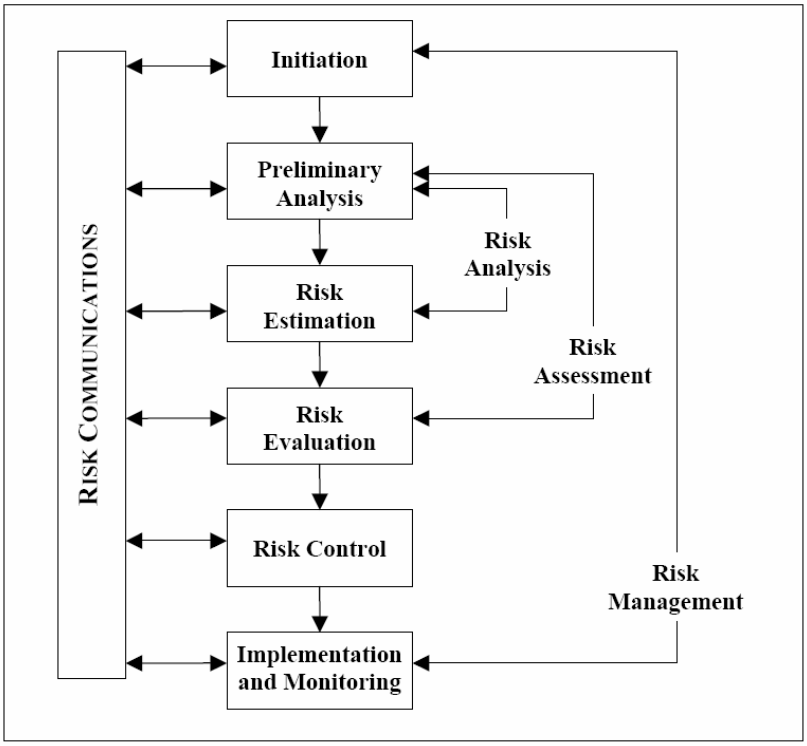


Figure 3.1 The Canadian Standards Association risk management approach (Noble et al., 2005).

1. **Initiation:** The potential climate change impact and the risks associated with it are defined. The stakeholders, organisations or groups that should be involved in the process are identified. Responsibilities, resources, timeframes and authorities are assigned. Other concerned stakeholders and interested parties are identified, information needs are assessed and the consultative process is initiated.
2. **Preliminary Analysis:** The scope of the issue and the decisions that will be needed are decided. The hazards and the risks are defined using risk scenarios and those who could be affected identified. The analysis of stakeholders who could be affected and/or interested is started. The consultation process is implemented and the risk information "library" started.
3. **Risk Estimation:** The methodology for estimating or quantifying the frequency and severity associated with the hazards is selected. Estimations are made of the frequency of risk scenarios. The consequences or potential results of the risk scenarios are estimated. Through ongoing consultation with stakeholders, the stakeholder analysis is refined.
4. **Risk Evaluation:** The costs of negative outcomes and benefits are estimated, based on the stakeholders' values. The consultation process and stakeholder analysis continue. The acceptability of various risks to stakeholders is assessed.
5. **Risk Control:** Feasible risk control options and opportunities are identified. Risk control options are analyzed and evaluated in terms of cost, benefits, effectiveness, acceptability with stakeholders, residual risks and other factors. Through ongoing consultation with stakeholders, the risk control options are decided.
6. **Action and Monitoring:** An implementation plan is developed. Selected risk control measures are implemented. Financing and communications strategies are developed and implemented. The effectiveness of risk management process is evaluated. A monitoring process and "sunset" timeframes (if applicable) are established. Dialogue with stakeholders is continued. The entire process is repeated with updated information and experience, as appropriate.
7. **Risk Communications:** Risk communications comprise a continual and meaningful dialogue among stakeholders at all stages in the process, including the final decision-making process. It is important to include all stakeholders, including parties who *think* they are stakeholders. Ineffective risk communications may lead to irreplaceable loss of management credibility, unnecessary and costly conflicts with government, difficult and expensive approval processes and bitter and protracted debates with stakeholders, diversion of management attention from important problems, non-supportive and critical employees, and unnecessary human suffering due to high levels of anxiety and fear.

Figure 3.2. Description of steps in the risk management process, applied to adaptation to climate change (Noble et al., 2005).

Table 3.1 Definitions of risk in the literature (Brooks, 2003).

Author(s)	Risk definition
Smith, 1996 (p5)	Probability x loss (probability of a specific hazard occurrence) *Hazard = potential threat*
IPCC, 2001 (p21)	Function of probability and magnitude of different impacts
Morgan and Henrion, 1990 (p1)/Random House, 1966	"Risk involves an 'exposure to a chance injury or loss'"
Adams, 1995 (p8)	"a compound measure combining the probability and magnitude of an adverse affect"
Jones and Boer, 2003; (also Helm, 1996)	Probability x consequence *Hazard: an event with the potential to cause harm, e.g. tropical cyclones, droughts, floods, or conditions leading to an outbreak of disease-causing organisms.*
Downing et al., 2001	Expected losses (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period *Hazard: a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area.*
Downing et al., 2001	Probability of hazard occurrence *Hazard = potential threat to humans and their welfare*
Crichton, 1999	"Risk" is the probability of a loss, and depends on three elements, hazard, vulnerability and exposure."
Stenchion, 1997	"Risk might be defined simply as the probability of occurrence of an undesired event [but might] be better described as the probability of a hazard contributing to a potential disaster…importantly, it involves consideration of vulnerability to the hazard."
UNDHA, 1992	"Expected losses (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability."

In the context of climate change, vulnerability is defined by the Intergovernmental Panel on Climate Change (IPCC) 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." In other words, the vulnerability approach takes into consideration not only the impacts predicted by climate scenarios and socioeconomic scenarios, but also a system's capacity for coping with those impacts.

Prioritizing adaptation action requires the identification of vulnerable systems — human and natural — the costs if these fail, the scope to reduce this risk, and the ability to capture any potential benefits (Allen Consulting Group, 2005). As shown on Figure 3.3, vulnerability is a function of exposure to climate factors, sensitivity to change and capacity to adapt to that change. Systems that are highly exposed, sensitive and less able to adapt are vulnerable.

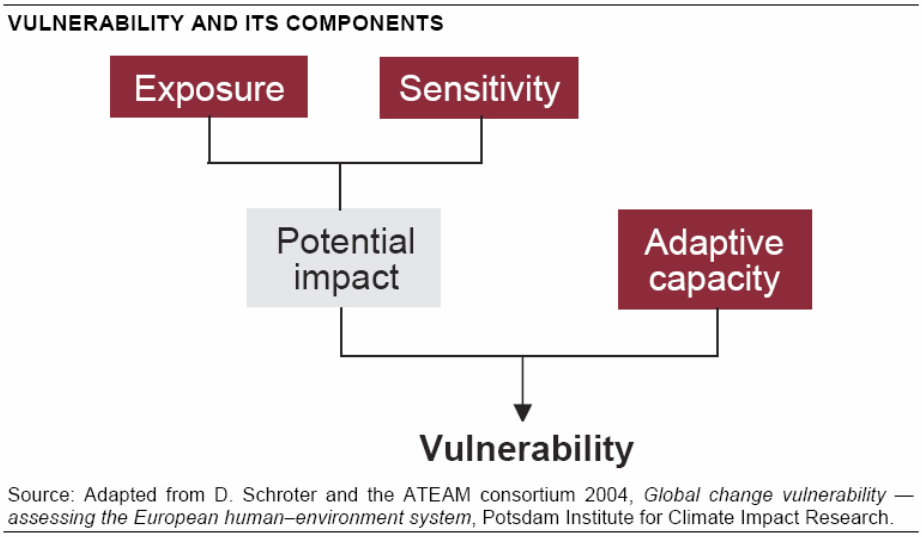


Figure 3.3. Vulnerability and its component (Allen Consulting Group, 2005).

Another way to define the concept of vulnerability is given in Figure 3.4.

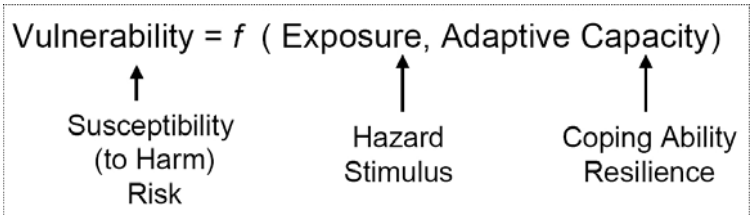


Figure 3.4. Vulnerability and its component (Allen Consulting Group, 2005).

It is important to distinguish vulnerability from sensitivity (Lemmen and Warren, 2004), which is defined as "the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli." Sensitivity does not account for the moderating effect of adaptation strategies, whereas vulnerability can be viewed as the impacts that remain after adaptations have been taken into account. Therefore, although a system may be considered highly sensitive to climate change, it is not necessarily vulnerable. Social and economic factors play an important role in defining the vulnerability of a system or region.

The framework for assessing comparative risk should incorporate system vulnerability, the consequences of system failure or reduction, and the scope to improve likely outcomes through planned adaptation.

The vulnerability approach is an iterative process involving five steps (Lemmen and Warren, 2004):

- engage stakeholders;
- assess current vulnerability;
- estimate future conditions;
- estimate future vulnerability; and
- assess and implement options.

The starting point for a vulnerability assessment is the system itself (e.g. community, region or sector) and this approach builds a strong foundation of knowledge regarding an area and its vulnerability before laying future climate scenarios over that matrix, reducing in this way the high degree of uncertainty associated with the old approach (IC, 2006). Figure 3.5 provides a general outline of the vulnerability approach.

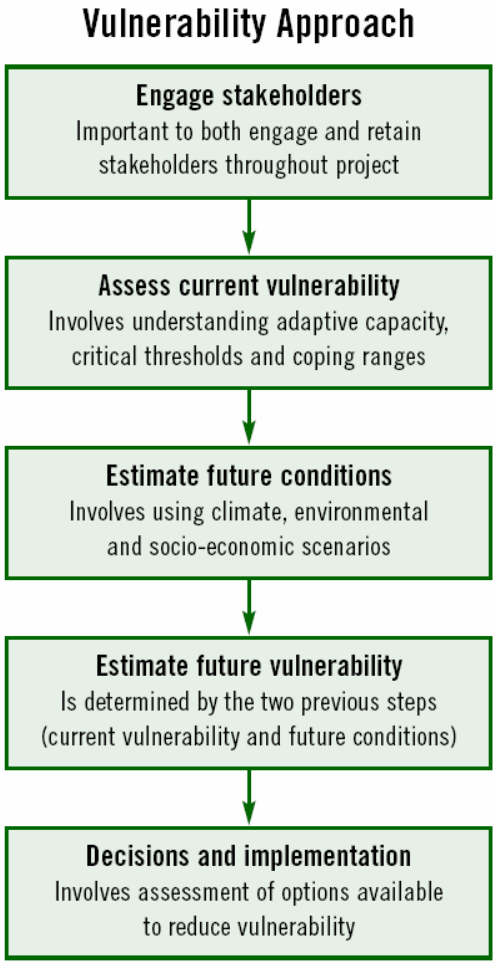


Figure 3.5. Steps in the vulnerability approach – process should be iterative (Lemmen and Warren, 2004).

The current vulnerability of a system is influenced by the interrelated factors of adaptive capacity, coping ranges and critical thresholds (Lemmen and Warren, 2004). Adaptive capacity is defined as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. More simply, adaptive capacity is a measure of a system's ability to adapt to change.

By examining response to past climatic variability, it is possible to define the coping range of a given system (Figure 3.6). The coping range refers to the "range of circumstances within which, by virtue of the underlying resilience of the system, significant consequences are not observed"(Yohe and Tol, 2002). Critical thresholds can

be viewed as the upper and lower boundaries of coping ranges, and are usually location specific. Significant impacts are expected to occur when critical thresholds are exceeded.

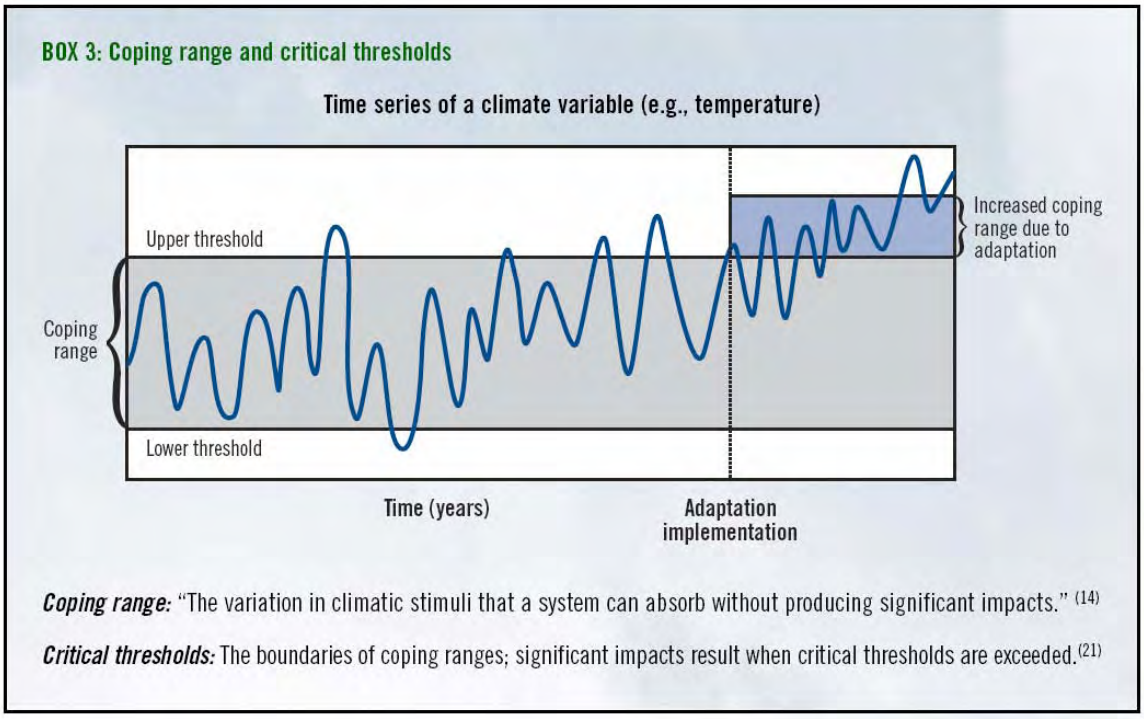


Figure 3.6. Coping range and critical thresholds (Lemmen and Warren, 2004)

It should also be recognized that future vulnerability depends not only on climate change but also on development pathway. This is why recent studies have been based on climate change scenarios but also on socio-economic scenarios (Lemmen and Warren, 2004; Semadeni-Davies et al., 2004, 2007 and 2008).

3.2. Quantifying the vulnerability

For water infrastructure, quantifying the risks and vulnerability implies taking into account (CSIRO, 2007):

- Extreme events
- Accelerated degradation of material and structures
- Resource demand pressures

A recent Australian report (CSIRO) bases its risk and vulnerability on the Australian Standard AS/NZS 4360:2004 + HB436 Risk Management. The assumptions used are as follows:

1. In assessing the risk using the Australian Standard AS/NZS 4360:2004 + HB436 Risk Management, the consequences were assessed using the worst case scenario for an event or impact on materials over time;

2. No adaptation response has been undertaken to mitigate against climate change impacts for 2030 and 2070;
3. The financial impacts estimated do not include consequential losses;
4. All dollar figures are in 2006 dollars;
5. The social and governance risks are considered in the risk assessment, with some of the risks identified being directly related to forced management responses imposed by a combination of climate change impacts to infrastructure and expectations of service delivery;
6. Where possible quantitative measures were used to classify the level of risk, and link likely consequences to historical events; and
7. It is acknowledged that a proportion of the infrastructure assessed would be near the end of its design life and was intentionally included as replacement of these assets is at risk of not being designed for future climatic conditions.

The same report (CSIRO, 2007) describes the aspects assessed :

- Infrastructure services – Negative impacts to human-made physical infrastructure and the intended service it provides to the community, industry, government and the natural environment;
- Social – Negative impacts to human health, amenity and community. Level of public response to impacts;
- Governance – Negative impacts to management of organisations and government. Legal, regulatory and management responses; and
- Finance – Costs including necessarily ancillary plant/equipment to maintain (e.g. air conditioning equipment), repair and replace infrastructure and the intended service it provides. Wider economic impacts are not implied.

Table 3.2 provides a qualitative evaluation of the consequences for the infrastructure whereas Table 3.3 gives the qualitative measures of likelihood. A combination of the two tables was thereafter used to produce the risk rating matrix shown in Table 3.4. The water sector was recognized as a sector with high riks (CSIRO, 2007).

Another example for a decision-support matrix is given in Figure 3.7 (CSA, 2006).

Table 3.2. Qualitative evaluation of the consequences (CSIRO, 2007).

Level	Descriptor	Infrastructure Service	Social	Governance	Financial
1	Insignificant	No infrastructure damage.	No adverse human health effects or complaint.	No changes to management required.	Financial loss of less then $2M[1].
2	Minor	Localised infrastructure service disruption. No permanent damage. Some minor restoration work required. Early renewal of infrastructure by 10-20%. Need for new/modified ancillary equipment.	Short-term disruption to employees, customers or neighbours. Slight adverse human health effects or general amenity issues. Negative reports in local media.	General concern raised by regulators requiring response action.	Additional operational costs. Financial loss $2$10M).
3	Moderate	Widespread (state) infrastructure damage and loss of service. Damage recoverable by maintenance and minor repair. Partial loss of local infrastructure. Early Renewal of Infrastructure by 20-50%.	Frequent disruptions to employees, customers or neighbours. Adverse human health effects. Negative reports in state media.	Investigation by regulators. Changes to management actions required.	Financial loss ($10M-$50M).
4	Major	Extensive infrastructure damage requiring extensive repair. Permanent loss of regional infrastructure services, e.g. a bridge washed away by a flood event. Early renewal of Infrastructure by >50%.	Permanent physical injuries and fatalities may occur from an individual event. Negative reports in national media. Public debate about infrastructure performance.	Notices issued by regulators for corrective actions. Changes required in management. Senior management responsibility questionable.	Major financial loss ($50M-$200M).
5	Catastrophic	Permanent damage and/or loss of infrastructure service across state. Retreat of infrastructure support and translocation of residential and commercial development.	Severe adverse human health effects – leading to multiple events of total disability or fatalities. Emergency response. Negative reports in international media.	Major policy shifts. Change to legislative requirements. Full change of management control.	Significantly high financial loss (>$200M).

Table 3.3. Qualitative measures of likelihood (CSIRO, 2007).

Level	Descriptor	Description
A	Almost Certain	The event is expected to occur in most circumstances
B	Likely	The event will probably occur in most circumstances
C	Moderate	The event should occur at some time
D	Unlikely	The event could occur at some time
E	Very Unlikely	The event may occur only in exceptional circumstances

Table 3.4. Risk rating matrix (CSIRO, 2007).

Likelihood	Consequences				
	Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
A (almost certain)	L	M	H	E	E
B (likely)	L	M	M	H	E
C (moderate)	L	L	M	H	E
D (unlikely)	L	L	M	M	H
E (very unlikely)	L	L	L	M	M

E - Extreme risk, requiring immediate action.
H - High risk issue requiring detailed research and planning at senior management level.
M - Moderate risk issue requiring change to design standards and maintenance of assets.
L - Low risk issue requiring action through routine maintenance of assets.

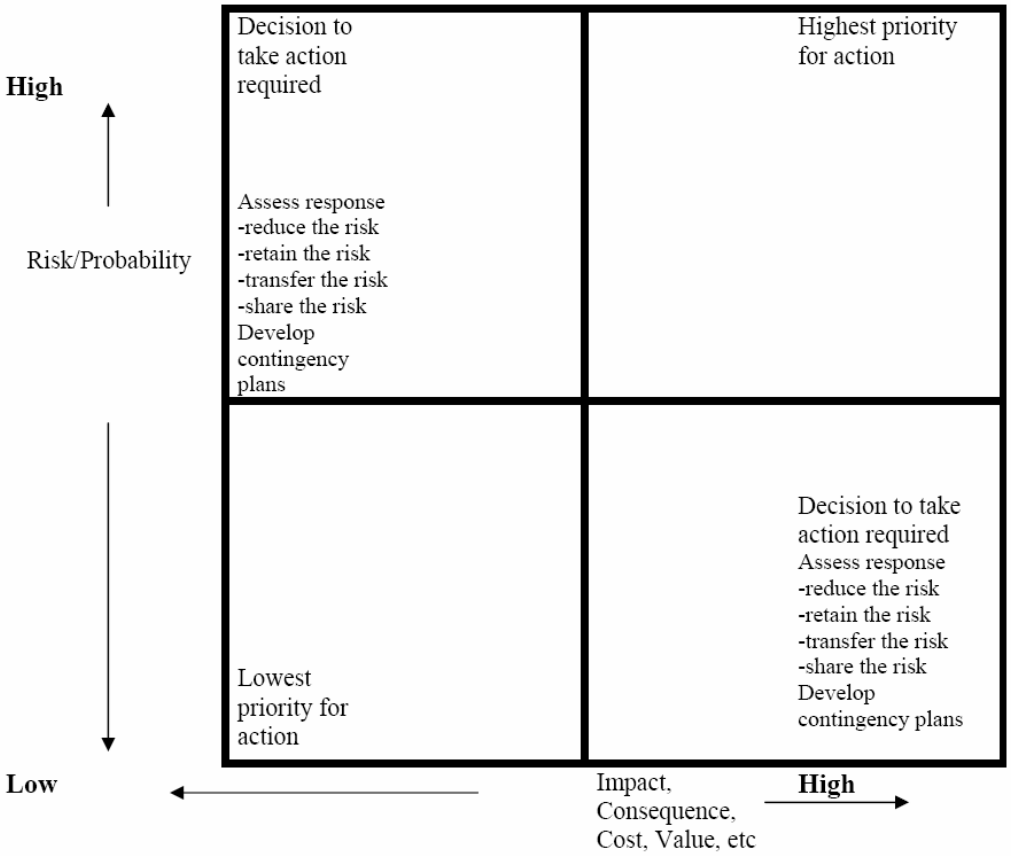


Figure 3.7. Sample Decision-support Matrix on Infrastructure Impacts/Adaptation priority setting (CSA, 2006).

Certain attributes of infrastructure influence its adaptability to change (IC, 2006). For infrastructure with long life spans (like many elements of the stormwater and wastewater systems – see Figure 3.8) "expected changes in climate may occur considerably earlier during the expected service life, possibly forcing expensive reconstruction, retrofit or relocation." Many reports (Mirza and Haider, 2003; Knight, M. et al., 2003) have highlighted the fact that the infrastructure deficit is important (see Figure 3.9) and that just bringing all municipal infrastructure up to an acceptable level will be costly. Clearly,

there are limited funds for maintaining our infrastructure and building new infrastructure, let alone researching, redesigning and retrofitting infrastructure for climate change impacts. On the other hand, if so much of our infrastructure is in need of replacement or rehabilitation, then this may be an opportune time for climate change adaptation to become an element of infrastructure design (IC, 2006).

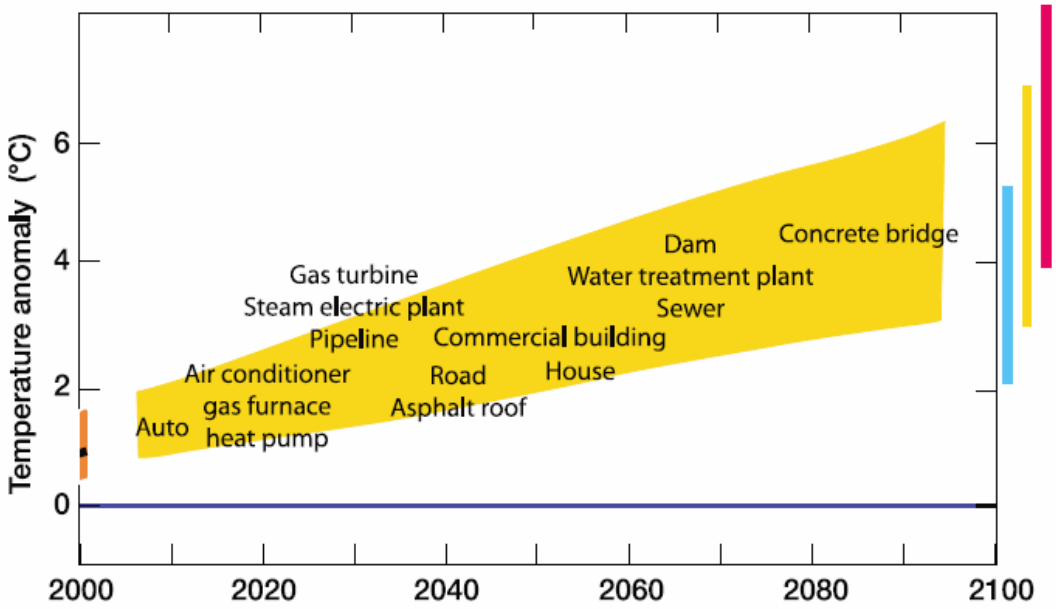
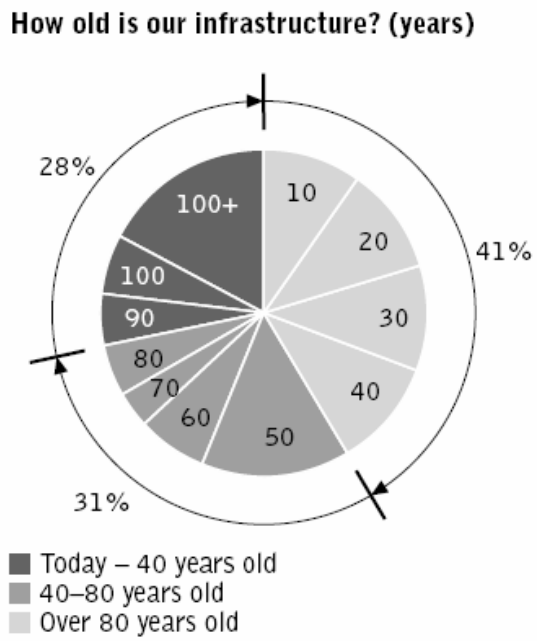


Figure 3.8. Typical infrastructure lifetimes in North America (Field et al., 2007).



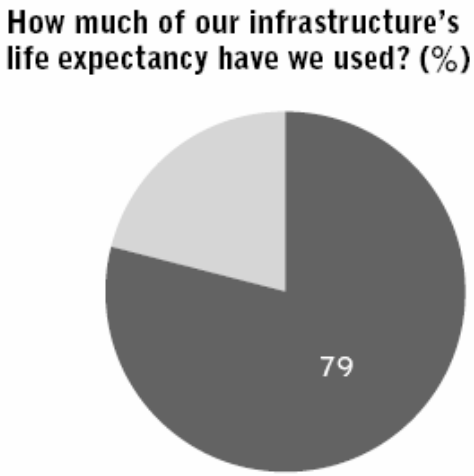


Figure 3.9. Statistics for public infrastructure in Canada (Knight et al., 2003).

3.3. Adaptive responses

Figure 3.10 illustrates the different classes of adaptive responses. Depending on the characteristics of the system, it may be needed to implement an autonomous or planned response. The autonomous adaptation is a response to change as it occurs, essentially a response induced by realized climate trends or events. Both human and natural systems will adapt autonomously to climate change. By contrast, planned adaptation is a response in anticipation of an event (Allen Consulting Group, 2005).

CLASSES OF ADAPTIVE RESPONSE

		Planned	Autonomous
Natural		*(human intervention required)*	- Changes in growth period - Changes in species - Migration of ecosystem - Relocation of wetland
Human	Private	- Insurance - Raising houses - Managing natural systems	- Changes in farming - Air conditioning
	Public	- Early warning systems - Building codes, zoning laws - Relocation - Urban greening - Managing natural systems	- Water management - Raising dikes - Beach nourishment - Subsidies

Source: Adapted from N. Minmura 2004, *Past Findings and Future Discussions on Adaptation — Opportunities, Limitations and Barriers,* presented at PCC Expert Meeting on The Science Address UNFCCC Article 2 including Key Vulnerabilities.

Figure 3.10. Classes of adaptive responses to climate change (Allen Consulting Group, 2005).

There exists a wide range of responses to the threat of climate change, which have been summarized by the United Nations Environment Programme (Feenstra et al., 2003):

- *Bear the loss*
- *Share the loss*
- *Modify the threat*
- *Prevent effects*
- *Change use*
- *Change location*
- *Research*
- *Educate, inform and encourage behavioural change*

Figure 3.11 shows and develops the different available adaptation strategies.

Category	Explanation	Example
Bear the costs	Do nothing to reduce vulnerability and absorb losses	Allow household lawns and gardens to wither
Prevent the loss	Adopt measures to reduce vulnerability	Protect coastal communities with seawalls or groins
Spread or share the loss	Spread burden of losses across different systems or populations	Crop insurance
Change the activity	Stop activities that are not sustainable under the new climate, and substitute with other activities	Make ski resort a four-season facility to attract tourists year round
Change the location	Move the activity or system	Move ice fishing operations farther north
Enhance adaptive capacity	Enhance the resiliency of the system to improve its ability to deal with stress	Reduce non-climatic stresses, such as pollution

Figure 3.11. Adaptation strategies (Lemmen and Warren, 2004)

The decision to invest in adaptive capacity requires a consideration of the costs and expected payoffs or benefits of a decision — and the time profile of those investment flows. Decision makers must decide between irreversible, short run investments in adaptive capacity, which one may or may not in the end require, and the potential long term benefits of that investment (Allen Consulting Group, 2005). Adaptation is ultimately about maximizing welfare over time. The decision to adapt need not be a once and for all, immutable decision; the optimal response may be a blend of responses — reviewed and revised periodically through time as more information and experience comes available.

The ability of natural systems to cope with these challenges will be largely dependant on their *autonomous* or reactive capacities — their innate ability to withstand and successfully respond to changes in the climatic and environmental conditions to which they are currently adapted. The autonomous adaptive capacity of human systems will also be tested by climate change. However, the ability of human beings to analyze, plan and coordinate action also allows for a *planned* adaptation response. Adaptation planning represents a strategic approach to climate change that seeks to build systems more able to cope with future climate events. This approach is represented in Figure 3.12.

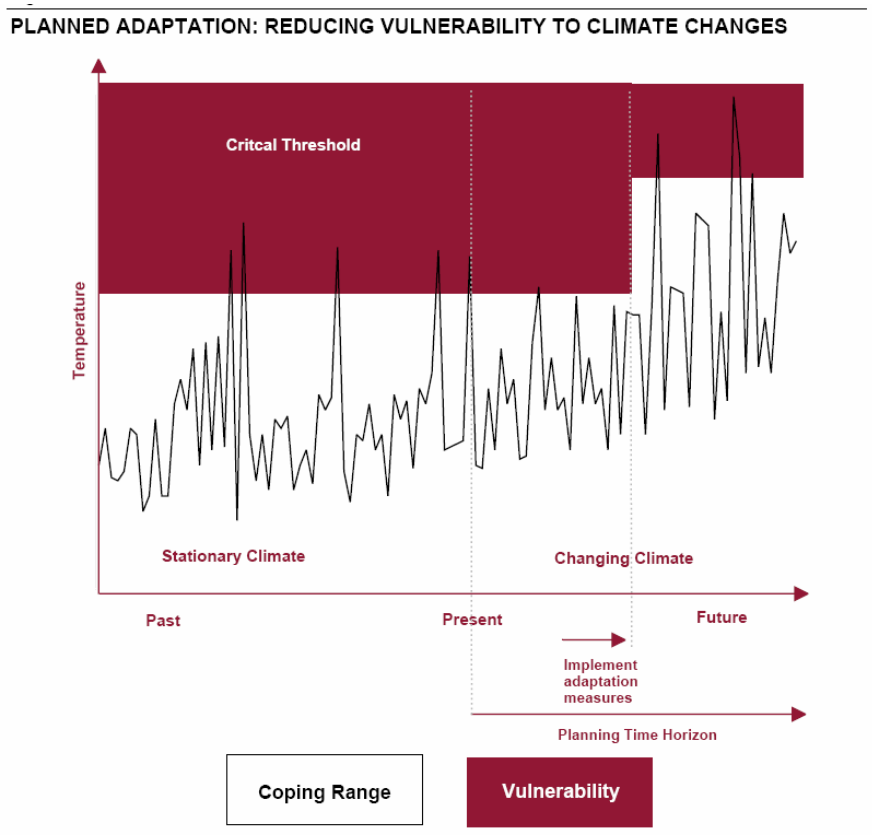


Figure 3.12. Planned adaptation to climate change (Allen Consulting Group, 2004).

Keys issues for planning adaptation are presented in Figure 3.13.

Issues for consideration:

- What are the key threats, potential costs and disruptions that would be associated with greater variability in the climate system and incremental changes to the range of current climate outcomes?
- What changes and resources are required to enable vulnerable industries, activities and eco-systems to cope better with climate change?
- What knowledge or capacity gaps might exist within your region or industry to climate change risks?
- How do you expect the climate vulnerabilities of key systems to change over time?
- Who has responsibility for responding to these threats, and how effectively are social and environmental exposures reflected in their decision-making?
- Are there current policies and regulations in place that inhibit adjustment and adaptation in significantly exposed areas and activities?
- How can government efforts best be directed toward facilitating adjustment to climate change and enhancing risk assessment and planning processes?
- What are the costs and opportunities for improving the capacity of existing systems to cope with more variable or extreme climate events?
- Are there simple low cost actions that can be taken now that will protect against heavy costs later?
- What are the priority areas for government coordination and stewardship?

Figure 3.13. Issues to be considered in planning adaptation responses and reducing vulnerability (Allen Consulting Group, 2004).

'No regrets' and the 'Precautionary Principle' are two policy stances that have emerged as key words in the greenhouse policy literature. They apply both to strategies to reduce emissions and how to cope with potential impacts. Smith (1997) reports simple definitions:

- the 'no regrets' option can be regarded as 'measures worth doing anyway' (p. 15)
- the 'precautionary principle' 'can be stated as a means 'to invest more than would otherwise have been invested' in order to '… enhance the economy's ability to adapt should climate change damages occur'(p.26).

As discussed before, adaptation and mitigation actions need to account for the variable lifecycles and service life of infrastructure (Auld et al., 2007b). Lifecycle considerations are important to infrastructure planners, designers, owners and operators.

4. REVIEW BY TYPE OF INFRASTRUCTURES

As noted by Lemmen and Warren (2004), water resources are frequently cited as one of the highest priority issue in Canada. Water infrastructure is perhaps the most vulnerable of all types of infrastructure to climate change, and the importance of water to human health, the economy and the environment also make it one of the most critical types of infrastructure. Furthermore, this type of infrastructure has the potential to suffer the greatest damages or losses associated with climate change unless proactive adaptation actions are taken. The impacts of climate change on water infrastructure could result in a myriad of problems such as increased water demand, water apportionment issues, loss of potable water, increased water quality problems, increased risk of flooding, and sewer overflows (IC, 2006).

Sanitary sewers, stormwater sewers (with drainage for roads) and sewage treatment represent a large part of the total public infrastructure (see Table 4.1 - Harchaoui et al., 2003). Impacts on these elements from climate change could therefore have important consequences.

The expense of adapting water infrastructure is a key issue (IC, 2006). For example, one study estimated the cost for wastewater treatment adaptation in Canada and found that Niagara region's costs may range from $8 to $24 million, while Toronto's costs may range from $633 million to $9 billion (Dore and Burton, 2003). Rather than costly adaptations such as changes to pipe size, changes and modifications such as increases in reservoir capacity may be sufficient in some cases. A study in North Vancouver found that drainage infrastructure could be "adapted to more intense rainfall events by gradually upgrading key sections of pipe during routine, scheduled infrastructure maintenance." When changes to infrastructure such as pipe size *are* necessary, it is predicted to be less costly than the possible losses due to failed infrastructure.

Table 4.2 shows the projected impacts on the meteorological and hydrological parameters for Canada (Noble et al., 2005). The most important factor is the increase in extreme rainfall events, which would influence the level of service for stormwater sewers and wastewater sewers and treatment plants.

Table 4.1. The structure of public infrastructure capital stock by asset (current prices) (Harchaoui et al., 2003).

	1961		1973		1979		1988		2000	
	$Billion	%	$Billion	%	$Billion	%	$Billion	%	$Billion	%
	Local public infrastructure capital stock									
Highways and roads	1.4	47.9	5.0	48.8	11.1	47.0	20.8	42.9	35.5	45.0
Sewage treatment	0.3	11.2	1.2	11.4	2.8	11.9	6.3	13.0	9.6	12.2
Sanitary sewers	0.4	12.8	1.3	13.1	3.3	13.8	7.5	15.5	13.7	17.3
Bridges	0.1	4.2	0.4	4.0	1.0	4.3	2.2	4.6	3.5	4.4
Canals and waterways	0.1	3.9	0.5	4.5	1.2	5.1	3.0	6.2	4.5	5.7
Outdoor recreational	0.1	4.7	0.4	4.3	1.1	4.6	2.2	4.6	3.2	4.0
Waste disposal facilities	0.1	2.9	0.3	2.5	0.6	2.6	1.2	2.4	1.5	1.9
Irrigation facilities	0.1	5.2	0.5	5.0	1.0	4.4	2.2	4.5	2.9	3.7
Other	0.2	7.1	0.7	6.4	1.5	6.4	3.1	6.3	4.5	5.7
Total	**2.9**	**100.0**	**10.2**	**100.0**	**23.6**	**100.0**	**48.5**	**100.0**	**78.9**	**100.0**
	Provincial public infrastructure capital stock									
Highways and roads	2.9	68.4	10.2	69.4	22.6	68.1	34.9	64.2	44.7	68.7
Bridges	0.3	7.7	1.1	7.3	2.6	7.9	5.0	9.2	6.2	9.5
Sewage treatment	0.2	4.2	0.6	4.2	1.5	4.4	2.7	5.1	2.5	3.9
Sanitary sewers	0.2	4.3	0.6	4.4	1.5	4.7	3.0	5.5	3.1	4.7
Canals and waterways	0.1	2.0	0.3	2.2	0.9	2.6	1.8	3.4	2.1	3.2
Reservoirs	0.1	1.5	0.2	1.5	0.5	1.4	0.8	1.5	0.9	1.4
Outdoor recreational	0.1	2.4	0.3	2.2	0.8	2.3	1.3	2.3	1.1	1.6
Irrigation facilities	0.1	2.1	0.3	2.0	0.6	1.8	1.1	2.0	1.1	1.7
Other	0.3	7.5	1.0	6.8	2.3	6.8	3.7	6.8	3.4	5.2
Total	**4.2**	**100.0**	**14.6**	**100.0**	**33.2**	**100.0**	**54.4**	**100.0**	**65.1**	**100.0**
	Federal public infrastructure capital stock									
Highways and roads	0.4	18.6	0.9	19.6	1.5	19.9	2.0	18.1	2.1	18.9
Trunk and distribution mains	0.2	7.4	0.3	7.7	0.6	8.0	1.0	8.9	1.1	9.4
Docks, wharfs, piers, terminals	0.2	10.8	0.5	11.6	1.0	12.7	1.6	14.8	1.4	12.6
Sewage treatment	0.1	5.9	0.3	6.1	0.5	6.3	0.8	7.0	0.8	7.0
Sanitary sewers	0.2	9.0	0.4	9.6	0.8	10.0	1.2	11.4	1.3	11.8
Runways	0.1	4.3	0.2	3.9	0.3	3.6	0.3	3.0	0.3	3.1
Rail track	0.1	2.3	0.1	2.6	0.2	2.5	0.2	1.9	0.3	2.8
Bridges	0.0	2.1	0.1	2.2	0.2	2.4	0.3	2.6	0.3	2.8
Electric power construction	0.2	8.5	0.3	7.8	0.5	6.9	0.6	5.9	0.4	3.8
Communication towers	0.1	2.4	0.1	2.0	0.1	1.5	0.1	0.6	0.1	1.3
Other Communication	0.1	2.7	0.1	2.0	0.1	1.5	0.1	0.6	0.1	1.2
Canals and waterways	0.0	1.2	0.1	1.5	0.1	1.7	0.2	2.2	0.3	2.5
Reservoirs	0.1	2.3	0.1	2.6	0.2	2.6	0.3	2.6	0.2	2.2
Outdoor recreational	0.0	1.6	0.1	1.5	0.1	1.6	0.2	1.6	0.3	2.4
Irrigation facilities	0.0	1.8	0.1	2.0	0.2	2.0	0.2	2.1	0.2	1.8
Other	0.4	19.0	0.8	17.5	1.3	17.0	1.8	16.7	1.8	16.3
Total	**2.2**	**100.0**	**4.4**	**100.0**	**7.7**	**100.0**	**10.9**	**100.0**	**11.2**	**100.0**

Table 4.2. Main projected trends for meteorological and hydrological parameters (Noble et al., 2005).

	Observed to Date (2000)	Projected
Global mean temperature (IPCC 2001)	▪ 0.6+ or –0.2^{0}C (20^{th} Century)	▪ 1.4 to 5.8^{0}C (1990-2100)
Canadian mean temperature	▪ 1^{0}C (20^{th} century)	▪ 2 to 4^{0}C (by 2040-60, CGCM)
Total Precipitation (2040-2060)	▪ ++ at high altitudes, + at mid latitudes ▪ less in southern Prairies in summer	▪ 0 to 20% more in North, slightly less in mid continent in summer (HadCM3)
Streamflow (or soil moisture) Mid Continent	▪ -10% (Southern Prairies, 1967-1996)	▪ -30% by 2050 (by 2050, CGCM 2xCO_2)
Date of Spring Breakup	▪ Earlier 82% of basins (1967-96)	▪ Earlier
Extreme Rainfall	▪ Up to 16% increase in intensity of heavy one-hour rainfalls	▪ 100% increase in frequency of heavy rain events

Barrows et al. (2004) also summarize the main projected impacts on meteorological parameters :

Temperature

- average annual warming by the 2080s of between 1 and 9°C depending on the region
- greater warming in winter and spring than in summer and fall (as suggested in recent climatic trends)
- greatest warming in the north, particularly in the High Arctic
- least warming in the southern Atlantic region

Precipitation

- Wetter conditions for Canada as a whole by the 2080s
- Strongest geographic contrast occurs in summer with up to 25% wetter conditions north of 60°N and up to 25 % drier in the south-central Prairies by the 2080s
- Up to 25% increase in wetness in spring for the southern Prairies by the 2080s
- Fall and winter are the seasons of greatest increase in dryness for southern Ontario and Quebec by the 2080s
- A change in precipitation type from snow to rain with warming temperatures

It should be mentioned that the latest National Assessment Information, which is due to release in the immediate future but was not available for this review, should confirm these overall trends.

Berggren (2007) gives another summary for the main changes to be expected (Table 4.3) and comments as to how these changes could impact on urban drainage systems. See also section 2.1 for general information on trends for Canada.

Table 4.3. Climate change parameters possibly affecting urban drainage systems and a summary of the type of change that might occur according to IPCC, 2007, focusing on Europe and North America (Berggren, 2007).

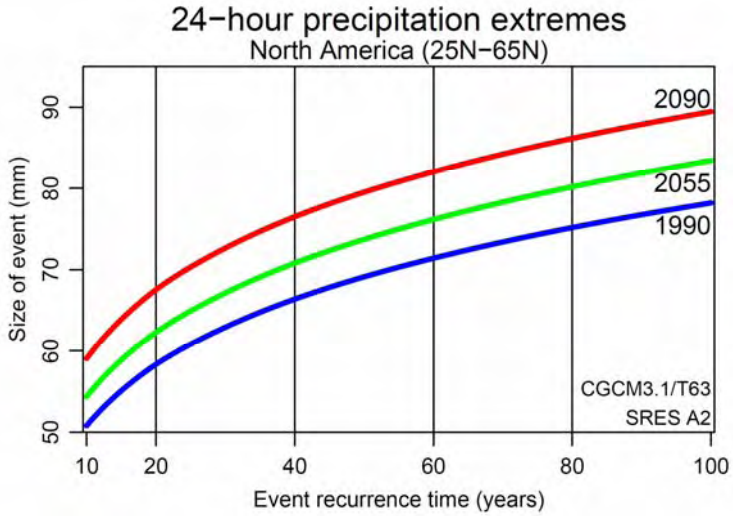
Climate factor		Changes, observed and modelled from IPCC (2007)
Temperature		The global mean surface temperature has risen by 0,74°C ± 0,18°C over the last 100 years (1906-2005). It is very likely that the warming will continue in the 21st century, and warming for the northern hemisphere is likely to be above the global mean. In Europe and North America, the largest warming is likely to be in the Mediterranean and in the southwest (North America) in the summer, and in the northern parts during the winter.
Precipitation	Amount	The changes in precipitation amount differ from area to area; in general, dry areas will become drier (e.g. Mediterranean) and wet areas wetter (e.g. north Europe).
	Intensity	In general, the intensity will increase, as the hydrological cycle intensifies due to increased temperature.
	Frequency	Return-periods of rainfall events regarded as extreme today may occur more frequently.
	Type	Duration of snow season and snow depth is likely or very likely to decrease in most of Europe and North America, except for the northernmost part of Canada where snow depth is likely to increase.
Sea level		The global average sea level rose during the 20th century, more rapidly during the last decade (1993-2003), and will continue to rise in the 21st century. Thermal expansion of the ocean and loss of mass from glaciers and ice caps has contributed to the sea level rise. The sea level rise was not geographically uniform in the past and will not be that in the future either.
Extreme weather events		Increases in the number of heat waves, heavy precipitation events, and total area affected by drought have been observed. Changes in storms (frequency, intensity etc) and small-scale severe weather phenomena have not been easy to estimate, due to e.g. the close relation to natural variations, and insufficient studies and measurements.

One of the problem when trying to analyze the climate change impacts on sewer systems is that most of the available scenario data and historic trend analyses, which are used to evaluate whether conditions are becoming more extreme over time, are available only at daily, monthly or seasonal time steps (Barrow et al., 2004). Without developing climate change scenarios at higher spatial and temporal resolutions and providing a measure of uncertainty with the scenarios, engineers will be unlikely to

consider answering questions concerning, for example, the likelihood of a municipal storm sewer failing in a 5-hectare catchment in Toronto as useful when the precipitation scenarios have been derived from climate model output at a coarse temporal scale (usually monthly) and for a grid box representing at least 40,000 km^2. Hence, until climate change scenarios are provided at the spatial and temporal scales which are of use to this community and an estimate of the uncertainty is associated with the scenarios, they are unlikely to be considered seriously by this community.

The timing of the future climate changes is probably one of the most important elements of a climate change scenario for this community. The lifecycle of infrastructure and related systems consists of a number of phases including planning and design, approval, construction, maintenance, redesign, approval, retrofitting, maintenance, redesign, and so on. This introduces a tremendous inertia into the system such that generally less than 5% of stock (buildings, pipes, roads, bridges, etc.) is turned over in any given year. When conducting cost-benefit analyses or broader service planning exercises, infrastructure planners/developers/managers need to know about the climate futures expected at specific times with similar levels of certainty as is required for demand factors (population growth, expenditure, travel, etc.) or material factors (performance/fatigue/failure rates). Until probabilistic and other techniques are sufficiently refined to treat and communicate these uncertainties, it will be difficult to convince people that action is a necessary precaution (until significant changes in infrastructure failure that can be readily attributed to climate change are observed).

Figure 4.1 shows the decrease of the level of service that could result from climate change in Canada.



This diagram shows the size (in mm) of extreme events (represented as annual maximum 24-hour precipitation) averaged over Canada and their corresponding recurrence time (in years) for current (1995) and CGCM1-projected future (2050 and 2090) climates. It clearly indicates a reduction in the waiting period for the recurrence of the same extreme event in the future. For example, extreme precipitation with a 40-year return period in the current climate will occur in less than 25 years , and about 15 years on average by the middle and the end of the 21st century, respectively. [Figure courtesy of Francis Zwiers, Meteorological Service of Canada]

Figure 4.1. Extreme events and their corresponding recurrence time for different projected future climate conditions (update of the figure in Barrow et al., 2004, as provided by F. Zwiers in 2006). Based on work reported in Zharin et al. (2007) – Ref. Joan Klaassen, EC).

One of the main problem to analyze climate change impacts for urban hydrology and sewer networks is to derive rainfall data at an adequate scale, both spatially and temporally. Climate model data in its original form often provides spatial and temporal resolution too coarse for proper use in simulations of urban drainage systems, e.g. when the runoff pattern will be rapid because of impervious areas within cities. The climate models usually reproduce temperatures well, but they have greater difficulties reproducing extreme precipitation, especially intensities and patterns of heavy rainfall, according to the IPCC (2007).

Mailhot et al. (2007) discuss the problem of downscaling the results from models at different scales. Even if the RCMs (Regional Climate Models) grid box size is much smaller than the GCMs' (e.g. for the Canadian Regional Climate Model (CRCM), the grid box size is 45 km · 45 km while, typically, it is in the order of 300 km · 300 km for GCMs), the comparison with rainfall data from stations is still challenging especially when short duration and very localized intense events are considered. Therefore, in order to use RCMs output to compute statistical indices related to extreme rainfall events in a future climate, it is crucial to investigate how these estimated indices compare with those based on available rainfall data. Figure 4.2 shows the area studied; Figure 4.3 shows the results of the study, using an ARF (Areal Reduction Factor) approach.

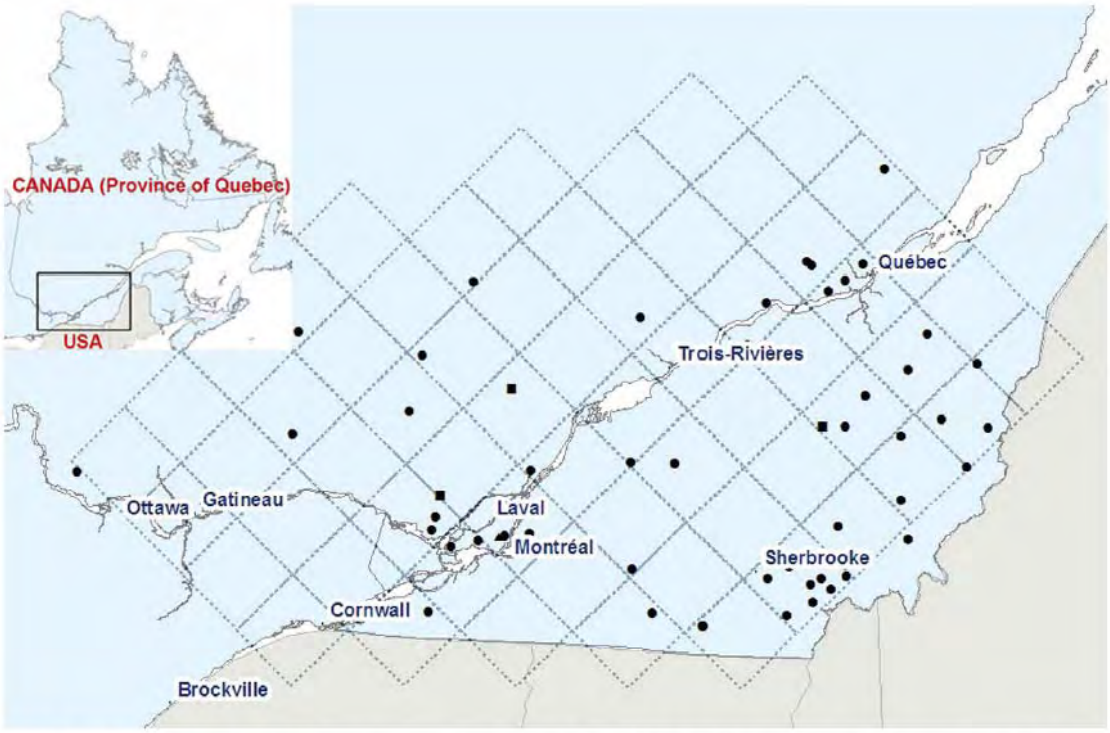


Figure 1 Area under study. Dashed lines represent the contour of the 61 CRCM grid boxes; the 48 circles are rain gauge stations used for the analyses of rainfall on 2-, 6-, 12- and 24-h durations; the triangle is a station used for the analysis of rainfall on the 24-h duration only; the three squares are rain gauge stations used for the analysis of rainfall on the 2-, 6- and 12-h durations.

Figure 4.2. Area under study in Mailhot et al. (2007).

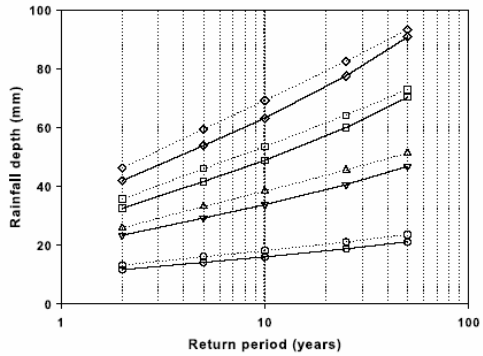


Figure 7 IDF curves at the grid box scale. Continuous curves refer to control climate while dotted curves refer to future climate. Circles, triangles, squares and diamonds are respectively for 2-, 6-, 12-, and 24-h events.

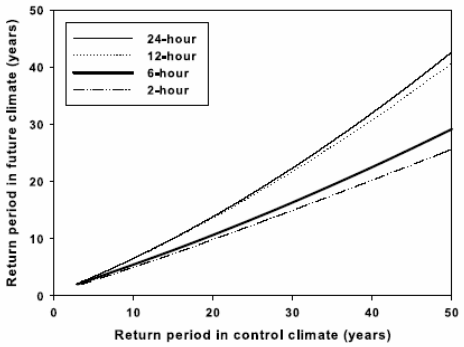


Figure 8 Return periods in control climate and corresponding return periods in future climate at the grid box scale.

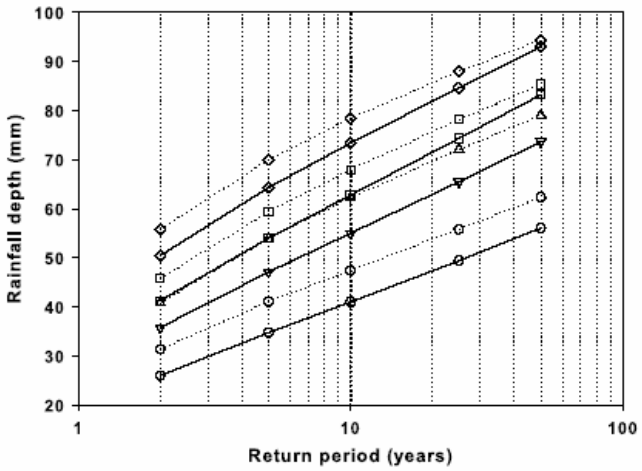


Figure 10 IDF curves at the station scale using intensity-dependent ARF. Continuous curves refer to control climate while dotted curves refer to future climate. Circles, triangles, squares and diamonds correspond respectively to 2-, 6-, 12-, and 24-h events.

Figure 4.3. Results from Mailhot (2007) to obtain future climate IDF curves at a station.

Nguyen et al. (2007a, 2007b) give another approach to to describe the linkage between large-scale climate variables for daily scale to AM precipitations for daily and sub-daily scales at a local site. Results of this numerical application has indicated that it is feasible to link daily large-scale climate variables to daily AM precipitations at a given location using a second-order bias-correction function. Furthermore, it was found that the AM precipitation series in Quebec displayed a simple scaling behaviour within two different time intervals: from 5 minutes to 1 hour, and from 1 hour to 1 day. Based on this scaling property, the scaling GEV distribution has been shown to be able to provide accurate estimates of sub-daily AM precipitations from GCM-downscaled daily AM amounts. Therefore, it can be concluded that it is feasible to use the proposed spatial-temporal downscaling method to describe the relationship between large-scale climate predictors for daily scale given by GCM simulation outputs and the daily and sub-daily

AM precipitations at a local site. This relationship would be useful for various climate-related impact assessment studies for a given region. the proposed downscaling approach was used to construct the IDF relations for a given site for the 1961-1990 period and for future periods (2020s, 2050s, and 2080s) using climate predictors given by the HadCM3A2 and CGCM2A2 simulations. It was found that AM precipitations at a local site downscaled from the HadCM3A2 displayed a small change in the future, while those values estimated from the CGCM2A2 indicated a large increasing trend for future periods. This result has demonstrated the presence of high uncertainty in climate simulations provided by different GCMs.

Berggren (2007) has summarized the different approaches used so far to circumvent the problems associated with scales. The different ways to perform these operations, found in the literature, are described in this thesis as *static, semi static* and *dynamic*:

> ***Static:*** e.g. topographical studies due to changed (increased) sea water level (Johansson *et al.,* 1991; Ahnoff and Kant, 2002; SMHI, 2006: Göteborg study) and/or rainfall studies and model simulations due to changed (increased) design rainfall intensities, with a fixed percent (Niemczynowicz, 1989: 10, 20 and 30 % increase; Johansson *et al.,* 1991: 5 and 20 % increase; Watt et al., 2001; Waters *et al.,* 2003: 15% increase).
>
> ***Semi static:*** e.g. studies and model simulations due to changed observed temperature and precipitation in a range and not for one fixed value only, e.g. by Semadeni-Davies (2004; 2003: precipitation varied between -10 to +40%, and temperature varied between -5 to +15%), which also used response surfaces as a tool to present the results. Another example is the Delta change method used by Semadeni-Davies *et al.* (2006) where present and future climate simulations from a climate model are compared in order to determine monthly changes, which are then applied to observed rainfall data. The Delta change method was further developed for this approach by Olsson *et al.* (2006; 2007/Paper I) with the focus on intensity. Another approach is performed by Denault *et al.* (2006), where historical rain series are analysed with linear regression and the detected trends used in order to build potential future rain scenarios in the form of IDF-curves from design rainfall were developed.
>
> ***Dynamic:*** studies and simulations are performed with dissagregated climate model data. Onof (2002) compared two different products for disaggregation, StormPac and Cascade, which are developed by UKWIR, and found that the Cascade method was a better method for assessing impacts on urban drainage systems. The Cascade method, for example, is used by Ashley *et al.* (2005). Research in this field is also performed by SMHI for RCA3 model data, described by Olsson (2007).

The division of different techniques, or approaches, into static, semi-static, and dynamic can be compared to the division described by Kundzewicz and Somlyódy (1997) for hydrological studies: *(comments from Berggren in her thesis, in italics)*

> *(i)* Study of a long-time series of hydrological observations (instrumental) and proxy records; search for patterns in these data. *Not directly applicable for urban*

hydrology, but could be applicable for studies of rainfall trends e.g. by Rauch and De Toffol (2006).

(ii) Sensitivity studies of hydrological models (what-if philosophy), i.e. assuming changes to climate variables and studying impacts of these changes on hydrological variables. *Possible way for urban hydrology as well. (e.g. Niemczynowicz, 1989; Waters et al., 2003; Semadeni- Davies, 2003; 2004)*

(iii) Treating an output from a GCM as an input to a hydrological model, decomposition of GCM results (few widely spaced nodal points) into individual catchments. *Some sort of disaggregation possible for urban hydrology (e.g. Ashley et al., 2005; Grum et al., 2005; Semadeni-Davies et al., 2006; Olsson et al., 2006)*

(iv) Examination of existing hydrological data; search for records similar to a scenario. *Could be possible for urban hydrology, perhaps somewhat similar to the approach performed by Denault et al. (2006)*.

A recent study (Cheng et al., 2007) has also addressed these concerns. The overall purpose of this study was to estimate possible changes in the frequency and magnitude of extreme rainfall/streamflow and their associated flooding risks in the 21st century for four selected river basins in Ontario. Considerable effort was made in this study to transfer GCM-scale scenarios to station-scale information using statistical downscaling transfer functions. Through the statistical downscaling process, the GCM model bias was removed and the quality of climate change projections was much improved. However, conclusions made in the study about climate change impact analysis still relied on GCM scenarios. As a result, there is corresponding uncertainty about the study findings.

The impacts of climate change on sewer systems will admittedly be different on combined systems, partially separated systems and fully separated systems. Table 4.4, from Kije Sipi (2001), and Table 4.5, from Berggren (2007), summarize the specific parameters and the key impacts in each case.

Table 4.4. Impacts of climate change parameters on different types of sewer systems **(**Kije Sipi (2001)**).**

Climate Change	Expected Climate Change Impact		
	Combined Systems	**Partially Separated Systems**	**Fully Separated Systems**
Increased rainfall event peak intensities, similar event type and annual volume	Increased risk of basement flooding. Lower level of service.	Minor impact on peak flows and available capacity.	Minimal impact on peak flows and available capacity.
Increased frequency of large volume and high intensity rainfall events, same annual volume	Increased risk of basement flooding. Lower level of service. Potential increase in CSO volume but reduced CSO frequency.	Increased risk of surcharge and basement flooding. Lower level of service.	Potential impact on available capacity for growth. Increased risk of sewer surcharge and risk of flooding.
Increased rainfall event frequency and annual event volumes, minimal increase in peak intensities or frequency of large volume events	Minimal impact on system capacity. Increase in CSO volumes and frequencies.	Potential increase in risk of system flooding. Potential impact on wastewater treatment costs (volume and quality).	Potential impact on wastewater treatment (volume and quality).

Table 4.5. Examples of impacts in urban drainage systems during high intensity rainfall events. **(**Berggren (2007))**.**

Combined system	▪ If the sewer system has too low a capacity, the water level in the system can *cause basements to be flooded* ▪ Increased amount *of combined sewer overflow (CSO)* can cause environmental problems concerning the receiving waters and also jeopardize the drinking water sources ▪ If the ground water level rises because of a higher amount of precipitation, more ground water will *infiltrate into the pipes*, and thus decrease the capacity of the system
WTP (combined system)	▪ At a wastewater treatment plant, during times of high flows, *dosages of chemicals* for the processes can become unnecessarily high ▪ Increased amount of urban *polluted runoff* can reach the treatment plant, which will cause more pollutants, e.g. heavy metals, in the sludge.
Pump stations	▪ Pump stations can easily become flooded as they often are located in low-lying areas. There is then a risk of getting *pipe surcharge* in the system if water is damming up backwards in the system ▪ Increased amount of *pump station sewer overflow* can cause environmental problems concerning the receiving waters and also jeopardize the drinking water sources
Separate system (only storm water)	▪ If the system has too low a capacity, the water level in the system can cause *surfaces in a city to be flooded* ▪ If the ground water level rises because of a higher amount of precipitation, more ground water will *infiltrate into the pipes*, and thus decrease the capacity of the system ▪ Heavy precipitation over urban areas can cause a *rapid runoff and wash of urban surfaces* and thus higher concentrations of pollutants, e.g. heavy metals, will go to BMPs or receiving waters
Infiltration basin	▪ The *infiltration capacity may decrease* if the ground water level rises, and cause, for example, *surface flooding*
Storm water pond	▪ At storm water ponds, the amount of *sediment losses* during heavy rain may increase if the pond is insufficiently dimensioned, and there are no by-pass facilities. Thus polluted sediments may reach the receiving waters.

The following section will discuss relevant literature for each type of systems.

4.1 Wastewater systems

Niemczynowicz (1989) is the earliest literature found concerning urban drainage impacts due to climate change. The case study is from Lund (in the south of Sweden), which has a total catchment area of 1769 ha, and about 30% of the area is impervious. Rainfall input for the simulation, from both IDF-relations and the Chicago design storm (CDS), increased by 10, 20, and 30%. The results showed an increase of combined sewer overflow (CSO), an increase of total inflow to the sewerage system, and also significant flooding problems for the sewerage network when rainfall intensity increases by 20 and 30%.

Semadeni-Davies *et al.* (2006; 2007) also showed similar results from their study of the old city centre in Helsingborg (also in the south of Sweden). The permeable areas contributing to sewer infiltration were 2914 ha, and impervious areas contributing to direct storm water inflow were 164 ha. The results showed an increase of WTP inflow, both from storm water runoff and sewer infiltration, increased volume of combined sewer and pumping station overflows, and also increased CSO volumes for the future.

The rainfall input for the modelling was an observed rainfall series that was transformed according to the changes presented by RCA0 (Rossby Centre Atmosphere Model, SMHI) via the Delta change method (using storms and drizzle as dividing sectors). In the study, urban development was also included in the scenarios; a total of 4 storylines were used, of which one describes the current situation (Semadeni-Davies *et al.*, 2006).

Ashley *et al.* (2005) suggested that potential effects of climate change on urban property flooding are likely to be significant in the future, according to a study performed in the UK. Four catchments, representing three different types of catchments, were studied regarding their potential impact due to climate change: flooding within the urban area (two catchment areas), coincident flooding involving local river systems (one area), and coincident flooding involving tidal effects (also one area). The sizes of the catchment areas ranged from 3934 ha (34 % impervious) to 727 ha (15% impervious). The damages were presented as the number of properties affected, and the estimated economical damage was also presented. Scenarios of future development were also used (the corresponding emission scenario in brackets): National enterprise (B2), World market (B1), Global sustainability (A2), and Local stewardship (A1F1 (fossil fuel intensive SRES scenario)) (Ashley *et al.*, 2005).

Semadeni-Davies (2004) discusses the impacts of climate change on the waste water inflows in a cold region. The author examines the aspects related to a change in the length and timing of the snow season, which could have a great impact on infiltration and runoff volume going to the treatment plant. It also emphasizes the need to consider both climatic change and changes in society within urban stormwater management impact assessment.

Consequences for receiving water bodies
Niemczynowicz (1989) showed potential environmental impacts due to an increased amount of pollutant released to receiving waters. The studied substances were suspended solids (SS), biological oxygen demand (BOD7), phosphorus, copper, zinc, and lead. The assumption was a 30% increase in rainfall would increase these substances in amounts from 32-71% (the highest increase for phosphorus) (Niemczynowicz, 1989). Semadeni-Davies *et al.* (2006; 2007) showed that the total load of nitrogen released to receiving waters via overflow would increase in the future. Denault *et al.* (2002) found that the environmental impacts of climate change and urbanisation (increase of the impervious areas in the city) indicate a great vulnerability for the natural ecosystems of the receiving waters.

4.2. Stormwater systems

Relatively to wastewater systems, more studies have been completed on the climate change impacts on the drainage systems. Three studies will be discussed more in detail as they are somewhat larger in scope. Other more regional studies will also be cited.

Kije Sipi (2001)

The study examines these issues by completing a sensitivity analysis using hydrologic simulations. Hypothetical surface areas of multiple land use types were assessed along with existing urban and rural drainage basin models. The climate change impacts were evaluated mainly in terms of changes to the drainage system peak flows and runoff

volumes. However, the incremental construction cost and the variations in the drainage system level of services (frequency of flooding for example) were also analyzed.

A work plan was developed to achieve the objectives and accordingly, this study is divided into three parts: one that evaluates the climate change impacts, one that reviews the current water resources engineering regulatory framework and one that explores potential adaptation alternatives.

Generally, the simulation results indicated increases in peak flows and runoff volumes equal to, or greater than the given increase in precipitation and irrespective of the drainage design and analysis method used. In certain situations, the proportional increase in peak flows is almost twice the projected increase in precipitation. The resulting impacts of these findings indicate future increases in drainage infrastructure costs and a reduction in the level of service of existing systems. Table 4.6, 4.7 and 4.8 give the results,

Table 4.6. Increases in runoff volumes as a function of imperviousness for various simulated increases in rainfall intensities (Kije Sipi, 2001).

	Imperviousness and Ratio of Future to Existing Runoff Volumes	
Increases in Rainfall Intensities	20%	80%
5%	1.08	1.06
10%	1.15	1.11
15%	1.23	1.17
20%	1.31	1.22

Table 4.7. Sensitivity of pipe sizes and associated costs with respect to rainfall intensity and design method (Kije Sipi, 2001).

Variable	Expected Impacts of Increased Rainfall Intensities on Variable of Interest
Average Pipe Sizes*	Computed average pipe sizes are smaller with the Rational Method (RM) than with the Hydrograph Method.
Increase in Average Pipe Sizes	The increases in required pipe sizes vary from 2% for a 5% increase in rainfall intensity to 8% for a 20% increase in rainfall intensity for the 2, 5, and 10-year return period service level using the RM method. Using the HM method, the required increases in pipe sizes ranged from approximately 5% for a 5% increase in rainfall intensity to 15% for a 20% for any of the three service levels.
Associated Average Cost	The increases in costs associated with larger pipe sizes vary from 4% for a 5% increase in rainfall intensity to 15% for a 20% increase in rainfall intensity for the 2, 5, and 10-year return period service level using the RM method. Using the HM method, the incremental costs increase by approximately 8% for a 5% increase in rainfall intensity to 15% for a 300% for any of the three service levels.

Table 4.8. Selected examples of impacts of increased rainfall intensities on storage-related variables (Kije Sipi, 2001).

Variable	Expected Impacts of Increased Rainfall Intensities on Variable of Interest
Required Storage Volume	To control the runoff from a 100-year storm, a 5% increase in rainfall intensity will require approximately 11% more storage volume for the Rational Method (RM) and 16% for Hydrograph Method (HM) and 17% for the Continuous Simulations Method (CSM). A 20 % increase in rainfall intensity will require approximately 48% more storage volume for RM, 45% for HM and 66% for CSM. The proportional increases in required storage volume are even higher for 2 and 5-year return periods.
Service Level	The capacity of an existing storage facility, sized to control the runoff rate from a 100-year event would be exceeded by a future 1:50 year event if rainfall intensities increase by a mere 5%. Its capacity would also be exceeded by a future 1:15 year event if rainfall intensities increase by 20%.
Probability of Overtopping Storage Facility	Expressed another way, the impacts on storage capacity would be such that the probability of overtopping an existing storage facility designed to handle a 100-year event would be increased by a factor of two for an increase in rainfall intensities of 5%. For a 20% increase in rainfall intensities, the probability of overtopping the same facility would increase by a factor of almost seven.

Watt (2003)

The report provides a brief examination of the sensitivities of Canadian stormwater infrastructure to changes in climate. Case studies are described in which simple scenarios of future climate are incorporated into urban runoff models for catchments located in Burlington and Ottawa, Ontario. Potential impacts and mitigation options are analysed and summarized.

The sensitivity of urban stormwater infrastructure to changes in climate depends in part on the magnitude of the expected change. The sensitivity is also a function of the type of infrastructure, classified as:

- transmission structures (e.g., gutters, ditches, pipes, streets, channels, swales, urban creeks, and streams),
- management structures for quantity control (e.g., roof tops, ponds, urban lakes, and infiltration devices),

- storage structures for quality control, and
- Combined Sewer Overflow (CSO) abatement structures.

A summary of the data needs for urban drainage systems is given (Table 4.9).

Table 4.9. Meteorological data needs for stormwater infrastructure design (Watt et al., 2003).

Data Type	Urban Stormwater Infrastructure	Time Specifications	Return Periods	Locations
Rainfall IDF	▪ storm sewers	Durations from 5 minutes to 24 hours	2-100 years	Stations in all Canadian municipalities where record length ≥ 25 years
Rainfall temporal distribution	▪ management structures for quantity control	Durations of 1 hour and 24 hours	Not applicable design storm represents average of actual storms with return periods ≥ 2 years	Stations in all Canadian municipalities where record length ≥ 25 years
Critical rain plus melt sequences	▪ storage structures for quantity control (incl. BMPs for winter conditions) ▪ storage structures for quality control and impacts on receiving waters	Sequences from 6 hours to 3 days	2, 10 and 100 years	All Canadian municipalities where melt is significant and where record length ≥ 25 years
Critical temperature sequences	▪ storage structures for quality control and impacts on receiving waters	Time step of 1 hour and sequences of 8-24 hours	2, 10 and 100 years	Stations in all Canadian municipalities where record length ≥ 25 years

The analyses completed were based on a simplified assumption of a 15 % increase in the rainfall quantities, using typical design storm (AES). Different mechanisms were also looked at as a means to adapt to the simulated increases in runoff peak discharges and volumes. The results are given in Table 4.10 to 4.12.

Table 4.10. Runoff simulation results for the Malvern urban catchment (Watt et al., 2003).

Case	Runoff Volume (10^3 m^3)[1]	Peak Discharge (m^3/s)[1]	Time to Peak Discharge (min)[1]
Present Rainfall (24.5 mm)	1.9	1.5	22
Present Rainfall + 15% (28.2 mm)	2.3	1.7	22
Roof Disconnection (Full Roof)	1.4 (-39%)	1.0 (-39%)	22 (no change)
Roof Disconnection (Back Roof Only)	1.8 (-20%)	1.4 (-18%)	22 (no change)
Increased Surface Storage	1.8 (-19%)	1.5 (-14%)	22 (no change)
Install ICDs (orifice induced ponding)	2.3 (no change)	1.5 (-12.5%)	26 (+18%)

[1]percent change values relative to 'Present Rainfall+15% case

Table 4.11. Differing storm intensities and number of pipes over capacity (Watt et al., 2003).

Increase in Storm Intensity (%)	No. of Pipes Over Capacity[1]	Percent of Pipes Over Capacity[1]
5	10	7
10	25	18
15	34	25
20	41	30

[1]total of 137 pipes

Table 4.12. Implications of structural stormwater management measures (Watt et al., 2003).

Structural Measure and Physical Description	Rating of Implications		
	Environment	Social	Aesthetic
Pipe replacement • excavation, removal and replacement of existing storm sewer pipes	– increased flows to the receiving water body (i.e. erosion potential rises) (4)	– no impact on social structure (3)	– during construction (5) – after completion (i.e. new pavement) (1)
Disconnecting impervious areas • roof leaders are allowed to spill onto lawns and runoff can infiltrate to replenish soil moisture and percolate to groundwater	– greatly reduces flows in storm sewers (1) – potential for resupply of urban groundwater (1)	– reduces need to water the lawn (2) – water may spill onto neighbour's property (2)	– no obvious aesthetic impact (3)
Change in surface storage • construction of berms on public land (e.g., playgrounds) so that runoff is stored and allowed to infiltrate to replenish soil moisture and percolate to groundwater	– reduces flows to the storm sewer (2) – potentially replenishes the urban groundwater table (2) – concern of pollutants concentrating on grass (4)	– lands may not be accessible for extended periods of time after a rainfall event (i.e. they must be allowed to dry) (4)	– berms can be unsightly if allowed to grow with weeds (4) – ponding water may be viewed as breeding ground for mosquitoes (4)
Reduction in rate of stormwater input • orifices in the catchbasins restrict the rate of stormwater input to the sewer system, and promote ponding of water on the street surface	– reduces the rate of stormwater input to the system thereby reducing erosion potential (2)	– ponding on the streets could impair "normal" vehicular movement (4)	– no obvious implication (3)

1 = Major positive implication
2 = Minor positive implication
3 = No obvious implication
4 = Minor negative implication
5 = Major negative implication

Mailhot et al. (2006, 2007)

This study, detailed in the report in French (Mailhot et al, 2007) and summarized in different papers (Mailhot et al., 2006; Rivard et al., 2007) used a somewhat different approach to come up with climate change impacts on urban drainage systems, using statistical analyses on historical storms and deriving typical design events. An analysis was also performed to examine how source control measures could be used to mitigate these impacts so that the systems could still provide the adequate level of service and an acceptable risk level. The fact that these source controls could indeed compensate for a large part of the expected increases associated with CC for less intense rainfall events and that they could, in many cases, be easily implemented, reinforces the need to re-evaluate the overall design approaches for the design of stormwater sewer networks. In that perspective, source controls should not be viewed as an alternative to traditional approaches to drainage but should rather become an integral part of urban drainage planning (Rivard et al., 2007).

Firstly, an evaluation of the extreme rainfall in future climate was made, using a regional climate model. IDF curves under the future climate were produced based on this analysis. Secondly, using historic rainfall data for the region, a taxonomy was developed for the observed rainfall temporal patterns and different generic rainfall patterns could therefore be defined (Figure 4.4). Using finally the rainfall quantities defined by the IDF curves for the future climate and assuming that the temporal rainfall patterns would not significantly change (an assumption that would have obviously to be proven as the mass curves could indeed change in a changing climate), an analysis was performed to estimate the impacts on peak discharges and runoff volumes (Figure 4.5). Four generic land uses were considered: 100% imperviousness (roads or parking lots), high density residential (65% imperviousness), low density residential (35% imperviousness) and undeveloped (0% imperviousness). The choice of the appropriate rainfall mass curve and duration was based on a comparison of the synthetic mass curves and statistical analyses with the historical rainfall data (Figure 4.5). Once the appropriate mass curves are selected for each land use, the future climate design storms are obtained by using the future climate IDF curves. SWMM (Stormwater Management Model) was finally used to estimate the peak discharge and runoff volumes for the future conditions. Table 4.13 gives a summary of the results obtained for 2 land uses.

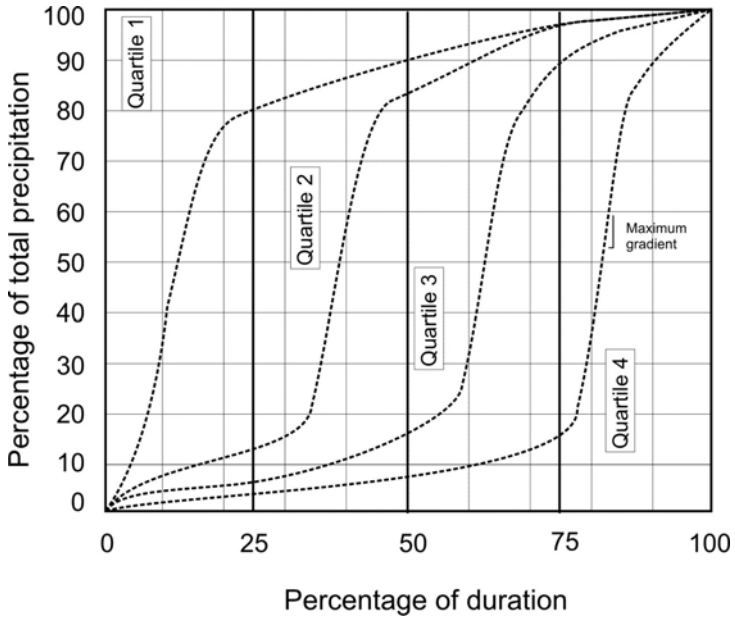


Figure 4.4. Taxonomy of storms (Rivard et al., 2007).

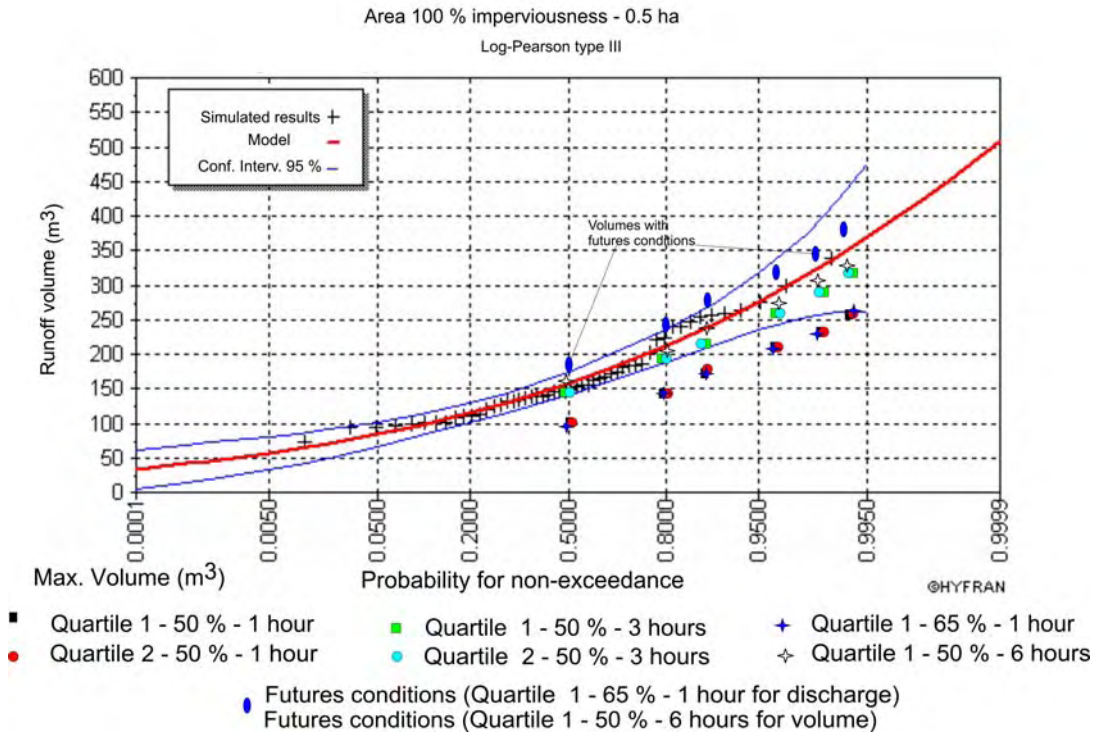


Figure 4.5. Example of analyses to select appropriate design storms (Rivard et al., 2007).

Table 4.13. Percentage of increase for rainfall and runoff parameters for different land uses.

Land use	Parameter	Return period			
		2	5	10	100
Parking lot	Rainfall	23 (for Q) 13.5 (for V)	19.7 (for Q) 18.2 (for V)	17 (for Q) 17.8 (for V)	13.8 (for Q) 15.3 (for V)
	Q	21.2	24.8	22.8	16
	V	14.3	18.9	18.6	15.8
Low density residential	Rainfall	23	20	17	14
	Q	33.3	37.9	32	24.1
	V	49.0	35.6	26.7	21.1

Q = peak discharge; V = runoff volume.

Other studies

Semadeni-Davies et al. (2007) give the results of a study for the City of Helsingborg (Sweden). Apart from climate change scenarios, it also incorporates the use of water management storylines for subdivision and looks at the interrelations. As well as the current drainage situation, two progressive storylines for urban drainage were simulated. The storylines can be summarised as: (1) no-change; (2) population growth and urbanisation with a pipe-based separate stormwater system; and (3) source control and flow regulation. The storylines were based on current trends in Swedish urbanisation.

Climate change was simulated by altering a high-resolution rainfall record according to the climate-change signal derived from a regional climate model. Subdivision and urbanisation was simulated by altering model parameters chosen to reflect current trends in demographics and water management. The simulations were run for a 15 month period. It was found that city growth and projected increases in heavy rainfalls, both together and alone, are set to raise peak flow volumes and increase flood risk. Conversely, installation of a sustainable urban drainage system (SUDS) has a positive effect on the urban environment in general and can largely allay the adverse impacts of change road.

Not exclusively from a climate change point of view, Heany et al. (1999) looked at different scenarios for urban development in the context of drainage and sewer systems. This could provide background for development of future scenarios or storyline. Another paper (Engel-Yan et al., 2005) also discusses the development of sustainable neighbourhoods, which could be taken into account as storylines are developed.

Denault *et al.* (2002) showed that climate change would not have a dramatic impact on the current drainage infrastructure in the Mission/Wagg Creek watershed (BC). Still, according to the authors, the existing system of 440 ha (45 % impervious areas) was not entirely adequate to convey the 10-year event, which often is the design standard. The rainfall input was calculated from measured rainfall data (5min, 2h, 24h) using regression analysis to describe the trend of future rainfall (design storms). However, the impacts on the natural ecosystems of the creeks in the catchment (watershed) were suggested to be far more damaging than the impacts on the infrastructure (Denault *et al.*, 2002). The results indicate that, even in the case of combined urbanization and climate change effects, the effort and costs required to upgrade existing infrastructure would not be excessive and can be managed through long-term planning. The authors pointed out however that this finding, however, is characteristic of North Vancouver and may not apply to other watersheds. North Vancouver has a steep topography and the runoff water is carried downstream rapidly, which might explain why there is not more surcharging in the system. More surcharging and flooding problems could probably be expected in watersheds with flatter gradients.

Bridgeman and Gregory (1999) discuss the potential impact of climate change on sewer systems from the point of view of the water and sewerage undertakers in the UK. The author analyzed the results from the Regional Climate Model and their application to the design of sewer systems. No final results were discussed however as the research was in progress.

The Ontario Chapter of the Soil and Water Conservation Society produced a report in 2007 (Bruce et al., 2007) on the impacts to soil and water from higher intensity rains. Table 4.14 is extracted from this report, showing expected increases in intensity or frequency of heavy events. Increase erosion could become a problem for control of runoff quality in ponds and watercourses. The authors report that maximum intensities for one day and for 30 to 60 minute durations have been rising, on average, at rates of 3 to 5% per decade, although not all stations exhibit this upward trend. Climate models project continued increases of this order. Another study shows that heavy one-day rains above a certain high threshold have been increasingly frequent in this region since 1950. Increases in frequency have been greatest in summer but have also been substantial approximately 4% per decade,
in early spring (March, April, May). A further preliminary analysis for a few stations suggests a shift to heavy rainfall events earlier in the season especially May. Total precipitation has increased by a lesser amount, except for increased snowfall in the lee of the more ice-free and warmer Great Lakes.

Table 4.14. Expected increases in rainfall intensity and frequency ((Bruce, J. et al. OC – Soil and Water Conservation Society, 2007).

RAIN CHANGE		**EROSION CHANGE**
Average increase in intensity or frequency of heavy events		**Estimated increase in erosion (Upland areas)**
March, April	4% per decade	9% - 12% per decade
May	7% per decade	16% - 20% per decade
June, July, August	5% per decade	12% - 13% per decade

Oberts (2007) discusses the implications of climate change for drainage systems. He concludes that we need to look at basic design input parameters defined by climate and re-evaluate current and future designs to make sure they are adequate for higher, flashier runoff. Kunkhouser (2007) presents different approaches whereby stormwater management is a mean to adapt to climate change. She concludes also that there is an opportunity to see appropriate stormwater management measures and new design approaches as means of adaptation.

5. Review by region

5.1 Canada

A good summary of available literature for infrastructure by Canadian regions is given in IC (2006). C-CIARN (Mehdi, 2006) also produced a report for municipalities. Regional and local vulnerability to climate change ranges significantly across Canada because of the diversity of climate change impacts and the range of economic, environmental, and geographic characteristics across the country (Lemmen and Warren, 2004). Once again, it should be pointed out that the latest National Assessment Information, which is due to release in the immediate future but was not available for this review, should confirm these overall trends.

Climate change vulnerability is determined by three factors – the nature of climate change, the climatic sensitivity of a region, and the capacity of the region to adapt to the changes. When all three factors are considered, it becomes obvious that northern Canada is one of the most vulnerable regions in the country (Girard and Mortimer, 2006) The North has experienced the most severe impacts to date, and it has limited adaptive capacity. Not surprisingly, several reports on infrastructure adaptation focus on northern adaptation.

Tables extracted from Noble et al. (2005) are given in each sub-section to highlight the projected impacts in each region.

5.1.1 Arctic

One of the greatest climate change concerns regarding infrastructure is the thawing permafrost in the North. In many parts of northern Canada, infrastructure including airstrips, pipelines, roads, railways, water and wastewater facilities, and building foundations are built over permafrost and rely upon its stability, yet permafrost will disappear partly or completely over large areas of the North should predicted climate change occur (IC, 2006; Couture et al., 2000). Climate change impacts and adaptation options for infrastructure in the North have garnered a fair bit of attention and research already. Table 5.1 summarizes the potential impacts.

Table 5.1. Projected climate change impacts in Canada's western Arctic and inland eastern Arctic (Noble et al., 2005).

Climatic changes	Potential impacts
Permafrost thawing, land slumps	Instabilities in building infrastructure, road
Loss of sea and river ice, movement of wildlife	Wildlife and hunting disrupted
Sea level rise, storminess, less ice	Shore erosion in northwest (Beaufort Sea shore)
Higher temperatures and evaporation	Forest fire increase
Thawing roads, lower minimum flows	Winter road and barge transportation reduced
"Grasshopper effect"* in south accelerated transporting toxics north more rapidly	Increased toxic contaminants
Reduced flooding of fresh water deltas	River ecosystem productivity reduced
Loss of sea ice	Greater commercial ship transportation and resource exploitation – Arctic sea and channel

Sources: Bruce et al., 2000. Cohen, S.J., 1997, Natural Resources Canada, 2000

5.1.2 British-Columbia

Some studies on climate change have been produced by or for the Greater Vancouver Regional District (Taylor and Langlois, 2000; Sheltair Group, 2003). The authors from the Sheltair Group concluded that the costs and benefits of implementing adaptation strategies needs to be considered against the increased vulnerability and potential costs that can occur from various climate change impacts. A full risk assessment needs to be conducted on Greater Vancouver's vulnerabilities to climate change and other anticipated or potential shocks to the urban system. The risk assessment can then be used to develop an integrated urban systems risk management strategy, in which climate change is only one threat amongst many.

Table 5.2. Projected climate change impacts in British Columbia and southern Yukon (Noble et al., 2005).

Climatic changes	Potential impacts
Lower mean annual flows	Decline in hydropower
Lower flows, seasonal changes in flow	More intense conflicts between water users and between Canada and U.S.A.
Sea level rise, storminess	Potential for south coastal flooding
Milder winters, warmer summers, more lightning	Forest fire insect and disease increases
Warming ocean and rivers	Fishery changes, e.g. reduction in cold water species
Heavier rains	Flash flood and landslide increases
More winter rain, less snow	Shorter ski season
More and longer hot spells	Longer smog episodes, lower mainland
Permafrost thawing	Building, infrastructure instabilities

Sources: Beamish et al., 1997. Bruce et al., 2000. Moore, 1996. Rory et al., 1998. Shaw et al., 1998.

5.1.3. Alberta – Prairies

Khandekar (2000) assesses the trends and change in extreme weather event for Alberta and the Canadian Prairies. He concludes notably that the perception that global warming and climate change would lead to increase in extreme weather events appears to be inconsistent with observation in the Canadian prairies so far. The economic impacts of weather extremes and the linkages to global warming and/or societal changes need to be more accurately assessed for Canada and the prairies.

Table 5.3. Projected climate change impacts in the Prairies, north of 55°N (Noble et al., 2005).

Climatic changes	Potential impacts
Permafrost thawing, land slumps	Building, utilities, pipelines instability
Milder winter, warmer summers, more lightning	Increased frequency and intensity of forest fires and forest insect infestations
Warming waters	Cold water lake and river fish species further north

Sources: Natural Resources Canada, 2000. Schindler, 1997.

Table 5.4. Projected climate change impacts in the Prairies, south of 55°N (Noble et al., 2005).

Climatic changes	Potential impacts
Higher temperatures and evaporation, glacier retreat	Increased agricultural drought incidence and intensity
Declines in river flows and water levels	Competition for declining water supplies
Lower flows	Reduced hydropower production
Lower minimum flows, higher water temperatures, more high intensity rains	Water quality problems
More and longer heat waves	Increased urban smog episodes

Sources: Brown et al., 1997. Gregory et al., 1997. Wetherald & Manabe, 1995. Wheaton, 1994.

5.1.4 Ontario

A recent guide has been produced specifically for Ontario (Bruce et al., 2006). Tables 5.5 and 5.6 are extracted from this reference. The risk management approach is used to discuss the impacts and adaptation processes. The report and the annexes provide a good overall framework for municipalities.

Other documents have been prepared for the Great Lakes Region (UCS – ESA, 2005) and more specifically for the Hamilton area (Ormond, 2004).

Table 5.5. Expected increase in meteorological and hydrological parameters for Ontario (Bruce et al., 2006).

	To date	By 2050
Total Rainfall	+ 1% per decade	+1% per decade
Extreme Rain Events	+5-7% per decade especially in spring (May)	+5% per decade
Total Runoff and Groundwater	Little change	Decline 10-20% (more evaporation)
Great Lakes Levels (Flow at Niagara which integrates effects on lakes above the Falls)	-7% (30 years)	Decline 0.3 to 1 metre in levels
Severe winter storms	Increased Intensity	15-20% increase in intensity

Table 5.6. Climate change observations and projections for Ontario (Appendix 1 - Bruce et al., 2006).

Table 1 for Annex I: Climate Change Projections and Observations for Canada		
	Projected	**Observed to Date (2000)**
Global Mean Temperature	1.4 to 5.8ºC (1990-2100)	0.6 plus or minus 0.2ºC (20^{th} century)
Canadian Mean Temperature	2 to 4ºC (CGCM – 1975-95 To 2040-60)	**> 1ºC (20^{th} century)**
Total Precipitation	(2040-2060) 0 to 20% more in north slightly less in mid continent in summer (HadCM3)	**1950-1998 ++ at high altitudes, + at mid latitudes** **Southern Prairies little change**
Streamflow (or soil moisture) Mid-continent	-30% by 2050 2 x CO_2 (CGCM)	-10% Southern Prairies (1967-1996)
Date of Spring Breakup	Earlier	Earlier: 82% of basins (1967-1996)
Extreme Rainfall	2 x frequency of heavy rains for 2 x CO_2 (CGCM)	Up to 20% increase in heavy 1-day falls in US and SE Canada (early summer)
Water Vapour in Troposphere (lower atmosphere)	Increase	Statistically significant increase over N. America except NE Canada
Mean Sea Level Rise	40-50 cm (mean IPCC projections) 1990-2100	10-20 cm (1900-1999)
Arctic Sea Ice extent	-21 to -27% by 2050	-3% per decade since 1978 (year round ice extent)
Snow Cover Extent Dec, Jan, Feb.	-15% by 2050 N. America (CGCM)	-10% (1972-2000) Northern Hemisphere
Late Season Snow Pack in Rockies – Apr. 1	Less (more melt over winter)	30% less since 1976 Fraser River Basin
Glacier Retreat South of 60ºN e.g. Glacier National Park	None left (by 2030)	2/3 reduction in numbers (from 150 to 50) (1850–1990s)
Severe Winter Storms Frequency and intensity	15% to 20% increase $CO_{2\ \text{level doubled}}$ (CGCM)	(1959-1997) **N of 60ºN - Increased frequency and intensity** S of 60ºN - Increased intensity

Source: Data from Akinremi et al., 1999; Angel and Isard, 1998; Boer et al., 2000; Carnell and Senior, 1998; Gregory et al., 1997; IPCC, 2001; Karl et al., 1995; Lambert 1995; McCabe et al., 2001; Mekis and Hogg, 1999; Moore, 1996; Ross and Elliot, 1996; Sarnko et al., 2002; Stone et al., 2000; Zhang et al., 2000; Zwiers and Kharin, 1998.

Notes: Had CM3 = Hadley Centre (UK) Climate Model version 3
2 x CO_2 = doubled pre-industrial level of CO_2 equivalent (by latter half of twenty-first century)
CGCM = Canadian Global Climate Model (CCCma) (Environment Canada, University of Victoria)
++ = significantly more
+ = more

Table 2 for Annex I: RAINFALL TRENDS Summary of results (all positive over the region)		
	Observed trends 1970-2000	*Projected trends to 2050*
30 minute extremes	5% per decade (Adamowski) 4.5% per decade to 1996 (SWCS)	5% per decade
daily extremes	7% per decade (May, June, July) (Stone) 5% per decade (over year) to 1996 (SWCS)	3% per decade over the year (20 year return period) 2 ½ - 6% per decade (rainfall with probability <5%)
annual rainfall	1% to 3% per decade	1% per decade

Table 5.7. Projected climate change impacts in Great Lakes-Upper St. Lawrence basin (Noble et al., 2005).

Climatic changes	Potential impacts
Lower Great Lakes levels and flows of channels and St. Lawrence	Increased shipping and navigation costs Reduced hydropower production Reduced access for water supply intake and recreational boating Dredging requirements increase, stir up polluted sediments
Shorter Great Lakes ice season	Increased lake effect snows Easier winter navigation
Declining groundwater and low river flows with increasing demand	Reduced water availability and competition for water in tributary basins
Lower minimum flows and levels	Late summer, autumn water quality problems
Heavier short duration rainfalls	Increased flash floods and drainage over-taxing Increased threat of erosion and polluted runoff from agricultural operations
Longer, more intense hot spells	Health effects of increasing smog and heat stress
More winter rain, less snow	Winter snow/ski season shorter, southern Quebec and Ontario – longer golf season
More intense winter snow and ice storms	Paralyzing winter events increasing

Sources: Brown et al., 1997. Bruce et al, 2000. Canada Country Study, Ontario, 1997. Karl et al. 1995. Mortsch et al. 1997. Lambert, 1995. McCabe et al., 2001. Sanderson, 1993.

Other relevant information on the Great Lakes region is provided in Mortsch et al. (2003). For trends in rainfall, other relevant sources are Vincent and Mekis (2005) and Zhang et al., (2001).

5.1.4. Québec

The OURANOS consortium was born of the need for greater knowledge and a deeper understanding of the climatic phenomena that will affect the territory of Québec during the upcoming decades. To accomplish this, the consortium's research program has been grouped under two broad themes: *Climate science and hydrology* and *Impacts and adaptation strategies*. Numerous studies have been produced in the recent 5 years and can be in most cases downloaded from the site (www.ouranos.ca).

A report produced in 2004 summarizes the projected impacts for Québec and the adaptation approaches. Figure 5.1 shows the division of regions to analyze climatic change impacts in the Province. Water management in all the regions is a key aspect that will be impacted by climate change.

Seasonal ebbs and flows in the volume of water and in spring runoff caused by changing rainfall patterns will have direct consequences for the transportation, residence time, and dilution of pollutants, as well as for the temperature and, by extension, the quality of the water. The anticipated changes to the Saint Lawrence River's hydraulic regime could displace the plumes of effluents and waste, leading to a widening or lengthening of the contaminated area in the receiving waterway (Ouranos, 2004).

One expected aspect of climate change is an increase in the frequency of heavy precipitation. These events could result in more frequent floods and overflows into flood zones.

The proposed strategies of adaptation should focus on 5 primary issues (Ouranos, 2004):

- the sensitivity of the water resource,
- the needs of the main users,
- the state and capacity of the supply infrastructure,
- the vulnerability of the resource-infrastructure complex,
- adapting to climate change.

In matters of urban drainage, it will be necessary to review the design criteria for infrastructure. However, since it will not be feasible to rebuild all these networks from the ground up, innovative rainwater management methods based on new intensity-duration-frequency curves will be required along with the construction of high-capacity storage facilities to avoid floods and overflows. Given a framework in which meteorological data is constantly evolving, it will be necessary to re-examine design flows in light of environmental effluent goals so as to keep the standards for the discharge of wastewater treatment plants up-to-date.

Figure 5.1. Delimitation of regions in Quebec for climate change analyses.

Table 5.8. Projected climate change impacts in Central and Eastern Quebec (Noble et al., 2005).

Climatic changes	Potential impacts
Higher intensity storms and more frequent rain-on-snow events	Increase in floods and other weather related natural disasters
Sea level rise, increased storminess	Shoreline inundation and erosion in St. Lawrence Estuary and Gulf
Salt water intrusion up the St. Lawrence River with sea level rise	Changes in ecosystems and water supplies Lower St. Lawrence
Increased flows in central areas offset declines in upper St. Lawrence	Little net change in hydropower generation

Sources: Browne et al., 1997. McCabe et al., 2001. Natural Resources Canada, 2001. Whitfield et al., 2000.

5.1.5 Atlantic Canada

The Halifax Regional Municipality's ClimateSMART Initiative (Halifax, 2006) was developed to "help mainstream climate change mitigation and adaptation into municipal planning and decision making." This highlights the fact that some municipalities are beginning to mainstream climate change adaptation for infrastructure into local planning procedures.

The climate change impacts that HRM can expect to experience include:

- mean annual temperature will increase by 4-5°C by 2100 and annual precipitation will increase by up to l00 mm;
- the magnitude and intensity of tropical storms and hurricanes are projected to increase so a 1 in 100 year event becomes a 1 in 50 year event;
- compounding impacts will be felt, as sea-level rise of up to 80 cm will make coastal communities and infrastructure more vulnerable to erosion and storm surge flooding;
- this, in turn, will lead to increased overwhelming of HRM's infrastructure that is close to or beyond its maximum capacity;
- the increase in mean annual temperatures means warmer winters, which will lead to an increase in the spread of diseases such as West Nile Virus and Lyme disease; and,
- along with mean annual temperature increases, freeze-thaw cycles will increase, stressing our roads and bridge infrastructure.

In order to address impacts and reduce economic and social risks, HRM recommend to implement a ***risk management approach*** to address the impacts from climate change in a consistent manner.

Table 5.9. Projected climate change impacts in Atlantic Canada (Noble et al., 2005).

Climatic changes	Potential impacts
Sea level and severe storm increases	Coastal damages, inundation and erosion
Storm surges, more intense winter storms	Potential for major disasters
Heavier short duration rainfalls	Flash floods and overtaxing drainage facilities
More frequent winter breakups	More ice jam floods, New Brunswick, Western Nova Scotia
Continued lack of warming, or cooling	Eastern Newfoundland and Labrador, longer winter ice cover
Salt water intrusion with sea level rise	Ground water quality threatened in coastal areas, e.g. P.E.I.
Increased temperatures and evaporation losses	New Brunswick and Nova Scotia more frequent summer agricultural droughts
Warmer river waters, and coastal water in western part of Gulf	Atlantic salmon threatened and increased shellfish contamination
Continued cooling Labrador Sea	Cod stock, Labrador Sea slow to recover

Sources: Abraham et al., 1997. Arctic Sciences Ltd., 1993. Boer et al, 1998. Bornhold, 1993. Forbes et al, 1997. Hare et al., 1997. McCabe et al, 2001. Stone et al., 2000.

5.2 International

5.2.1 Australia

Australia has produced many reports on climate change impacts and adaptation approaches, both at the national level (Allen Consulting Group, 2005) and for different parts of the country (Victoria, 2007); CSIRO, 2005). For Melbourne (CSIRO, 2005), expected impacts include:

Sewerage System

- Increased potential for corrosion and odours caused in the sewerage network as a result of increased sewage concentrations associated with water conservation, increasing ambient and seasonal temperatures, and longer travel times within the sewer network
- Increased incidence of sewer overflows due to increased rainfall intensity during storms
- Increased risk of pipe failure and collapse due to dry soil conditions
- Increased salinity levels in recycled water due to rising seawater levels resulting in increased infiltration to sewerage network and at wastewater treatment plants

Drainage

- Increased flooding risk and property damage due to increased rainfall intensity during storms
- Increased risk of damage to stormwater infrastructure and facilities (e.g., underground drains, levee banks, pump stations etc) due to higher peak flows

Receiving Waters

- Reduced health of waterways due to changes in base flows
- Potential for negative water quality impacts in Port Phillip Bay due to increased concentration of pollutants entering Bay (longer periods between runoff events and

then high intensity events leading to concentrated pollutant runoff) and higher ambient Bay water temperatures.

5.2.2 UK

The UK has an important program of research for climate change (UK Climate Impacts Programme - UKCIP, 2001). The Tyndall Centre has also produced some research and issue papers on the subject (Tyndall Centre, 2007). A guide for London has been produced for developments (London, 2005). The authors recommend among different approaches to use Sustainable Drainage Systems (SUDS). SUDS mimic natural drainage patterns (e.g. by mimicking greenfield run-off rates for development in areas of flood risk) and can attenuate surface water run-off, encourage recharge of groundwater, provide significant amenity and wildlife enhancements, and by employing pollutant trapping and degradation processes, SUDS can protect water quality.

The SUDS approach includes:

- preventive measures like good housekeeping, rainwater harvesting, green roofs and water butts;
- filter strips and swales - vegetated landscape features with smooth surfaces and a gentle downhill gradient to drain water evenly off impermeable surfaces;
- infiltration devices like soakaways which allow water to drain directly into the ground;
- storm water tanks if necessary;
- permeable and porous pavements;
- basins, reed beds and ponds designed to hold water when it rains.

A recent guide (Shaw et al., 2007) describes an approach at the catchment level, the neighbourhood level and at the lot or building level.

ICF Int. (2007) has looked into potential costs of climate change adaptation for the water industry. For these analyses, In broad terms, two approaches to risk adaptation can be defined. A “precautionary” approach would seek to adapt to climate change risks through planned investment or changes in systems and / or economic behaviour. This approach underlies the analysis undertaken in this study in that we have sought to identify the potential cost of adapting water infrastructure to make it more resilient to forecast changes in climate. An alternative “market” approach could see a basket of responses and instruments based on insurance principles as a means of signalling the cost of climate change risks. Responding to climate change risks in the most efficient way will inevitably need a mix of measures that embrace both approaches. There will be trade-off between the costs of adapting and the costs of insuring against potential climate related damages. The report covers three main areas issues of direct relevance to the water industry: water quality impacts, stormwater management; and sea-level rise. Table 5.10 gives the potential effects of climate change.

ICF int. (2007) reported on a research from UKCIP on the possible impacts of climate change on sewerage system performance, and implications for future design to maintain current levels of service. The primary implication of the study was that the potential changes to sewerage system performance to adapt to the future climate are likely to be large if they are addressed only by modifying the network infrastructure.

Table 5.10. Potential effects of climate change on water utilities (ICF, 2007).

Climate Change Physical Effect	Effect on Water Utilities	Adaptation Measure(s)
Drinking Water		
Higher temperatures	Poorer influent quality/ increased concentration of microbes, other temp-dependent pollutants	Increased treatment costs to maintain same quality
Sea level rise	Salt water intrusion (primarily ground water systems)	Hydrologic barriers, desalinization, alternative sources
Higher proportion of precipitation in more intense events ("lumpier" hydrology)	High flows: more runoff creates higher concentrations of non-point source pollutants Low flows: More frequent droughts, so if system does not have ample supply, could exacerbate problems	Generally higher treatment costs during high-flow periods; Potential need for alternate supplies during droughts
Wastewater		
Higher temperatures	If effluent limits are based on ambient water quality, dissolved oxygen standard will be slightly harder to meet	Discharge less BOD, increase treatment costs
Higher proportion of precipitation in more intense events ("lumpier" hydrology)	If effluent limits are based on ambient water quality under specific low-flow conditions, receiving stream will have lower flows for a given recurrence interval	Tighter effluent limits on all pollutants will require higher treatment costs
Stormwater		
Higher proportion of precipitation in more intense events ("lumpier" hydrology)	For combined sewer systems, if standards are expressed in terms of hydrologic design conditions (e.g., no more than 4 overflows per year), it will be harder to meet the standard Design flows will be exceeded more frequently	Increase margin of safety in design specifications (implies higher hydraulic capacity, higher costs)

Some of the study's relevant findings were as follows (ICF, 2007):

- CSO spill volumes are expected to increase by up to 180% across the UK
- The frequency of spills for the whole year is much greater with the number of additional spills in the South being from 3 to 7 per year, but as much as an additional 12 times in the North.
- A reduction in summer flows is likely to reduce the amount of water available for the dilution of any polluting CSO discharges.
- The impact of climate change on WWTW inflows are likely to be small and will have minimal effect on biological processes.

- Storage solutions to meet coastal CSO impact standards were also shown to need to increase significantly for the 2080 to meet compliance; a 6 fold increase needed to meet the 10 spill per annum standard for shellfish waters was necessary and a 7 fold increase needed to meet 3 spills per bathing season standard.

- A comparison of additional storage required to meet salmonid water quality standards was carried out, for 2080, 2080 with a 20% reduction in river flow due to climate change.

- For many areas in UK, climate change may result in an 40% increase in rainfall depths in excess of the current values with a subsequent doubling of flood frequency and volume. Following an increase in rainfall will result in storage volumes to prevent internal property flooding needing to increase by more than two fold.

The UKWIR study also highlighted the significant areas of uncertainty in the estimation and modelling. Uncertainty in predicting future rainfall patterns suggests that approaches to sewer design should move towards a risk based approach rather than meeting design standards.

ICF (2007) also indicated that there are four key elements to converting knowledge about climate change impacts into strategies and actions for climate change adaptation:

- Recognize that climate change is not yet a “driver” of decisions.

- Recognize that few adaptation questions in water management have to (or can) be answered now.

- Develop tools to help classify water management decisions, and provide appropriate decision support systems to promote outcomes that increase resilience.

- *Decision support tools for water management decisions.* For example, engineering design objectives for combined sewer overflow controls are often expressed in terms of the “rational method,” which is keyed to hydrologic statistics on precipitation intensity, duration, and frequency (IDF). Decision support could be provided in the form of rules-of-thumb on how to adjust IDF to anticipate climate change, or recommendations for an additional margin of safety; such tools would provide a straightforward, clear way to incorporate climate change within the existing framework.

The authors finally recommend a decision making framework, shown in Figure 5.11.

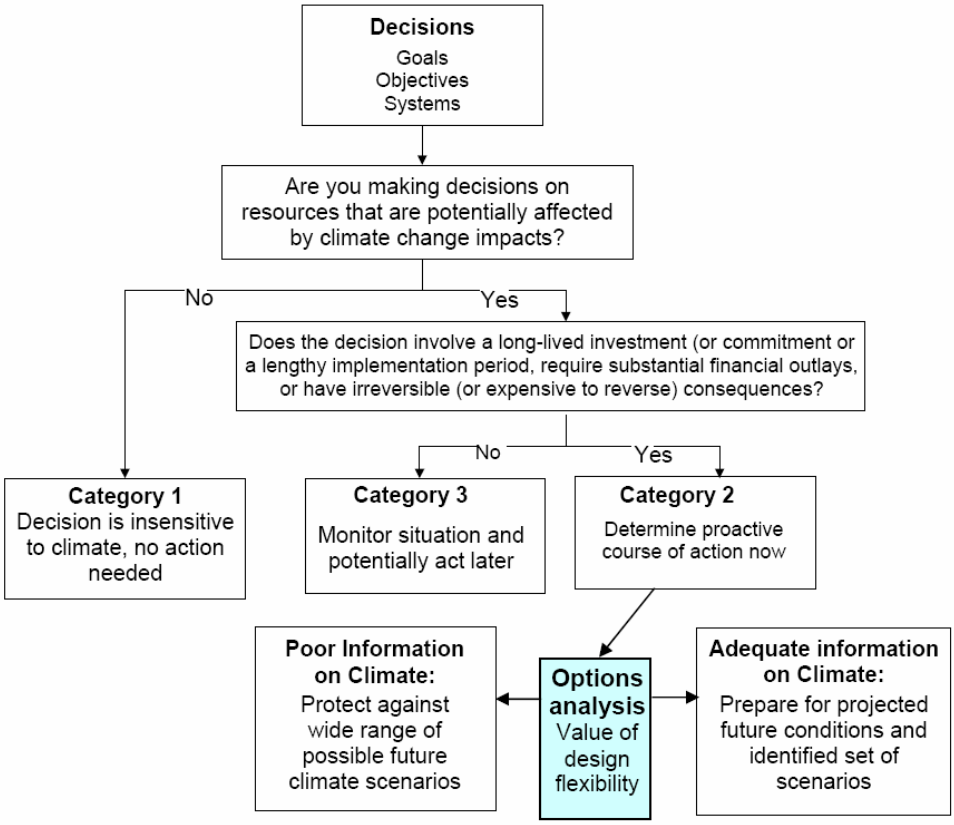


Figure 5.11. Climate change decision making framework (ICF, 2007)

Hunt and Watkiss (2007) have completed a literature review on climate change impacts on urban city centres. Case studies for many cities around the world are discussed and reviewed (see Table 5.11). It is noted that there are few predictions of storm damage risks specifically at a city level. This may reflect the difficulty in down-scaling the prediction of extreme events to an appropriate level. The New York study by Rosenzweig and Solecki (2001) is an exception here, using historical analogues to derive annualized losses for different storm frequencies. They calculate projected damages of approximately 0.1% of Gross Regional Product, annualized, and a probable maximum loss of 10-25% of GRP for one event.

Table 5.11. Major city studies considered in the review (Hunt and Watkiss, 2007).

City	Nature of study	Type
OECD		
Europe		
Athens	Study of future air conditioning demand for electricity from climate change. (Giannakopoulous et al, 2006)	Quantitative
Paris	Analysis of 2003 heatwave on health / infrastructure (impacts and some values), e.g. Gillet, 2006.	Historic
Lisbon	Impacts on heat related mortality with climate change (Dessai, 2003)	Quantitative
London	Several studies including economic impacts of historic extreme events, future climate change impacts, adaptation response (LCCP, 2002; 2006.) see below.	All
North America		
Boston	Climate's Long-term Impacts on Metro Boston. Transport, Energy, Health (all quantitative) and Water (valuation). (Kirkshen et al, 2006).	Quantitative Valuation
California (Los Angeles)	Heat mortality (quantitative), water availability and ecosystems under future climate (Hayhoe et al, 2004). Cayan et al (2006). Electricity. Miller al (2007)	Quantitative
Seattle	Climate Change and Seattle Department of Transportation (OCA, 2005). Consideration of recent events, and potential future multiple risks	Historic Qualitative
New York	Series of studies, e.g. Rosenzweig and Soleck et al, (2001; 2006) – quantification and valuation	All
Toronto Vancouver	Adapting To Climate Change In Toronto (health and energy) Ligeti, 2007 Climate Change Impacts and Adaptation Strategies for Urban Systems in Greater Vancouver (Sheltair, 2003) – qualitative assessment.	Quantitative Qualitative
Other OECD		
Sydney, Brisbane Melbourne	Australian GHG Office reports, as well as state studies, e.g. Victorian Government. CSIRO impact reports (e.g. Preston and Jones, 2006). Sector city studies (heath – impacts in all 10 Au/Nz cities), infrastructure (Victoria, CSIRO).	Qualitative/ Quantitative
Wellington, NZ	Climate's Long-term Impacts on New Zealand Infrastructure, Jollands et al 2006	
Mexico City, Tokyo	Disaster risk reduction in mega-cities: Making the best of human and social capital. Qualitative comparisons (Wisner, 2003)	Qualitative

5.2.3 Europe

Some reports were completed in Europe under larger organization. The European Water Association has given a preliminary opinion on the subject of the consequences of climate change for water management (EWA, 2006). Some of the key elements are:

- The EWA recognises that climate change will lead to increased droughts, floods due in part to more intense rainfall, heat waves and other ecological disturbances as well as impact on water resources across Europe. This will raise questions about the resilience of infrastructure and how vulnerable it is such events and it will also require a review of policy to determine if climate change effects are being fully accounted for.

- From the evidence available it is clear that climate risk factors now have to be built into water cycle management and it is important that funds should be available to support the practical consequences of this.

- The EWA believes that climate change factors need to be incorporated into the design of sewerage systems; climate change risk factors need to more widely used in flood risk.
- management; water resource planning must incorporate the social and economic impacts of climate change in addition the resource implications and the EU needs to ensure that climate change is incorporated into directives and other legislation.

The European Environment Agency has also published some reports (EEA, 2005; 2007). The main points to be highlighted include:

- Development and implementation of adaptation measures is a relatively new issue. Existing adaptive measures are very much concentrated in flood defence, which has enjoyed a long tradition of dealing with weather extremes. Concrete adaptation policies, measures and practices outside this area are still scarce. Therefore, there is considerable scope for advancing adaptation planning (EEA, 2005).

- In recent decades more intense rainfall events have occurred and parts of Europe have experienced extreme weather events in the form of severe floods, droughts and heat waves (EEA, 2007).

- From the sustainable development perspective, the top priority for adaptation in the water sector should be to reduce the vulnerabilities of people and societies to shifts in hydro-meteorological trends, increased climate variability, and extreme events. A second priority should be to protect and restore ecosystems that provide critical land and water resources and services (EEA, 2007). Climate change impacts can also be limited by structural and technological change, and/or regulatory and institutional change.

- Implementation of any of these strategies takes considerable time, particularly if substantial step changes are needed. Successful adaptation will also require interactions between multiple levels of government.

- The need for research on the vulnerability of society and ecosystems to climate change impacts is felt by many countries, particularly for the water sector. Better databases on frequency, intensity and effects of extreme events and on national adaptation practices, including responses to these extremes, would facilitate the development of effective adaptation strategies.

6. LITERATURE FOR ENGINEERING DESIGN AND STANDARDS

The vulnerability of different types of infrastructure and the potential impacts that new engineering requirements, codes and standards will have on climate change vulnerability are largely unknown (IC, 2006). At present, almost all infrastructure has been designed using climatic design values that have been calculated from historical climate data under the assumption that the average and extreme conditions of the past will represent conditions over the future lifespan of the structure.

Existing Canadian climatic design values are in need of upgrades and regular updates. In Canada, as in other countries of the world, “current longstanding gaps and deficiencies in the determination of climatic design values prevent optimum decisions from being made on infrastructure reliability and safety.” (Auld and MacIver, 2005).

There are many reasons why climate change adaptation options are not yet regularly incorporated into infrastructure design and why climatic design information does not include climate change projections. These include uncertainties in climate change projections, uncertainties and gaps in existing climatic design values, and a shortage of sufficient climate station records (Auld and MacIver, 2007b).

IC (2006) concluded that:

- We do not have a good understanding of the vulnerability of different types of infrastructure, nor do we know what potential impacts new engineering requirements and codes and standards will have on climate change vulnerability.

- Infrastructure design must change. Engineers need new and updated climatic design values, revised codes and standards, and new methodologies to incorporate potential climate changes into engineering procedures. More current climate data and its analyses are needed for this work. The federal role in areas such as monitoring and reporting is essential.

- There is a need for more communication (information sharing and training) between climate change researchers, policy makers, engineers, architects, operators or asset managers in order to mainstream climate change adaptation into design, maintenance and restoration of infrastructure.

Adaptation also requires non-structural approaches, targeted at reducing community vulnerability to changing natural hazards. There are many services that can be employed by governments for this purpose, some of which include: hazard assessment and monitoring, planning and building codes, prediction and warning systems and public education and research (McBean and Henstra, 2003).

CSA (2006) also looked at the implications of climate change for Canadian standards. The main conclusions are:

- Mainstream infrastructure design establishes a prudent balance between capacity, resilience, cost, reliability and durability without compromising safety. Furthermore, many existing standards and codes rely heavily on statistical

models based on historical weather data in order to establish infrastructure design parameters and thresholds. This is a fundamental building block of the current practice.

- Normal mainstream practice assumes that past weather extremes will represent future weather conditions. Under changing climate and weather conditions, this assumption will no longer apply. The 1995 National Building Code of Canada included a section explaining the growing uncertainties that climatic design values will be subjected to under changing climate conditions.

- However, the literature reviewed points to evidence that historical weather patterns may not be as relevant in the future as they were in the past. If weather data is indeed no longer as relevant as in past, then this has a profound impact on the capacity for structural infrastructure systems to adapt. Many leaders and practitioners within the structural and infrastructure design communities have been aware of this issue and related debates for many years. However, until a more fully developed toolkit exists and is proven, implementation of alternative mainstream responses will be minimal.

- Up-to-date climatic design values are needed to reflect the latest state of the changing climate. This will help infrastructure designers and owners to take actions to avoid or mitigate premature deterioration, reduce the overall cost of ownership, and improve service levels. These are fundamental building blocks of adaptive capacity, and provide a means of avoiding adaptation deficits. While a changing climate is one possible driver for good design practice, it is not the only driver.

- Until such time as a radically different approach to structural design emerges, high quality, reliable climatic data with sufficient geographic dispersion and density, will remain a key element of designing, building and operating resilient infrastructure systems. Presently, responsibility for the maintenance of climatic data resides primarily with the federal government.

- Much of this research enters the mainstream of practice via CSA's technical committees and the standards that they develop. Hence, a robust research and development community focused on the infrastructure/adaptation file and its proactive involvement with CSA technical committees will help to enhance adaptation.

A national survey of Canada's infrastructure has also ben completed recently by CSA (2007). 82% of respondents indicated that they accept that Climate Change issues will affect their practice. Engineers working in building or water sectors are significantly more predisposed to this with scores of 88% and 87% respectively. While most respondents agreed (82%) that Climate Change will affect their practice, far fewer always or mostly consider Climate Change impacts in their decisions today (27%). the responses indicate that solutions may not be as well-known, or that the weather data that engineers rely upon is not sufficiently forward-looking to be useful to engineers at present. While results varied by category, there appears to be a significant gap between the need to consider the impacts of Climate Change within infrastructure engineering and the state of practice today.

CSA (2007) also looked at the curriculum for engineering and climate change impact and adaptation. Some key findings include:

- There is an already available body of knowledge on climate change responses for built infrastructure and it is expected that this knowledge-base will continue to evolve and improve over time.
- There seems to be a significant gap between what engineers presently know and what they would need to know to deal with Climate Change issues more effectively.
- Climate Change should be considered as one of many stressors or factors that infrastructure engineers will need to consider in the future, and should not be considered in isolation.
- Infrastructure engineers acknowledge that they need much more knowledge if they are to incorporate Climate Change into their practice.
- Climate Change represents a relatively new challenge for most engineering disciplines.
- While much of the education required needs to be developed and instilled at the university curriculum level, efforts must be made to also build awareness with practising engineers through alternative sources such as distance learning, workshops, papers and continuing education courses.
- Removal of systemic barriers will also help to accelerate the integration of climate change considerations into mainstream engineering practice. For example, codes and standards have a profound influence on engineering decision-making. Codes and standards developers and stakeholders have further work to do, so as to ensure that Canada's complex network of codes and standards enable rather than inhibit climate change responses and solutions. Furthermore, there was evidence that at least some decision-makers don't yet support or require climate change issues to be considered as part of technical decision-making. This also has implications for how effectively engineers can address climate change issues in their day-to-day work.

Another recent report (CSA, 2007) positions CSA as an integrating player for climate change adaptation. Many standards produced by CSA will be impacted by climate change and CSA is currently reviewing how these standards may need to be revised given our changing climate, and whether new standards are required to manage the emerging risks.

Other discussion on engineering design and standards are given in Kije Sipi (2001):

- Changes at the policy level must translate into improvements to the drainage design methods and their applications as well as construction procedures used by local governments. Where possible, relevant national standards and guidelines should be adapted to deal with the new drainage design requirements resulting from climate induced changes to hydrologic regimes.

- A second avenue for adaptive solutions deals with the current design philosophies. Drainage design criteria should be reviewed and revised based on a cost-benefit analysis and risk assessment considering the threat of climate change. Life-cycle implications must be built in to the resulting design criteria.

- A third area that can potentially yield adaptive solutions is changing current methods of analysis and design. Instead of using simplistic methods such as the "Rational Method" which is reliant on historical data (IDF-based), deterministic modeling, which is based on using projected meteorological time series might be a more appropriate analysis & design method. There will be a need to adopt simple but adaptive design approaches to counter potential increases in complexity of the design methods due to the changing climate. This review process should take place within a larger framework establishing national guidelines on drainage design and analyses methods.

- A review of drainage design methods, their applicability and usage in the context of climate change should be completed within a larger framework establishing national guidelines on drainage design and analyses methods.

Recent analyses to derive IDF curves for future climate include the studies of Mailhot et al. (Mailhot et al., 2007; Rivard et al., 2007), He et al. (2006) and Prodanovic and Siminovic (2007). The analysis by Mailhot et al. (2007) was discussed previously. He et al. (2006) used results from GCM to derive synthetic design storm (Chicago type) to analyze existing sewer networks in Calgary (Alberta). The derived IDF curves are shown in Figure 6.1 and the resulting discharges in Figure 6.2. It was concluded that for storm-water drainage system engineering design, the changes in the mean and variance of rainfall extreme events have a large effect on the design, since these changes result in a change in the frequency of extremes, which is used as a design criterion.

Finally, Prodanovic and Siminovic (2007) looked at IDF curves for London (Ontario) in a changing climate context. Two climate change scenarios are selected for this work: scenario B11 (dry) and B21 (wet). These scenarios are chosen as the most appropriate for the study of extremes (especially the study of extreme rainfall). Both are based on the IPCC (2001) scenario story lines B1 and B2. Outputs of the study indicate that:

- The rainfall magnitude (as well as intensity) will be different in the future.

- The wet climate scenario (recommended for use in storm water management design standards) reveals significant increase in rainfall magnitude (and intensity) for a range of durations and return periods.

- The increase in rainfall intensity and magnitude has major implications on ways in which current (and future) municipal water management infrastructure is designed, operated, and maintained.

- The design standards and guidelines currently employed by the City of London should be reviewed and/or revised in the lights of the results of this research to reflect the impacts of climatic change.

Figure 6.3. shows the resulting IDF curves.

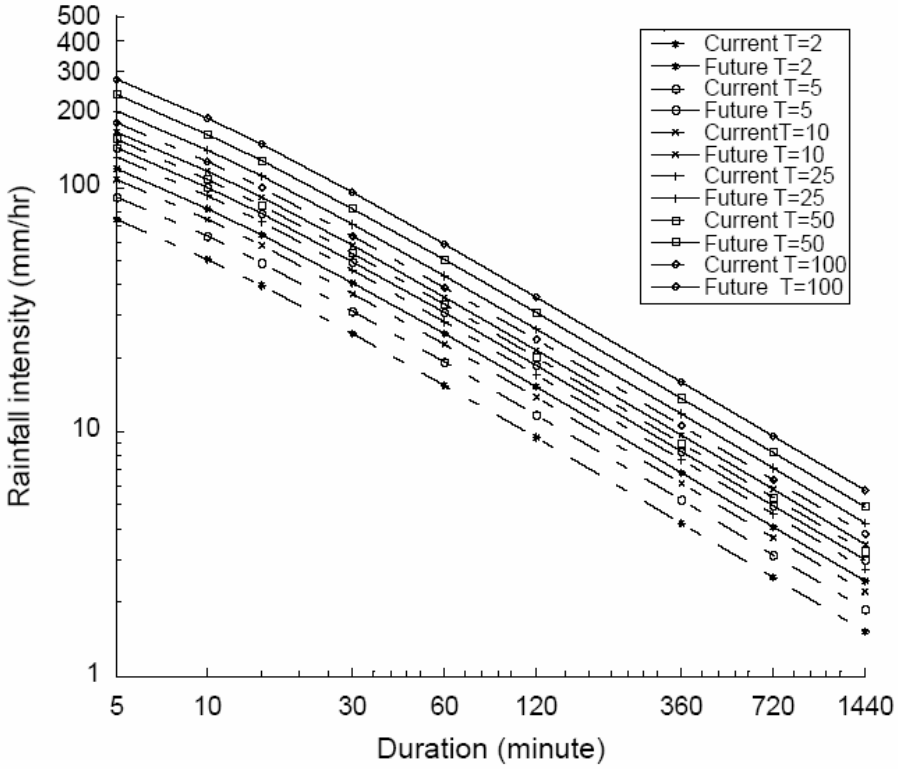


Figure 6.1. IDF curves for current and future climatic conditions in Calgary (He et al., 2006).

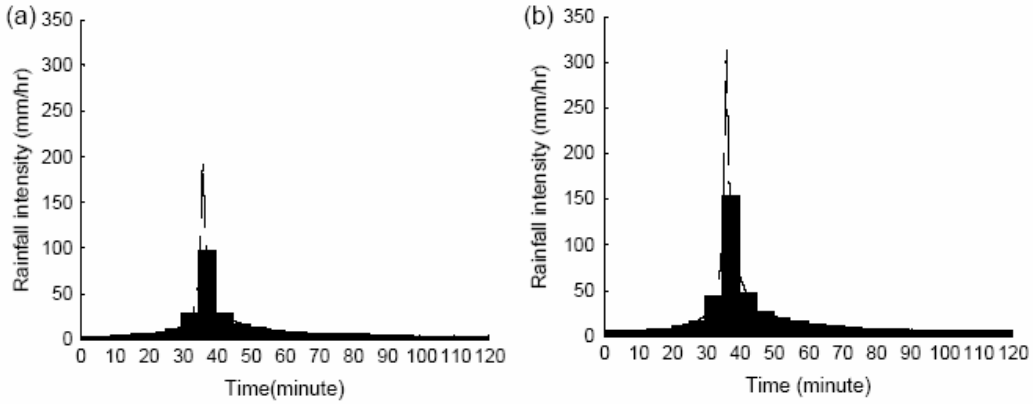


Figure 4 The hyetographs for current (a) and future (b) climatic conditions

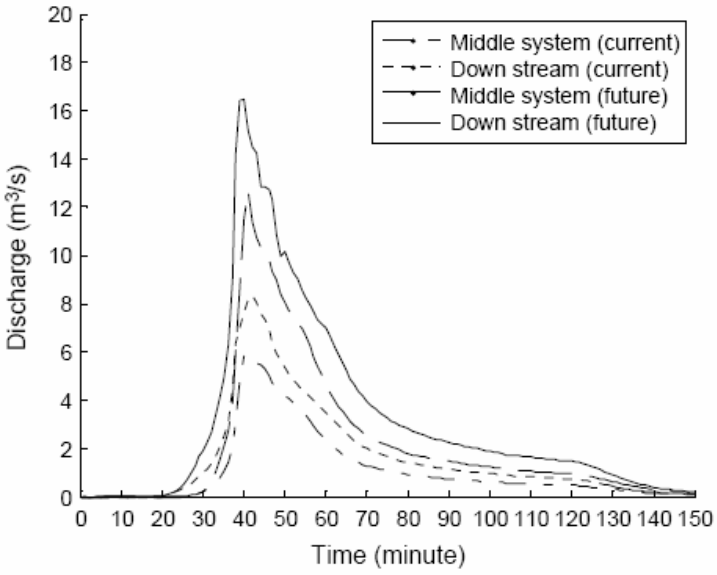


Figure 5 Discharges in pipes for current and future climatic conditions

Figure 6.2. Results of simulations with PC-SWMM for a sewer system in Calgary for current and future climatic conditions (He et al., 2006).

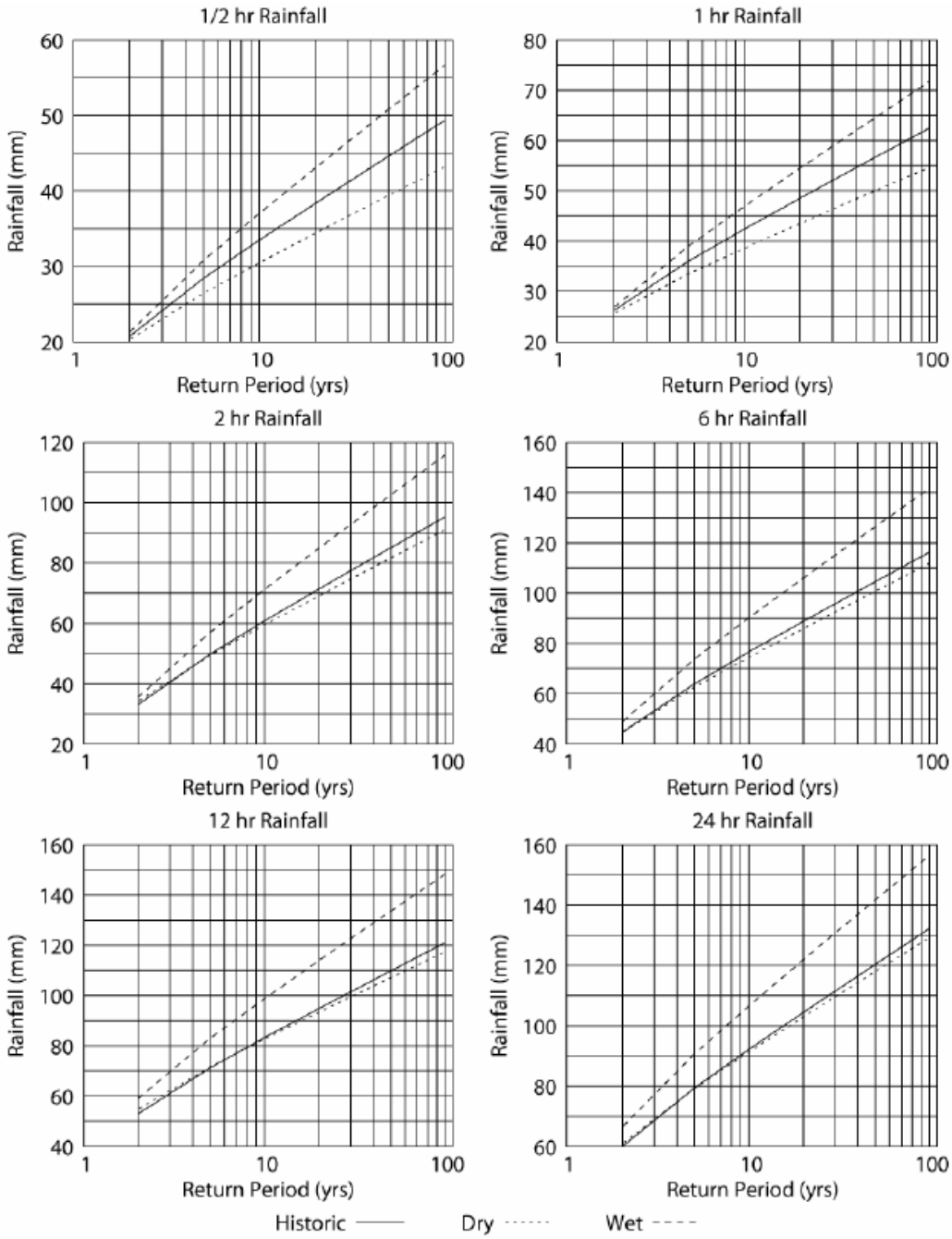


Figure 6.3. Results with adjusted IDF curves for London (On) (Prodanovic and Siminovic (2007)).

Another reference on rainfall is Cobbina (2007).

IC, 2006

Adaptation measures for water infrastructure are controversial because of the uncertainties surrounding climate change impacts and the significant environmental, economic, and social costs associated with building new infrastructure. Instead, much of the literature on water infrastructure adaptation stresses the importance of implementing

"no regrets" measures. "A "no regrets" climate change adaptation provides benefits to the community whether anticipated climate changes materialize or not.

In addition to "no regrets" measures, there are opportunities for mainstreaming climate change into infrastructure planning processes (IC, 2006). Including climate change considerations into these practices would mainstream climate change into water management, and, consequently, water infrastructure planning.

Vulnerability and risk assessments should replace the current dependence on historical climate data. Regularly updated climate design values that reflect the latest changes in regional climate, including precipitation variables, are required for the updating of design codes and standards. Currently, engineers use historical climate records when designing most urban water drainage systems. If precipitation patterns change, urban drainage systems could fail, causing problems such as sewer backups and basement flooding.

In conclusion, although municipalities are beginning to implement some "no regrets" adaptations for water supply and wastewater infrastructure, more data needs to be collected, more research needs to be conducted, engineering designs need to change, climatic design values need regular updates, and actions need to take place to mainstream climate change adaptation in order to adapt our water infrastructure.

7. KNOWLEDGE AND RESEARCH NEEDS

IPCC (Field et al., 2007)
The major limits in understanding of climate change impacts on North America, and on the ability of its people, economies and ecosystems to adapt to these changes, can be grouped into seven areas.

- Projections of climate changes still have important uncertainties; especially on a regional scale.
- There is a need for improved understanding of the relationship between changes in average climate and those extreme events with the greatest potential impact on North America.
- we have few tools for assessing the conditions that lead to tipping points, where a system changes or deteriorates rapidly, perhaps without further forcing.
- Few studies address the interacting responses of diverse sectors impacted by climate change.
- Very little past research addresses impacts of climate change in a context of other trends with the potential to exacerbate impacts of climate change or to limit the range of response options
- Indirect impacts of climate change are poorly understood.

- understanding of the options for proactive adaptation to conditions outside the range of historical experience is limited.

Watt (2003) also identifies some gaps in knowledge, which could be presented in three categories: climate change impacts, urban hydrology and water quality.

Climate Change Impacts
The most important knowledge gap in this category is the change in storm rainfall quantiles for durations of 24 hours or less (an increase of 15 percent has been assumed in this study). If BMP design were to become more sophisticated, the change in the distribution of rain vs. no-rain days might also be important.

Urban Hydrology
The current generation of urban hydrology models was developed before BMPs were popular and hence most models are generally unable to incorporate small-scale measures (both quantity and quality) or large-scale quality measures (e.g., extended detention ponds). In addition, they usually lump a number of inlets for pipe design. There is a need, therefore, for a "next generation" urban runoff model that makes use of recent developments in computing science and knowledge of urban runoff processes. However, some of these processes are not well understood (e.g., infiltration in urban areas under frozen, thawing and thawed conditions; transport of pollutants).

Water Quality
Water quality is perhaps the most important of the three categories. The knowledge requirements include :

- Sources, source inventories, pathways and fate of contaminants as well as microbial pollutants in the urban environment.
- Regional diversity in processes due to climate, surficial geology, urban development practices, etc.
- Effectiveness of control measures in protection of receiving waters and both aquatic and terrestrial ecosystems, and human health, by policies and source controls, site best management practices (BMPs), community BMPs, and watershed-level measures. This knowledge should contribute to the eventual substitution of effluent criteria with ecological risk assessment of receiving waters.
- Increased vulnerability of ecosystems by secondary effects of stormwater management measures (risk of contamination of groundwater, heating of ponds and wetlands, release of contaminants from sediments, and risk to aquatic life and wildlife through uptake of contaminants and exposure to pathogens).
- Cumulative and combined effects of urban effluents on receiving waters and their ecosystems, with respect to intermittent exposures to varying concentrations.

The following recommendations address quality and quantity issues associated with accommodating climate change. Research studies and programs should be developed to complete the following (Watt, 2003):

- Update IDF curves and 1-hour design storms for Canadian urban centres.
- Encourage the practice of urban stormwater infrastructure design based on modelling for two scenarios, design storm based on the record to 2002 and a revised design

storm based on expected climate change. Until better estimates are available, the revised design storm should be 15 percent larger than that based on current conditions **(Note : the 15 % was selected arbitrarily in the Watt study as it appeared to be the trend shown in the literature at that time).**

- Determine the total cost of retrofit measures for various system sizes and various sizes of municipality (e.g. the cost of orifices for a 100-manhole system in a municipality of 50,000, 200,000, 1,000,000 persons).
- Conduct a combined fact-finding/feasibility study to determine the need for, and necessary attributes of, a "next generation" urban runoff model.
- Determine appropriate adaptive measures to accommodate elements of climate change other than storm rainfall in terms of the protection of receiving waters and both aquatic and terrestrial ecosystems.

It is not necessary to prove to the engineering/planning community that an ounce of prevention is worth a pound of cure once a particular problem has been made compelling enough. "Engineers in general and municipal engineers in particular are often viewed as being more conservative than the average citizen. Whether or not this is true, the fact remains that most engineers will not revise long-standing design inputs unless the revised input can be defined with an acceptable level of uncertainty. Simply put, a reliable authority must state, for example, that storm rainfall in a specified region of Canada is expected to increase by a certain amount, with a defined margin of error, by a particular point in the future" (Watt *et al.,* 2003).

Semadeni-Davies et al. (2008) noted that, while many researchers have recognized the need for a range of climate change scenarios in order to combat uncertainty within GCMs and regional climate models, the equally important notion of landuse change scenarios or storylines has hitherto been less well represented in impact assessments. A failure to account for such changes implies a society that is unable to respond to global change whether it be environmental, political or economic and which is devoid of technical innovation. The worldwide trend towards SUDS for instance, not only improves the urban environment through blue–green space creation, it also offers some future protection in the face of both urbanization and climate change and should be recognized as a valuable adaptation to change. By presenting a broad range of possible outcomes for future drainage problems in Helsingborg (in Sweden), each of which is plausible given current trends in city development, the paper has demonstrated the need for urbanization storylines within climate change impact assessments and has provided an example of storyline development and use for urban drainage systems.

Appendix C.3

Roads and Associated Structures Literature Reviews

Engineering Literature Review: Roads and Associated Structures: Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change

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1.0 EXECUTIVE SUMMARY

This report provides a summary of the findings from the literature scan, directed at identifying engineering literature that relates to road and associated infrastructure vulnerabilities in light of climate change. The scan was carried out over the course of several weeks in late 2007/early 2008. Although many Canadian transportation agencies are thinking about the potential vulnerabilities and associated engineering impacts, very few agencies have completed any formal analysis at this time. A few agencies currently have some on-going activities that are expected to be completed in 2008, but the majority have not started to examine the engineering aspects of how the change will need to be addressed in design, construction and maintenance.

Initially over 75 websites were examined with primary focus on provincial and territorial departments of transportation and cities and municipalities. Several searches were carried out under the title, "Climate Change Impacts on Roads and Bridges" and variations of this title. Although climate change and it's impact on transportation and specifically roads and associated structures is appearing in various reports and documents across Canada, available detailed information on engineering impacts was limited to non-existent.

In addition, several searches through the library and various relevant technical societies did not result in any substantial findings of engineering reports. Subsequent to that exercise, over 100 emails were sent to various engineering professionals from all sectors including, public-private-academic, including all members of the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Roads and Associated Structures Expert Working Group (RASEWG) group, contact lists provided by Engineers Canada, other professional networks, etc. This report summarizes the information that was located.

This report includes a brief introduction and background on climate change in general and the related predicted impacts on road infrastructure and associated structures, with primary focus on bridges. These sections are followed by project scope and objectives and methodology of assessment. The summary of findings provides some more specific details and has been prepared using available public agency documents that were located during the aforementioned search. Finally a few closing comments are made and the references and bibliography, as per the terms of reference are provided.

2.0 INTRODUCTION

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) is conducting the first national engineering assessment of the vulnerability of public infrastructure to the impacts of climate change. Four categories of infrastructure are being assessed:

- Buildings
- Roads and associated structures i.e. bridges and culverts
- Stormwater and wastewater systems
- Water resource systems

Expert working groups (EWGs) have been formed in each of the four infrastructure categories. They consist primarily of engineers who are subject matter experts in the design and/or operation in the particular infrastructure. The EWGs report to the PIEVC. The PIEVC is supported by a Secretariat operated by the Canadian Council of Professional Engineers (CCPE), operating under the business name Engineers Canada in partnership with Natural Resources Canada through a Contribution Agreement.

The literature scan provided herein is directed at Roads and Associated Structures and will be reviewed by the Roads and Associated Structures Expert Working Group (RASEWG). This examines vulnerabilities from an engineering and not climate change perspective and is intended to ensure that no process or procedure for engineering vulnerability assessment has been overlooked.

3.0 BACKGROUND

3.1 Climate Change

Relatively little research has been completed to investigate the potential engineering impacts of climate change on infrastructure, and particularly roads and bridges. Potential impacts need to be addressed given the importance of road and bridge infrastructure on economic and social activity. More specifically, climate change can impact: thermal cracking, frost heave and thaw weakening, permafrost melting, permanent deformation associated with warm and cold temperatures, to name a few. Current and past engineering designs generally assume a static climate whose variability can be adequately determined from records of weather conditions which normally span less than 30 years and often less than 10 years. The notion of

anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration [Mills 2007].

General methods for assessing the potential impacts of climate change on various aspects of society, economy and environment have been developed over the past two decades, largely based on approaches rooted in applied climatology or the hazards and risk assessment literature [Kates, 1985; Burton et al., 1993; Bruce et al., 2001]. The leading international source of guidance on climate change impact assessment is the Intergovernmental Panel on Climate Change (IPCC), an organization that is responsible for periodic reviews of the scientific literature on aspects of climate change science, impacts and adaptation assessment, and emissions mitigation [IPCC, 2001, 2007].

3.2 Road Impacts

As with other forms of infrastructure, the fundamental concern related to a changing climate in road and pavement design and management is the potential for premature design failure. Current and past designs generally assume a static climate. The increase in temperatures and associated precipitation bring challenges and raise the possibility that the frequency, duration or severity of thermal cracking, wash outs due to flooding, rutting, frost heave and thaw weakening may be altered leading to premature deterioration [Mills 2007].

Analysis of deterioration-relevant climate indicators at 17 sites, located in Southern Canada suggests that, over the next 50 years, low temperature cracking will become less problematic; structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths; and higher extreme in-service pavement temperatures will raise the potential for rutting [Mills 2007]. Further evidence from this study indicated that that permanent rutting on asphalt roads and cracking such as longitudinal and alligator issues will be exacerbated by climate change with transverse cracking becoming less of a problem. In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life [Mills 2007].

In Northern Canada, Snow Roads provide transportation routes. There are several examples of areas where the roads and pipelines have been disturbed by thawing permafrost. In addition, snow roads have been important for Oil and Gas Extraction and the Forestry Industry.

With the thawing of the permafrost, alternative methods for bringing supplies in will be required in some communities. It has also been shown that the permafrost has warmed and the depth of the layers of thaws each year is increasing. In short, it is expected that permafrost will shift several hundred kilometres this century [GM 2007]. In addition, Hayley and McGregor [Hayley 2007] noted that Winter and Ice Roads are used extensively in Canada to resupply remote communities and to support resource development. In particular, the Tibbitt to Contwoyto Winter Roads in the Northwest Territories supports the diamond mine industry and current climate change has already impacted the operation and initiated the need to shorten operating season [Hayley 2007].

Additional rainfall, resulting in flooding and lane closures is also a potential engineering vulnerability. For example, in New Brunswick [GNB 2005], road closures due to flooding are posted on their website. This has been occurring as there are many areas of the province that are low-lying and susceptible to flooding. The provincial department of transportation makes every effort to sign or barricade roads where there is risk to motorists. However, water levels can increase quickly, and drivers are warned to use appropriate caution whenever they encounter water over the road. Similar examples of road closures and washouts can be found across Canada.

Another key point is the change in the timing and duration of Seasonal Load Restrictions (SLR) and Winter Weight Premiums (WWP) which are applied to many roads located in Canada. Application of seasonal load restrictions to certain parts of the highway network can lead to lost productivity and a substantial impact on the economy. Once these restrictions are in place, the payload of certain heavy vehicles must be reduced [Tighe 2006].

One of the largest challenges particularly in Northern regions of Canada, is to design and monitor roads concisely to mitigate damage caused by seasonal effects. This is a complex problem as many of the roads are gravel or surface treated and there is limited funding available for the construction and maintenance of these facilities. Thus, it is vital that these roads are protected, particularly during the vulnerable spring thaw period. In order to properly protect these facilities, it is necessary to monitor them in a coordinated manner which utilizes both temperature and pavement data [Tighe 2006, Baiz 2008]. The use of real time data is essential and may lead to the need to instrument many sections of road to closely monitor the conditions so that roads can be adequately identified and that potential damage

due to overloading during weakened conditions can be avoided. Instrumentation may include Road Weather Information Systems (RWIS), thermister strings, strain gauges, moisture probes, etc. [Tighe 2006]. There are several current initiatives on-going in Ontario, Quebec, Manitoba, New Brunswick and British Columbia to better understand the relationship between pavement strength and thaw weakening.

For road authorities that manage much of the primary paved road network in Canada, the key adaptation issues will not simply focus on how to deal with potential impacts, but rather when to modify current design and maintenance practices to accommodate these changed conditions. The basis for such decisions often falls back to an assessment of relative costs (between status quo and various designs or interventions) borne by the public, road users and, to the extent permitted in contractual agreements, by private sector construction and maintenance providers [GNB 2005, AIT 2007]. Many agencies do employ some form of Pavement Management and this will assist in tracking vulnerabilities and in-service performance.

3.3 Bridge and Culvert Impacts

Additional rainfall, resulting in flooding will also impact bridges and culverts. Again, in areas that are low-lying and susceptible to flooding, alternative designs may be required. The provincial departments of transportation may need to close roads in areas of vulnerability and certainly make this information available to the travelling public.

Planning for new bridges and culverts will require modification in engineering design to ensure the new structures can withstand the change in length and frequency of weather events, as well as hydrological changes. The safety margin for building structures will need to be adjusted to allow for greater variability in weather and account for a wider range of extremes, especially considering that many bridges today are being designed for 100 year design lives. There also may be pressure to consider alternative modes of transportation, particularly transit, which may result in different long term loads on the structures [AIT 2007].

Another important element to consider includes identifying structures which may be vulnerable to receding permafrost, flooding or landslides. Drainage Infrastructure Management Systems will be required to link locational referencing data and specific to assist with

this effort. Further impacts may include revision to maintenance costs and timing required to carry out the maintenance.

4.0 PROJECT SCOPE AND OBJECTIVE

The primary purpose of this literature scan is to focus on the engineering vulnerability with particular emphasis on technical societies, municipal publications and reports and engineering consultant reports. The emphasis of the scan is on vulnerabilities and design considerations for roads and associated structures, namely bridges and culverts. Also included in this report is a Bibliography of references for inclusion in the overall National Engineering Assessment and these are provided in Appendix A.

4.1 Methodology of Assessment

The main focus of this effort was to briefly review the 2007 PIEVC literature scan on climate change and focus this effort on identifying recent engineering studies that have been carried out. Initially over 75 websites were examined with primary focus on provincial and territorial departments of transportation and cities and municipalities. Essentially searches were carried out under the title, “Climate Change Impacts on Roads and Bridges”. Although climate change is appearing in various reports by public sector agencies across Canada, available detailed information on engineering impacts was limited to non-existent. In addition, several searches through the library, various professional networks and various relevant technical societies did not result in any substantial new information.

Subsequent to that exercise, over 100 emails were sent to various transportation professionals from all sectors including, public-private-academic, including all members of the PIEVC RASEWG group, contact lists provided by Engineers Canada, other professional networks, etc. This report summarizes the information that was located.

In general, there were very few examples of Engineering Reports, both in Canada and elsewhere which discuss climate change impacts on roads and bridges and specifically how they can be addressed in engineering design/construction/maintenance. However, on the positive side, many agencies are thinking about this issue and are in the process of putting forward plans to carry out studies in the longer term. Most of the people that did respond to the emails in this literature scan stated specifically that they felt there was a need to research the engineering impacts. Many practitioners feel that the

traditional designs do not account for these changes and that appropriate design changes to accommodate different climates should be incorporated into the design manuals and codes.

5.0 SUMMARY OF FINDINGS

5.1 Road and Pavement Infrastructure

The most detailed efforts found in the area of roads were studies carried out by Mills et al [Mills 2007] as part of the Government of Canada Climate Change Impacts and Adaptation Program managed by Natural Resources Canada and Hayley et al [Hayley 2007] which was presented at the PIARC meetings in Paris 2007. This first study focused primarily on Southern Canada while the latter study focuses on Northern Canada with specific emphasis on Permafrost, Ice and Seasonally Frozen areas.

This Mills et al [Mills 2007] study involved using two sets of case studies to examine and investigate the generalized impacts of climate change. Two climate change scenarios were adopted for analysis in the current study: one based on the A2x emission experiment from the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model 2 (CGCM2A2x), the other from the B21 experiment run through the Hadley Climate Model 3 (HadCM3B21). The specifications of the CGCM2 and HadCM3 climate models, and performance in relation to other internationally recognized models, are also well-documented elsewhere [Flato et al., 2000; Flato and Boer, 2001; Gordon et al., 2000; CMIP, 2001].

Raw scenario surface temperature (minimum, maximum, mean) and precipitation (total) data for each model and experiment were obtained through the Canadian Climate Scenarios Network [CCSN, 2005]. Monthly data were available for baseline (1961-1990) and three future 30-year temporal windows centred on the 2020s, 2050s, and 2080s. Given that the average design life of pavement infrastructure is about 20-30 years, only the 2050s scenarios were examined in the current study.

The data consisted of output for climate model grid cells, each of which spans 2.5 (HadCM3) to 3.75 (CGCM2) degrees latitude and 3.75 (both models) degrees longitude (i.e., over 100,000 km2). Each site was

assigned to the model grid cell in which it was located, except when the cell was designated as 'water' in the model specifications; in these cases, the nearest 'land' cell was used. Scatter plots of potential changes in annual and seasonal mean temperature and precipitation were prepared to indicate the position or severity of the CGCM2A2x and HadCM3B21 experiment results relative to other Atmosphere and Ocean General Circulation Models (AOGCM) scenarios for each site. Examples of annual scatter plots for the most northern (Edmonton) and southern (Windsor) study sites [Mills 2007].

In general, the CGCM2A2x and HadCM3B21 scenarios are average and conservative, respectively, when compared to other AOGCMs and experiments. Results for both are contingent on the realization of mid-century changes in climate derived from the CGCM2A2x and HadCM3B21 global climate modeling experiments. These scenarios are moderate compared to those from other models [Mills 2007].

The analysis involved applying the newly developed Mechanistic-Empirical Pavement Design Guide (MEPDG) to assess the impact of pavement structure, material characteristics, traffic loads, and changes in climate on incremental and terminal pavement deterioration and performance [ARA 2004]. Evidence from the six Canadian sites that were examined in that study was not as universal as that revealed through the first set of case studies but nonetheless suggested that rutting (asphalt, base and subbase layers) and cracking (longitudinal and alligator) issues will be exacerbated by climate change with transverse cracking becoming less of a problem on Southern Canadian roads due to warmer temperatures.

In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life as there would be more distresses and they would be appearing earlier in the pavement life. The effect of climate change was found to be modest, both in absolute terms and relative to variability in pavement structure and baseline traffic loads [Mills 2007, Tighe 2008]. Note, this study was only evaluating Southern Canadian roads and it would be expected that changes would be more dramatic for Northern Ontario roads depending on their climatic conditions.

Pavement engineers, with assistance from government and academic climate change experts, should be encouraged to develop a protocol or guide for considering potential climate change in the development and evaluation of future designs and maintenance programs. Incorporating other climate-related road infrastructure issues, for instance those

associated with concrete pavements, surface-treated roads, airfields, bridges and culverts, would also be beneficial [Mills 2007].

At a minimum, long time series of historic climatic and road weather observations—ideally greater than 30 years in the case of climate—should be incorporated into analyses of pavement deterioration and applicability of Seasonal Load Restrictions (SLRs) and Winter Weight Premiums (WWPs) or assignment of performance graded materials. Pavement design procedures that result in a higher resistance to deformation, longer service lives, and satisfactory surface characteristics are needed to satisfy the increased demand in road usage. The expected performance and service life of pavements are decreased by distresses such as rutting, fatigue, and low temperature cracking, distresses caused by increased axle loads, traffic volume, environmental conditions, and construction and design errors [Mills 2007].

There are many different consequences to climate change, and each has an impact on the pavement and road infrastructure. Severe weather events, including flooding and freezing rain, are predicted to increase with climate change. Both these occurrences would cause safety hazards for the transportation sector, and flooding could potentially cause the loss of some infrastructure. The delays caused by these occurrences would also have social and economic impacts on the transportation sector AIT 2007, Mills 2007].

If temperatures close to water's freezing point become more common in Canada, the resulting increase in frequency of the freeze-thaw cycle will likely cause pavement deterioration. In addition, with increased heat and drought, this will cause permanent deformation in the form of rutting. The drought conditions could also lead to an increase in forest fires. This would affect both roads and bridges by resulting in closures of certain routes and the loss of some infrastructure [AIT 2007].

Warmer winters may also be associated with a decrease in the amount of snow clearing required, as well as a change in the mix of sand and salt used on the roads. Warmer winters could also mean a decrease in the length of time where seasonal roads are available, and also a change in permafrost location. This would have a negative impact on communities and industries using these temporary roads. However, there could eventually be all-season roads in some areas. The subsidence of the ground due to melting permafrost could also affect pipelines and adjacent roadways. An increase in temperatures could

also mean a change in the timing and duration of seasonal weight limits for the trucking industry [AIT 2007].

Climate change will also potentially cause an increase in precipitation, which would contribute to flooding. For example a storm on August 19, 2005 washed out a portion of Finch Avenue in Toronto. It seems apparent that this type of event is expected to become more frequent in the next 50 years [CAP 2006].

An increase in precipitation would also cause an increase in soil moisture, resulting in slope instability and possibly an increase in landslides. Other indirect impacts would affect other sectors as well, such as agriculture and oil and gas, which in the long term will also affect the demand, timing and location for freight transportation [AIT 2007].

In terms of northern Canada, Hayley and McGregor [Hayley 2007] identified several challenges which are currently being faces in Northern Canada. In areas where roads are over permafrost terrain, the thin surface “active” layer thaws each summer. The frozen ground has variable proportions of ground ice and when the ice thaws it results in excess water under the roadbed and can result in settlement. Consequently, highly variable settlements can result in tremendous construction and maintenance costs. In addition, the long term performance of the road embankment can also be a problem. In essence, the subgrade warming combined with the ice-rich soils can result in failures and will need to be identified and properly accounted for in future designs [Hayley 2007]. Thus similar to the mitigation strategies for improved SLR and WWP, rate of thaw and utilization of engineering techniques for reducing thaw-settlement will need to be incorporated.

Another aspect to consider in Northern Canada is the reduced season for winter roads which are constructed with compacted snow and ice. In many cases, these are primary supply routes for northern communities but also are an essential part of the new diamond mining industry in Artic Canada [Hayley 2007]. In short, the aforementioned has identified several needs with respect to short, medium and long term engineering design adaptation. Specific design adaptations will need to be directed at both the project level pavement/geotechnical designs or site specific designs, but also they will need to examine networks and regions to ensure that design protocols are suitable for long term performance.

5.2 Bridge and Associated Infrastructure

Many of the situations described above in the previous section have relevance to bridges and will not be repeated in this section. Low-lying roadways and the associated structures are at risk of flooding from intense rainfall events. The intense rainfall provides a big concern as it results in culverts and bridges that might be vulnerable. For example, in the City of Toronto, there are 34 culverts and 70 bridges that may be vulnerable under intense rainfall conditions [CAP 2006]. Similar statistics would be expected for various other cities, municipalities and provincial and territorial transportation agencies.

An increase in precipitation would also cause an increase in soil moisture, resulting in slope instability and possibly an increase in landslides which could put some bridges and culverts out of service. Other indirect impacts would affect other sectors as well, such as agriculture and oil and gas, which in the long term will also affect the demand, timing and location for freight transportation [AIT 2007].

There is some uncertainty and variation in the climate change model results about future rain and snowfall levels on the prairies. A number of models show that rain and snow will not be sufficient to compensate for the warmer temperatures. The associated increase in evaporation rates in Saskatchewan being drier on average both in the south and north. Drier conditions will likely increase the frequency of droughts. This could potentially impact bridge and culvert life cycle performance. An additional concern is that summer rainfall may tend to occur as intense storms or 'cloud bursts' with increased risk of flooding and storm damage [SHI 2007].

The Ontario Ministry of Transportation (MTO) has examined the impact of climate change on structures. The purpose of the study [Coulibaly 2006] was to investigate the potential impact of climate change on highway drainage infrastructure including bridges, culverts, storm sewers and stormwater management facilities. The research used models that predict the climate change in terms of precipitation and water flow and the associated impact on different catchments areas [MTO 2006].

The MTO study relates the predicted Global Change Models (GCM's) temperature and precipitation predictions to local precipitation data. To determine estimates of local and regional values of future daily precipitation and variability, this study used data from eight rainfall

stations to represent typical southern and northern Ontario regions. Four stations were in the Grand River watershed and the other four rainfall stations were located in the Kenora/Rainy River watershed [MTO 2006].

To show how much, how long and how often precipitation occurs in the two test regions, rainfall intensity-duration-frequency (IDF) curves were derived using the GCMs and daily precipitation data from the rainfall stations. To detect rainfall trends, IDF curves were developed for four time periods, the present, 2020, 2050 and 2100 [MTO 2006].

The IDF curves showed changes in precipitation intensity, suggesting that by 2050 and 2100 a 24% and 35% increase in heavy, and more frequent, rainfall events can be expected. All correlations showed these increasing trends, except for the 2020s when there was a decrease [MTO 2006]. In short, the findings indicated that existing highway drainage infrastructure may be significantly affected by climate change. The study predicts that, by 2050, highway drainage systems designed to accommodate storms that occur once in 10 years may only be able to accommodate storms that occur once in 5-years. Larger highway drainage systems designed for a once in 50-year storm period might only be able to accommodate a once in 20-year storm period.

Another important impact of climate change in Northern Canada has been the need to replace ice bridges over fast flowing streams and rives with bridges, where in the past, ice bridges were sufficient and this is particularly notable in Manitoba [Hayley 2007].

From an engineering design perspective, it suggests that design flow rates (the estimated runoff flow rates) may need to be increased leading to larger bridges, culverts, storm sewers and stormwater management ponds to maintain the level of service provided today and to avoid potential constricted water flow and possible future flooding events [MTO 2006].

While this research provides some insight into the potential impact of climate change on highway drainage infrastructure based on a limited number of sites and a short period of rainfall record, more research is required to fully understand future climate effects on rainfall and flow rates before considering modifications to highway drainage design standards [MTO 2006].

Overall, from this search there are many questions that need to be addressed including: how will climate change impact the transportation sector, can these changes be handled by current design drainage systems and standards, and ultimately what needs to be done today to ensure future performance of structures in light of climate [MTO 2006].

6.0 CLOSING COMMENTS

Adaptation to the impacts of climate change will require long-term planning and several changes to the transportation sector. Current discussion, policy and programmes related to climate change generally focus on mitigation; however it will be important to integrate adaptation and mitigation efforts into design, construction and maintenance. Planning for new infrastructure will require modification in engineering design to ensure the new roads and bridges can withstand the change in length and frequency of weather events, as well as hydrological changes [AIT 2007].

The safety margin for building codes will have to be adjusted to allow for greater variability in weather and account for a wider range of extremes. Careful monitoring of weather information systems will also be important. There is also a need to monitor, and possibly map, areas vulnerable to receding permafrost, flooding or landslides. The transportation sector will also need to be prepared for any changes to maintenance costs [AIT 2007, MTO 2006].

Further research is required to determine what specific impacts climate change will have on a regional scale. Local research is also needed to determine the capacity of specific systems (for example, drainage systems) to deal with these impacts. Research could also determine the options available to transportation policy makers in dealing with the impacts of climate change. This would most likely be best achieved through effective use of Pavement Management Systems, Bridge Management Systems and Drainage Infrastructure Management Systems. Data from these systems can be provide the technical information so that vulnerabilities can be properly identified, diagnosed and rectified so that infrastructure damage can be ideally avoided or at least risk managed.

Several agencies including the North West Territories, Department of Transportation (NWTDOT) have commissioned Dillon Consulting to conduct a thorough analysis of impacts of climate change and some strategies on how to deal with the changes (report expected January

2008). In addition, NWTDOT are working with Engineers Canada on the vulnerability study and have offered a “test area” which includes a section of highway which is undergoing significant permafrost issues [McLeod 2008].

Many Canadian Transportation agencies including Transport Quebec, North West Territories, Department of Transportation and others, are participating in a Pooled Fund Transportation Association of Canada (TAC) Permafrost Project which is expected to start early in 2008 [TAC 2007]. It is expected that this effort will provide best practices for the construction and maintenance of Transportation Infrastructure in permafrost areas.

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Appendix C.4

Buildings Literature Review

March 2008

Public Buildings – Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change

Prepared for the Canadian Council of Professional Engineers
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1 Introduction

Climate change is expected to have wide-ranging impacts on many different physical infrastructures in Canada, including the public buildings which enable the provision of essential services such as health care, education, government, cultural activities and leisure. How climate change will impact on the ability of these buildings to deliver the services for which they were designed is an important topic to consider since any disruption, limitation, or alternatively, an increase in the costs of providing these services could have wider-scale societal and economic ramifications.

Engineering decisions made concerning construction and design, choice pf materials, building location, or other engineering parameters will have implications for the longer-term sustainability of the building infrastructure that is in the public domain. This is especially the case when viewed in respect of the potential impacts of future climate change since the operational lifetimes of these assets often exceed 50 years, during which time they will likely experience significant changes in climatic conditions that could impact building and material durability, resilience, and strength.

This report provides the result of a literature review on the potential impacts of climate change on public building infrastructure, with this review undertaken from the engineering perspective and focused upon literature in the 'grey literature' domain – namely, literature published by municipalities, provinces, and other government entities, engineers, consulting companies, or other stakeholders that might be having to deal with the present and future consequences of climate change. A further focus is on literature that has been published since 2006 since this study is meant to update earlier literature reviewed for the Canadian Council of Professional Engineers.

This first body of literature reviewed considers how changes in climate conditions might impact on building infrastructure and the vulnerabilities posed by climate change. This leads to a review of literature considering the design implications of expected changes in climate conditions when considering building design and construction, building use, and the maintenance and operation of the building.

1.1 Organization of report

The remainder of this report is organized as follows. The next section presents a general review of literature on climate change vulnerability, specifically in terms of the risk that climate change will adversely affect the ability of public buildings to provide the services which they were built for. Section 3 overviews the impacts of changes in climate conditions on public building infrastructure. This includes specific discussion of climate change impacts in terms of heating and cooling systems, building materials, building envelope, and building stability. The final section of the report considers the design implications related to adapting to and mitigating the potential impacts of climate change, with the conclusions then providing of policy options that should be considered in respect of the literature and material reviewed.

2 Vulnerabilities of building infrastructure to climate change

It is important to consider the impacts of climate change on public buildings in the context of their vulnerability to these environmental processes and the resilience that could be achieved through developing and implementing adaptive measures. In the specific context of climate change, vulnerability is defined by the Intergovernmental Panel on Climate Change (IPCC) [1] 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."

A few important terms stand out. First, vulnerability is about the inability to cope with the adverse effects of climate change. It is a function of the physical attributes of the climate impact, the properties of what is impacted in terms of its sensitivity to change, and the adaptive capacity to cope with the climate change impacts. Thus, some aspects of vulnerability are physical in nature, while others are defined by the ability, whether it is technological, process-based, or engineering related, to deal with climate impacts.

The vulnerability-centred approach for assessing impacts from climate change starts with an assessment of the vulnerability of a physical structure, what stressors are involved, how the physical asset is sensitive to this change, and what capacity exists to adapt to changing risks.

2.1 Assessment of vulnerability

The vulnerability posed by climate change for building infrastructure relate to the possible disruption or failure of services which these assets are ultimately meant to provide [2]. What underlies this vulnerability is that almost all of today's building infrastructure has or is currently being designed with the assumption that future climatic conditions (including averages and extremes) will reflect the historical climate [2]. This is in effect engrained within the decision-making framework of engineers through the use of codes, standards, or related instruments that rely upon climate design values to appropriate risk and help guide decision-making in respect of such parameters as bearing strength related to snow, wind or other weather parameters, or the choice and quality of constructions material. Climate change is expected to affect both averages and the return periods of extreme events, such as an expected increase in the frequency of heavy precipitation events (including heavy snowfall) [3]. Therefore, if climate design values are not updated on a frequency that reflects changes in climate conditions, building infrastructure may be at greater risk of failure or disruption.

In many situations the impacts of climate change are being compounded by physical weathering that has been accelerated due to the changing physical and chemical properties of the atmosphere and the local environments where these structures exist.

Other physical characteristics that increase vulnerability relate to geography, as many physical structures and public buildings in Canada are located in inherently risky locations, including close to seashores (e.g. regions of Vancouver such as Richmond, Delta, and New Westminster are threatened by rising sea levels [4, 5]), on river deltas, and flood plains (e.g. climate change is expected to increase the risk of flooding along the Red River in Winnipeg [6]).

Vulnerability is also a function of societal parameters and institutional frameworks that guide behavior and decision-making [2, 7]. The construction industry (and the codes and standards they rely upon) for example, have historically been slow to change, while land use planning and decisions regarding building materials and practices have often been dominated by short-term commercial interests rather than longer-term assessments where return on investment may not be clear. These processes contribute to heightened vulnerability since with climate change events may be unfolding on a much shorter time scale.

Scientific evidence indicates that the signature of anthropogenic forcing due to increasing atmospheric GHG concentrations is most evident in global temperature and weather patterns during the last 10 to 15 years [3]. In terms of Canada, there have been an increasing number of severe and notable precipitation and wind events throughout many regions. Bruce highlights a number of major precipitation events that occurred throughout south-central and eastern Ontario [8]. Data from these storms indicates that much higher amounts of precipitation associated with intense rainfall events have occurred in recent past, with these events significantly exceeding what occurred within the climate normal. Each event had profound impacts on built infrastructure, particularly extensive damage to roadways, and sewer backup into buildings. The occurrence and severity of these events, and the exceedance of climate normals, indicates the problematic nature of using historical data to help assuage risk if this data is not updated regularly to reflect changing climate conditions, and in particular, setting engineering standards that depend on weather parameters.

Auld and MacIver [9] contend that “climatic design values for codes and standards need to reflect the changing climate conditions and be assessed against regional trends to determine whether existing “margins of safety” have any remaining tolerance to accommodate increases in loadings. Locations and regions where climate trends are encroaching on tolerance limits require, on a priority basis, increases in climatic design values for new structures and potential structural reinforcement [or other adaptation actions] for existing “at risk” structures.”

As explained in section 2, the Arctic region has been experiencing accelerated climate change that is beyond what was projected by climate models. Environment Canada is currently working to advance methods to better allow related stakeholders to assess emerging risks associated with climate change.

In specific context to changes undergoing in Canada’s North, Auld reports on a number of new initiatives that may help to better inform the engineering community of changing

risks associated with climate change [10]. In particular, she explains that a potentially suitable option for understanding risk is to use trend analysis to help assuage changing risks associated with increasing temperatures, with trends considering data over a 20 or 30 year period with trend lines extrapolated to help indicated expected climate parameters into the future. Such trend analysis may be suitable considering both the recently observed acceleration in climate warming in the North, and because this has exceeded projections made by climate models. This has raised concerns about what other factors may be in operation which in turn are not captured by climate models.

Such analytical techniques may be especially relevant for Canada's North because of the sensitivities of many aspects of engineering to temperature, including both ground and air temperatures, and the urgency to have recent conditions accounted for in climate design values. It is also relevant because warming has exceeded projections in climate change models, thereby having some questioning the validity of using climate models for such work. Nonetheless, Environment Canada has indicated that they are working to improve climate models so that they are more useable in providing such information in the future.

2.1.1 Characteristics of climate variation

Future changes in climate conditions are expected to unfold differently across Canada's vast territory, with regional differences shaped in part by proximity to oceans, topographical features, and the patterns of general atmospheric processes. The Fourth Assessment Report on the Physical Science Basis of Climate Change released by the Intergovernmental Panel on Climate Change (IPCC) in 2007 describes how climate change is expected to evolve differently globally and regionally [11]. This source, along with recent analysis completed at Natural Resources Canada and Environment Canada [2, 11-14], allows the following summary to be made of expected climate change across each of Canada's regions:

- Nearly all of Canada is expected to experience an increase in temperature, although Northern Canada is expected to experience accelerated warming. On an annual-mean basis, when comparing the average temperature expected in 2090-2100 and the average between 1980 and 1999, projected surface air temperature warming is expected to vary from 2°C to 3°C along the western, southern and eastern continental edges, and between 5°C and 6°C in the northern region of Canada.
- Diurnally, night time temperatures are rising the quickest. Seasonally, winter time temperatures are rising faster than the summer.
- There is expected to be a slight poleward shift in storm tracks, shifting more moisture into Northern regions of Canada. Natural Resource Canada, in their recent study on adaptation to climate change impacts in Canada, note a marked decadal increase in heavy snow events in northern Canada [14]. Observed trends of increased precipitation have already been observed over many of Northern Canada, with increased snowfalls seen especially for the most northern locales [12]
- The coastal regions of Canada are expected to contend with rising sea levels.

- The frequency and longevity of heat waves is expected to increase. This is especially the case for the continental climate zones in Canada which stretch from western Alberta to Quebec. This is because these regions are less influenced by large water bodies.
- Continental North America is expected to experience more convective activity. This, in conjunction with increased atmospheric moisture, will increase the frequency and intensity of heavy precipitation events and thunderstorms.
- There is expected to be increased cyclonic activity along both the west and east coasts, with a more vigorous jet stream leading to increased precipitation in the north-western portions of the Northwest Territories.
- Although the snow pack is expected to decrease across most regions, winter snowfalls will likely increase due to more atmospheric moisture. This is especially the case for the leeward sides of the Great Lakes (due to enhanced lake effect snows), western and eastern coastlines, and in Canada's North. Generally, precipitation levels are expected to decrease in continental climates away from the Great Lakes.
- Permafrost conditions in Canada's North are expected to be severely impacted by climate change. This is particularly the case for the southern portions of the semi-discontinuous and discontinuous permafrost zones where permafrost might outright disappear. Accelerated warming in the far north may also result in permafrost conditions reverting to semi discontinuous in these areas.

As is evident, the majority and most severe climate change impacts are expected to occur along the coast lines (primarily related to increased wind, more intense and frequent precipitation, and rising ocean waters) and in Canada's North (primarily related to changing temperature regimes, increasing precipitation levels, and changes in permafrost conditions).

Recent observations of climate change in Canada's Arctic indicate that the climate in the north may be warming even faster than most general circulation and regional climate models predicted. There is a range of anecdotal evidence to support this, most telling being an alarming rate in the disappearance of summer time ice in the Arctic's water bodies [13]. In 2007, for example, there was observed record minimum ice cover over the Arctic Ocean and the subsequent "opening" of the Northwest Passage. This latter event was far earlier than projected by climate models which projected that the Northern Passage would not be free of ice for a number of decades into the future.

2.1.2 Sensitivities

What are the sensitivities of public buildings to climate change? These largely relate to the possibility that with changing climate conditions buildings will not be able to, or be limited, in the provision of the essential services they were initially built for. In particular, these sensitivities concern whether a building will be adequately able to protect occupants, equipment, materials, etc, from outside elements, to provide comfortable and safe levels of temperature, as well as ensuring an environment which is healthy and safe.

How to account for climate change in this regard is important seeing that buildings are constructed with life spans of 50 years or more. Thus, the initial engineering must ensure structural integrity over this time while also being able to provide the essential services listed previously. However, it must also do this in an economical way when considering capital, operational and maintenance costs, and thus adaptive measures, if put in place, must be done so in a way that does not increase costs beyond what is bearable by the consumer and society in general.

2.2 Systematic vulnerability

The vulnerability of public infrastructure to climate change must take into account the system-level variables that interact to impact on public infrastructure since these factors have wide-ranging consequences for building infrastructure, even if they are not as evident as the direct impacts resulting from climate change. Two factors of particular importance are considered in the following sections: vulnerabilities arising out of improper funding for the building and maintenance of infrastructure, and vulnerabilities arising from the use of out-of-date climate design values in the application of codes and standards.

2.2.1 A steady decline in spending on public infrastructure

Spending on public infrastructure, including that on buildings, has seen a significant decrease over the course of the last number of decades when measured against the size of Canada's economy. Auld, Klaasen and Comer [15] explain that public spending on a broad range of infrastructure projects equaled almost 4.5% of Canada's GDP in the mid 1960's, but this had declined to less than 2% in the 1990's. Furthermore, governments have been spending the majority of money on the building of new capital stock and not on the maintenance of present-day assets [16]. This decrease in public spending on public infrastructure has had a number of impacts. First, infrastructure, including buildings, have not been maintained, decommissioned, or replaced over a time where there has been significant increases in population (over 17% between 1990 and 2005), urbanization (at 82% urbanized, Canada' is one of the most urbanized countries in the world), and infrastructure use.

In many parts of North America, there is growing concern about premature deterioration of materials such as clay brick, reinforced concrete, wood support in wood frame buildings, etc. resulting from changing environmental conditions, including changes in the climate. Poor workmanship, poor design, and inappropriate designs and materials would only exacerbate these processes, enforcing the need for codes, standards and best practices that might better reflect changing climate conditions.

2.2.2 Inaccurate climate design values

In Canada and in most developed countries, a suite of codes, standards, and guidelines helps to set the minimum level to which building infrastructure must be built. These codes and standards are usually referred to in contract specifications as well as in municipal, provincial or even federal regulations. Climate change poses a significant challenge to the building codes in place since these depend on a set of climatic design values that have been calculated from historical data, with the assumption that average

and extreme values derived from this data will be consistent through time. One of the major issues is that many of the climate data used has not been updated in 10 years or more, with some of the most out-of-date have not been updated since the early 1960's. However, even if these values were updated on a regular basis, assuming that future risk reflects past occurrence may not be appropriate when considering that the climate is changing, especially when considering the more significant warming and more severe climate events that have occurred in the last 10 years.

Climate design values are reliant upon metrics of the return frequency of an extreme over a 10, 20, 50, or even 100 year period. This could include weather parameters such as wind speed, precipitation, temperature extreme, snow load, or snowpack. Structural failures can therefore occur when climate extremes approach or exceed their design values. For certain public buildings which are used for critical post-disaster management, such as schools and hospitals, basic engineering loads (which are partially determined using climate design values) are normally adjusted to ensure a proper safety margin [8]. This adjustment will also account for uncertainties in the strength of materials and also uncertainties in building technologies.

Auld and MacIver suggest that until uncertainties associated with the directions and magnitude of climate change are known (and therefore incorporated into climate design values), the safety factors used in codes and standards may need to be increased so to reflect the growing uncertainties associated with changes in climate conditions over the life time of an asset or infrastructure category. The authors further note that while the construction industry may be hesitant to include significant improvements (or adjust safety margins higher, as reflected in the codes or standards), and as result likely increase the cost of construction, there are methods and approaches available which will build upon the already practiced statistical analyses of risk that underlie many engineering practices and the regulation thereof. These methodologies include, for example, downscaling from larger scale climate models or the use of trend analysis to help extrapolate future climate conditions [2, 10, 17].

There is evidence now that many engineering structures in Canada's North are approaching their design limits for snowloads and in terms of the integrity of building foundations due to permafrost degradation [17]. This region, as explained previously, has seen accelerated warming in recent decades. In particular, design limits related to permafrost and snow loading has in many cases been exceeded or is coming very close to their threshold. The primary reason for this is that the current set of codes, standards, and guidelines used in Canada's North are outdated as the climate design values that they rely upon have been derived from outdated climate data that this does not reflect the new and changing climate conditions in the North. Another reason is that, in many cases, the effects of climate change are not accounted for in the standards or guidelines in place. For example, in regards to expectations of permafrost degradation, the only reference in the national model building code is that practitioners must use professional judgment to account for this in engineering decision-making [18].

2.2.3 Changing use of materials

The choice of construction materials can contributing to additional vulnerability to climate change since these are inherently more susceptible to the presence of moisture over extended periods of time. Examples include the use of thin sheets of gypsum or plywood as substrates behind thin veneers of cement plaster, stone, or masonry as these often do not perform well in presence of heightened levels of moisture, such as can be expected with climate change in many of Canada's regions. Increases in weather extremes, such as increased wind loading or snowloads, would increase the potential for more permeation of water and moisture into building walls. Other examples include prefabricated houses that are built with less durable material.

2.3 Vulnerability and adaptive capacity

As defined by Smit and Philisova [19], adaptive capacity refers to the ability or potential of any stakeholder to "address, plan for, or adapt" in terms of climate change impacts. For the engineering community, adaptation should be considered in the context of what choices in design, construction methods or materials or other engineering practices can be followed that would help buildings better perform in respect of a changing climate. Different approaches for building adaptive capacity for the public building stock in Canada are presented in section 4.

3 Climate change impacts on buildings

Climate conditions in general have significant impacts on buildings and decisions concerning building design, construction, operation, maintenance, and the ultimate use of the building structure. Climatic conditions play a significant role, for example, in determining the characteristics of the building envelope in terms of insulation properties, building strength in terms of wall and roof support, the quality and characteristics of materials used (particularly in terms of resilience, durability and strength), the size and characteristics of the heating, cooling and ventilation systems, as well as issues related to building stability.

Recent climate events and climate change have had an impact on each of these different areas. The winter of 2008, for example, saw record snowfalls across Ontario, Quebec, and the Atlantic Provinces, leading to numerous incidences of the structural collapse of public and private building structures. There have also been incidences of severe wind damage resulting from extreme wind events on both of Canada's coasts [20], and building subsidence due to the melting of permafrost in Canada's North [21, 22].

The rest of this section considers the above impacts from an engineering perspective by focusing attention on different components of a building when considering a structures entire life span, including heating, cooling and ventilation systems (HVAC), the strength of walls and roofs, building materials, and building stability.

3.1 Heating, cooling and ventilation systems

Changes in temperature resulting from climate change will fall within the minimal design life of many of the building infrastructures being built today, with these changes likely to

impact, in some cases significantly, the requirements for heating and cooling services provided to buildings in the future. This will mean changes in both the insulation requirements of buildings as well as the size of the heating and cooling systems required. In particular, insulation requirements are likely to decrease with cooling loads are likely to increase. Even if most equipment is replaced sufficiently quickly to allow accommodation for climate change with regards to HVAC systems, while heating will be reduced this will likely be offset by increased cooling demand. This implies a change in fuel source which could significantly affect the operational costs of buildings since, outside of Quebec, most of home heating is via fossil fuel-based furnaces while air cooling equipment is powered by electricity. Any changes in cooling loads would have notable impacts in Canada's North where the price of electricity is 4 to 5 times as high as in southern Canada [23].

Dumont [24], in assessing the impact of changing climate conditions on the heating and cooling requirements of homes and buildings, concludes that presently climate change is not accounted for when making decisions concerning insulation levels in the building stock. Dumont further emphasizes that often with large public buildings that are more complex and involve multiple companies involved with engineering, architectural design, landscape design, etc., there are incidences where the different components of a building are not put in place in an integrative way. Namely, with many large public buildings whose construction often involves a complexity of engineers, architects, etc., often different components of the building are effectively developed and planned in isolation. For example, decisions might be made to change the insulation characteristics of the structure, but this is not reflected by the size and configuration of the heating or cooling systems implemented. This lack of integration in the building design decreases the resilience of adaptive measures since these often operate in an integrative manner.

It is important to consider related research that has considered some of the engineering implications of climate change for similar climatological zones as to Canada. Frank [25] studied the potential impacts of climate change on heating and cooling energy demand for buildings in the Swiss Central Plateau. For the time horizon 2050-2100 a climatic warm reference year scenario was used that investigated the implications of a 4.4 degrees C rise in mean annual air temperature relative to the 1961-1990 climatological normals (similar to the climate change predictions made by the IPCC for Canada). The results of the analysis showed that the annual cooling energy demand for office buildings could increase by 223-1050% by the 2050 to 2100 period, while the heating energy demand could fall by 36-58% resulting in a shortening of the heating season by up to 53 days.

3.2 Strength of roofs and walls

Climate change is expected to impact on the frequency and intensity of precipitation and wind events in many of Canada's regions. These impacts will have implications for structural design and for choice of building materials when considering both building safety and durability of the building envelope and facades. There are a number of specific climate parameters that should be considered in the context of the potential impact on the structural strength of public buildings: changes in winter time precipitation and the

subsequent affect on winter snow loads, and the impact of changes in sustained and peak wind speeds associated with both cyclonic and convective events.

Future climate change is expected to impact precipitation regimes in Canada's North, particularly over western sections where there is expected to be an increased flow of moisture from the Pacific. This is currently a major concern of territorial and municipal planners in many Northern communities, and has been the focus of recent analysis and study by geotechnical specialists in the Northwest Territories [26]. Changing snow loads are also a concern for regions of British Columbia, northeastern Quebec and for regions to the leeward side of the Great Lakes.

There are a range of viewpoints on how climate change could impact on wind speeds associated with storm events affecting Canada's different geographical regions, but generally the confidence of what effects these might have is much less than that for temperature or precipitation. This is largely because wind is one of the most challenging outputs to simulate in climate models, with large variations observed when comparing various GCM modeling runs. In Canada's western regions, however, it is expected that there will be an increase in the intensity and frequency of wind storms, with related damages to buildings rising accordingly. There is also an increased probability of hurricanes or strong extra-tropical cyclones reaching as far north as the Atlantic provinces as the areal extent of sea surface temperatures (SSTs) conducive for tropical cyclogenesis moves north (SSTs have to exceed 26.7 degrees Celsius over a sufficient areal extent of ocean water for these storms to form) [27].

Perhaps due to this uncertainty, the expected impact of climate change on buildings in terms of wind speed (both peak gust and sustained winds) has not received much attention in the literature.

3.3 Building materials

Changes in atmospheric conditions associated future climate change will impact on the durability of materials, affecting both the building's structural strength and stability. This relates not so much to changes in extremes (such as heavy precipitation or wind events), but more so to changes in day-to-day weathering processes that contribute to premature deterioration of structures and materials. These climate change impacts include those resulting from wind-driven rain, freeze-thaw cycles, frost penetration, wetting and drying, wind-driven abrasive materials, the action of broad spectrum solar radiation and ultraviolet (UV) radiation, changes in atmospheric chemistry (specifically heightened levels of CO2) and atmospheric deposition of materials [15].

Most of these processes will increase the mechanical, chemical, or biologic weathering of materials, or the breakdown of material properties. Table 1 summarizes many of these physical weathering processes along with their expected impacts on physical infrastructure [15].

Table 1. Potential impacts of a changing climate on the weathering of infrastructure materials [15].

Examples of weathering processes likely impacted by the changing climate	Potential infrastructure impacts
• Increased freeze-thaw cycles (followed by decreases in warmest winter regions)	• Premature deterioration of concrete, pavement • Roof ice damming • Moisture damages
• Higher temperatures, increased chemical reactions • More freeze-thaw cycles in cold winter climates	• Increased corrosion; above some thresholds, decreases in corrosion rates • Accelerated deterioration of building facades • Premature weathering • Fractures and spalling
• More intense precipitation events • Changes in timing of seasonal precipitation, rainfall, length of season for wetting of surfaces	• Increased decay processes (e.g. wood) • Increased rain penetration (e.g. wind driven rain) and moisture absorption • Decreased durability of materials • Efflorescence and surface leaching concerns • Damaged or flooded structures

Specifying the appropriate materials for building construction and a given environment requires knowledge the operating environment and the various physical and chemical characteristics of the materials, as well as the transformations caused by the specific environment and the operation and maintenance of the particular facility being constructed [28]. Climate change will play an important role in this regards since it could change weather parameters such as changes in moisture (wetting and drying), freezing and thawing cycle, corrosion of reinforcing steel, and other physical, mechanical, and biological processes. Concrete is one of the most universally used materials in construction, Mirza [28] notes that there is considerable evidence that concrete structures can deteriorate prematurely if subject to aggressive environments as noted earlier. In addition, accelerated levels of carbon dioxide in the atmosphere can result in adverse chemical reactions that can enhanced surface deterioration [15].

3.3.1 Freeze-thaw cycles

Freeze-thaw cycles are an important environmental process that can have major impacts on the durability of a material since it is a very effective form of mechanical weathering. The physical processes involved with freeze-thaw are straight forward – as water freezes, it expands, while when it melts, it contracts. Thus, freeze-thaw action will work to break apart bonded materials such as concrete since water in pores and cracks will expand and then contract. The number of freeze-thaw cycles across most regions of Canada is expected to rise with future climate change (with the exception of extreme western Canada will it will decrease).

Freeze-thaw cycles are especially relevant to the large masonry surfaces and the facades of public buildings as these experience nearly daily frequency of freeze-thaw action when surfaces are impacted by snow or ice since these often melts in the daytime and freezes at night. This is of concern in many northern climates and especially in Canada as in many

of the most populated regions of the country, winter day-time averages are moving closer to the critical freezing mark. This, in conjunction with more variable climate conditions, means the greater likelihood for day time temperatures to move through the freezing mark where water changes state. Such is the case, for example, for centres such as Ottawa and Montreal. Historically, these centres were greatly influenced by the presence of a strong polar jet stream which kept temperatures well below zero in the winter months of January and February. However, in the last decade, the location of the polar jet stream has often been pushed northward during these months, meaning that temperatures in this populated corridor (and one with many public buildings), have been closer to the freezing mark.

3.3.2 Chemical and biological weathering

Climate change will also impact chemical and biological weathering processes. Auld et al. [13] describe how warmer temperatures result in faster chemical reactions, while wetter conditions can increase corrosion rates. Climate change will also likely change moisture regimes in regards to seasonal and annual rainfall which will affect the amount of time surfaces are wet. This, in turn, could impact on leaching and moisture balances that affect material decay.

An important chemical weathering process is rust and corrosion, particularly (in terms of buildings) the corrosion of reinforcing steel or rebar in concrete structures. The rate of corrosion is a function of available moisture or water that comes in contact with steel material in buildings. Climate change could therefore impact on corrosion rates on a number of levels. First, increased freeze-thaw action and the effect of breaking apart concrete form would expose reinforcing rebar, thereby leading to the potential for faster corrosion of these important supporting materials. Climate change is also likely to increase moisture levels through changing seasonal and regional precipitation patterns. This would be especially problematic for public infrastructures such as parking garages which already have higher corrosion rates due to the prevalence of road salt that finds its way into the structures.

Gu and Beaudoin (as cited in Auld et al. 2007) suggest that in Canada the repair bill for an approximate 600 parking garages identified to be impacted by corrosion due to road salt and subsequent premature rusting amounted to $200 million per year. The repairs for these structures can be especially costly since salt contamination can remain the concrete even after cleaning, patching, applying waterproofing membranes, etc, thereby continuing to corrode the rebar.

3.3.3 Impacts on the building envelope

Another climate impact to consider that can have serious consequences for the durability of building materials is the impact of climate change on the building envelope (i.e. walls and ceiling/attic/roof). Extremes such as wind events, intense rainfall, or hail or snow can lead to cracks or disrupt the surface of a building façade or roofing material which will in turn allow for the penetration and eventual accumulation of moisture inside of building walls. Such moisture accumulation, especially seeing that often walls have poor airflow, will lead to accelerated decay of wood materials through mechanical or biological

weathering, and consequentially, a reduction in the structural integrity of the wall. High moisture content within building walls can also lead to excessive growth of mold, which in turn can lead to biological weathering, mold, mildew, and rot. The ability of the building envelope to ensure that moisture does not enter the wall is therefore crucial in order to maintain the desired service life of a structure.

Auld et al. [15] discuss a number of examples of moisture damage resulting from envelope failure related directly to or impacted by climate events. In Vancouver, estimates were that widespread failures of building envelopes in condos in that city resulted in economic losses that reached approximately 1 billion dollars. Although this was largely due to poor and inappropriate construction practices and designs and was not a direct consequence of climate or climate change, the event underscored the vulnerability of built infrastructure to related processes.

Some of the most damaging weather parameters in terms of the impact on building envelopes are wind driven, heavy precipitation events. Especially with wood framed structures, high winds can first lead to shaking of the building structure. Water can penetrate through building façade, doors, windows, etc. This is exacerbated with low cost construction practices and when builders do not abide by building codes.

3.3.4 Building air and vapour barriers

In cold climates such as in Canada, vapour barriers are an important component of a building wall since moisture will seek to move towards the colder temperatures due to vapour pressure gradients. Ventilation pressure, stack effect, and wind loading will tend to move air through the envelope and in some cases act to increase the moisture content of the building wall. Thus, air and vapour barriers are important in helping to mitigate risks of wall component moisture that can lead to mildew growth, mold, and the eventual decay of wood material. Air and vapour barriers are generally placed toward the warm interior surfaces, protecting the wall contents from increased moisture from the warm interior.

Engineers, designers and builders must understand climate parameters to asses the level of effort to mitigate against potential moistures in walls and attics. The proper use of climate zones is a key parameter to managing and moisture flows inside of the building envelope. These are important because the methods for controlling moisture that flows through the building envelope (whether be through air flow or diffusion) will differ for each climate.

As described by Cornick [29], there are several climate classification schemes and climate index approaches which are available to help guide building moisture management practices. Climate classification schemes can be causation based (or climate classification which is reflective of the large scale climate processes and mechanisms that influence regional and local climatic conditions (e.g. air masses and latitude)), or those more of empirical origin and applied nature in terms of the observed impacts of climate conditions on the built environment. The Köppen classification scheme is an example of a classification scheme that combines both the causality approach with empirical

observations, and is largely based on temperature and human habitability. Climate classification schemes have evolved over the last century according to the needs of society, and there are now many specific to the building sector such as energy building codes and standards. Auld et al. [15] summarized an approach for assessing climate change impact regimes. This detailed in Lstiburek [30].

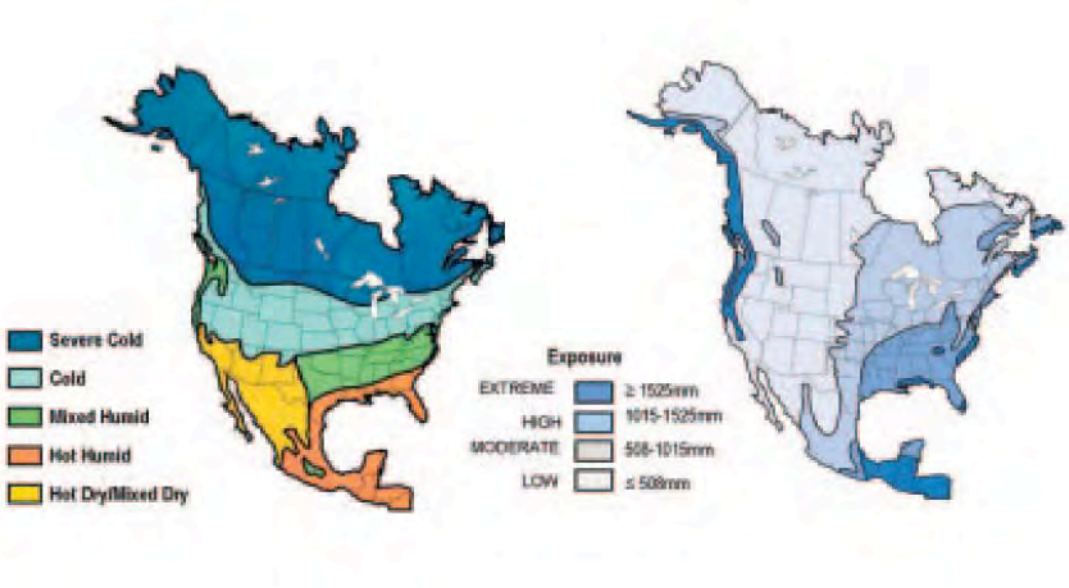
Table 2. Climate load zones characteristics (derived from Auld et al. [15])

Climate Zone	Climate Features	Building deterioration issues	Risk
Severe Cold	4,450 Celsius heating degree days or more	Rotting roofs, drafty rooms, poor radiant comfort, ice dams, mold, wet basements, window condensation, back drafting water heaters, peeling paint, and high heating-fuel bills	High
Cold	2,500 Celsius heating degree days to 4,450 heating degree days	Rotting roofs, drafty rooms, poor radiant comfort, ice dams, mold, wet basements, window condensation, back drafting water heaters, peeling paint, and high heating-fuel bills	Moderate
Mixed - Humid	Less than 2,500 heating degree days per year. More than 508 mm of annual precipitation	Increased moisture content in interior walls, rotting roofs, mold, wet basements	High

Considering the scheme presented in table 2, most of Canada would be classified as severe cold, while only the most southern areas in the Prairies and in Southern Ontario would be classified as Cold. A small region along BC's western coast would be classified as mixed humid.

Meanwhile, another important climatic parameter that affects interior moisture is average annual rainfall and the frequency and intensity of precipitation events. This is particularly important for managing rainwater infiltration. Similar to managing moisture due to the flow of air, there are ranges in managing moisture due to the rate of rainfall.
The figure below illustrates the present day climate zones in Canada in respect of both temperature and precipitation.

Figure 1. Canadian climate zones for both temperature and precipitation (15)



With climate change, it is expected that there will be changes in both the temperature and precipitation zones that will have to be accounted for in engineering choices and the mitigation efforts concerning moisture. In particular, the boundary between 'Cold' and 'Severe Cold' is expected to shift North. In addition, the temperature characteristics in each zone will likely also change in a way which affects the levels of efforts required for mitigation of moisture.

3.3.5 Ice damming

Building roof ice damming is also a major concern with construction in northern environments in general, and with climate change in particular. Ice damming occurs when water melts from the surface of the attic roof where heat loss is great enough to melt the snow. This water will drain off the roof, but may encounter areas where heat loss is less, and thus the water refreezes. This can create an 'ice dam', with water backing up. With all roofs, there is the potential for this water to back up under shingles which in turn can result in a number of impacts on the building envelop, including seepage of water into the attic and walls. This in turn can lead to increasing moisture and increased rates of rot, mildew, and mould. Climate change will likely increase the frequency and intensity of snowfall events, while also increasing the number of freeze-thaw cycles over the course of a year. This could therefore increase the likelihood for ice damming to occur.

Wood [31] suggests that ice damming results in tens of millions of insurance claims per year. During a 1999 ice storm in Southern Ontario, for example, most of the 50 million dollars in insurance claims were related to ice damming and seepage. Snow backing up in complicated roof designs can also be a problem. Since snow has a high insulating value, snow melt can occur from underneath. Electrical de-icing cables can be used to solve this problem. However, the easiest solution to prevent ice damming is to ensure that the attic is properly insulated since heat loss through the roof is the ultimate driver of ice

damming. If water from resulting melting of snow did not form, no water would be available to run into the eaves troughs.

3.3.6 Impacts on building materials due to changes in climate extremes

Most of the above discussion has approached the impacts of climate change on building materials in respect of changes in average conditions, such as changes in moisture content, air temperature, the chemical composition of the air, etc. However, the impact of changes in extremes on building materials must also be considered since the above processes will essentially make buildings more susceptible to changes in extreme conditions.

Based upon the current state of knowledge and suite of climate models, climate scientists have suggested that with climate change, changes in extreme precipitation will change more substantially than changes in the annual mean of precipitation, meaning that a 20-year rainfall or snowfall event could occur every 10 years by the mid point of the 21st century [32]. This would seriously jeopardize the resilience and durability of structures, with repeated extreme event loads leading to deterioration of materials and the possibility of the eventual failure of the structure. Auld and MacIver [13] subsequently conclude that this will effectively shorten the lifespan of existing structures in many regions.

3.4 Damage from sewer backup

Although not a direct impact as a result of climate change, the increased risk of sewer backup resulting from changes in the frequency and intensity of precipitation events is an important consideration for the engineering community.

There have been recent examples of heavy precipitation events leading to significant damages to buildings in Southern Ontario [33]. Two incidences in Toronto and other urban areas (2005) and Peterborough (2004) were of particular significance. During both of these climatological events, total rainfall and hourly rainfall rates exceeded the design limits of the sewer infrastructure, causing backup into homes, businesses, and some public buildings (for example, Rainfall amounts up to 175 mm recorded in Yonge/Steeles area, while 103 mm recorded in 1 hour at Environment Canada Downsview) [34]. This led to insurance claims totaling more than 360 million dollars.

3.5 Building stability

Climate change is expected to impact on building stability through processes related to melting permafrost and processes related to increased summer drying.
In terms of summer drying, resulting ground shrinkage can increase damage to building foundations caused by ground shrinkage. This will especially be a problem in Canada's prairies since it is in these regions where moisture deficits are likely to occur due to increased rates of evapotranspiration. Building foundations will be a greater risk in clay soils with poor permeability. A number of European municipalities, for example, are recognizing this as a climate change risk, and have included it within their climate change action plans [35].

Future climate change is expected to have significant impacts on buildings in Canada's North that depend on permafrost for stability. Frozen soils have a very strong bearing capacity and thus many structures are built upon permafrost. The choice of the foundation system is typically a function of the thermal-stability of the frozen ground as well as the load of the infrastructure. However, although the latter is assumed to be constant, climate change and increasing temperatures are causing a degradation of permafrost, impacting on the stability of building infrastructures that have historically depended upon this [21]. This is expected to be one of the most important impacts of climate change into the future, affecting design considerations and how buildings are stabilized and supported.

Hoeve et al. [36] undertook an investigation of the impacts on climate change in 32 different communities spread through the Northwest Territories in terms of the impact upon building foundations. Geographically, they considered communities in the far north such as Sachs Harbour to the most southern locales of the Territory, such as Fort Smith and Fort Laird. Commercial/institutional as well as residential buildings were assessed across regions underlain by sporadic discontinuous permafrost, extensive discontinuous permafrost, and continuous permafrost. It was concluded that thermal sensitivity is generally greatest in the southern NWT, in the area of discontinuous permafrost, while physical sensitivity (i.e. thaw settlement) is generally greatest in the northern NWT. Overall, building foundations in the Inuvik region were determined to the most sensitive to climate change impacts.

Couture et al. [21] undertook a survey of building infrastructures in Norman Wells where they particularly were interested in the performance of foundation systems over time. They first classified and categorized the construction types and foundation systems, and then evaluated the infrastructures performance history. The authors found that foundations that were not anchored into the bedrock with long steel beams or timber, but rather were reliant on shallower platforms, showed the most impacts in terms of changes resulting from changing permafrost conditions.

4 Design considerations

The above climate change impacts are briefly considered in terms of the implications on building design, construction, maintenance and use.

4.1 Heating and cooling

As stated, climate change will increase the requirements for cooling services, while decreasing the requirements for heating.

In studying some the engineering implications of these issues, Frank [25] concluded that efficient solar protection and night ventilation strategies capable of keeping indoor air temperatures within an acceptable comfort range (thus limiting the need for cooling plants) are set to become a crucial building design issue. Similarly, Holmes and Hacker [37] concluded that buildings in the future will be 'free running', either being entirely naturally ventilated (i.e. passive cooling) or mixed-mode (where mechanical cooling is only used when thought to be essential). As a result, temperatures in free running

buildings are more closely linked to those outside air temperatures, and can take better advantage of passive or low-energy comfort cooling.

Night-time ventilation (where the building structure is cooled overnight by drawing upon cool night time temperatures in order to provide a heat sink that is available during the occupancy period) is especially relevant for a northern climate such as Canada. In studying similar systems for like climate zones in Europe, Artmann et al. [38] concluded that there was a high potential for such cooling practices in most of Northern Europe with climates similar to Canada.

4.2 Strength of roofs and walls

One of the most important climate impacts to consider in regards to design implications affecting building structural strength is that of changing snow loads.

As suggested previously, the first task for mitigating against the risk of changing snow loads in regards to engineering practices is to ensure that the respective codes and standards engineers rely upon adequately reflect changing climatic conditions. Further to updating climate loadings with most recent data, this, as suggested before, could include such techniques as trend analysis or downscaling from climate models. However, to properly assess the reliability of this latter technique (particularly in Canada's North where accelerated climate warming has occurred), transient runs of these climate models should be tested against observed climate conditions.

Wind pressures must also be considered, specifically in terms of the frequency of severe convective events that can spawn tornadoes or violent down bursts. In 2007, for example, the first F5 tornado occurred in Embrum, Manitoba. Similarly, if cyclonic patterns and the increased probability of extra-tropical storms or hurricanes occurs as expected along Canada's eastern seaboard, this will likewise increase the risk of wind damage of the building structures.

Following an update in Canada's codes and standards, the major design implications for the engineering community would be to adjust the structural design of public buildings to reflect changing codes and changing climate risks.

4.3 Building materials

Due to changes in the frequency of intense wind events and in moisture regimes in the future (e.g. increase in humidity and in terms of precipitation levels), it will be important that building envelopes and enclosures are able to withstand wind actions as well as intense precipitation events [15]. This might mean that different formulations are used for construction materials to ensure that these are hardier and more durable under harsher or different climatic conditions.

Changes in climate conditions and atmospheric chemistry will also impact on the durability and strength of building materials. This will require investigation on the proper formulas for use in materials such as concrete, plaster, and building facades, all which are

susceptible at some level to changes in atmospheric chemistry (primarily changes in CO2 concentrations).

The engineering community will also have to be aware of how the important climatological parameters that influence moisture regimes could change. Presently, classification schemes such as presented earlier help to guide such approaches such as the hygrothermal approach (discussed below). In order to assuage proper mitigation efforts, care and attention should be given to how these might change into the future.

4.4 Hygrothermal approaches

In order to deal with problems associated with moisture in walls, a new discipline called hygrothemal analysis has developed within the engineering discipline [15]. Hygrothermal analysis considers rain, temperature, humidity and the interior climate as environmental loads with principal limiting conditions such as rot, decay, mold and corrosion. A damage function (damage process) analysis is then used to determine whether a limiting condition, such as mold growth, is achieved. As such, different weather parameters such as thermal regions, rain exposure zones and interior climate classes can be studied in order to understand the environmental loads that can be used to determine the moisture engineering practices needed for building envelopes and mechanical systems. What is especially essential in such analysis is the proper use of climate zones since these help indicate the range of climate factors affecting a structure.

4.5 Building stability

There are two aspects of building stability that should be considered in terms of design implications – compromises to stability due to melting of permafrost, and compromise of stability due to a drying out of soils. Due to the prevalence of the issue, only the first of these is discussed in this literature review.

4.5.1 Thermosyphons in Canada's North

'Cold climate engineering' is a branch of engineering which specifically accounts for the conditions in the North, particularly permafrost and the dependency on a stable cyrosphere for stability. There are a variety of engineering practices in the North which are used to help account for the regions unique geophysical conditions. In terms of foundation systems for buildings, this can include shallow foundations (sills, post and pad system, footings, piers, pad, fill, or slab), and deep foundations (timber, steel, and reinforced concrete piers). Other geotechnical solutions can be used as well, including the use of ventilated gravel pads or, increasingly, the thermosyphon. A thermosyphon is a device used by the construction industry to stabilize frozen ground by transferring heat from the ground services to the air in order to keep the ground frozen.

Although a number of recent studies have been completed on the role of thermosyphons in building in warm permafrost conditions [39], at present there are no comprehensive technical guidelines available to assist determining when thermosyphons are the best option foundation support system for a specific site and building, or guidance in terms of the standard to which they should meet. Thermosyphon supported infrastructure is also not dealt with in the National Building Codes of Canada, although guidance on

thermosyphon supported foundations were included in Government of Northwest Territory technical design standards and guidelines starting in the 1990's.
New structures in permafrost regions can be built over gravelly "thaw-stable" permafrost to avoid the worst consequences, but more costly up-front actions will be required to select the most reliable and least vulnerable sites as the permafrost thaws.

4.6 Relocation

In the most severe of circumstances, climate change will require the physical relocation of current structures, or the rezoning of land areas currently zoned suitable for building. This will be particularly relevant along Canada's coastlines, specifically areas of Vancouver and possibly also communities in Canada's North and along the eastern seaboard. Mitigation against sea level rise is costly, involving the building of dikes or seawalls. The most preferred approach to these challenges are assessments of land use zone planning in respect of changing climate risks.

4.7 Design for a 'diversified lifetime'

Fernandez presents the idea of designing a building using a 'diversified lifetime' approach to design where buildings and other structures become "designed for disassembly, separation technologies, materials reclamation and recycling, loose-fit detailing, lightly-treading foundations and other technologies that allow use to change over time" [40]. The general concept behind this approach to design is that buildings be designed using different design lives for different components. Therefore, if climate change is expected to impact on one component more substantially, then less investment should be placed into this. Auld and MacIver [9] suggest that for the building sector this could involve a strategy where short-term components of the buildings be designed for minimal climatic change and maximum flexibility, and more investment be geared towards longer-term parts of the building that will need to be able to cope with predicted climate change.

4.8 The role of maintenance and upgrading cycles

Since climate change is expected to change the return periods of many climate extremes, this would have to be accounted for in infrastructure maintenance and upgrading cycles. There have been numerous studies which have indicated that not only the design and construction of a building, but also the maintenance of structures influences the levels of damages that they might receive as a result of changes in extremes [12]. For example, analysis by Swiss Reinsurance shows that the mean marginal damage from wind storms for buildings increases exponentially with local peak wind gust velocity, but that damage curves increase much faster for buildings built with poor construction methods, materials, etc., or buildings that are not properly maintained.

5 Conclusions

In this report, literature has been reviewed that considers the vulnerability to climate change, specific climate change impacts, and design implications in specific context to public buildings. A number of conclusions are made, both related to the substantive material reviewed as well as the process of literature collection and review.

In terms of the substantive aspects of the literature review, a few points stand out. First, climate change impacts will have implications on structural design, the choice of materials used in construction, and the location of structures. The most pressing challenges for public buildings in Canada likely relate to the provision of adequate cooling and heating services. With climate change, these parameters are changing, specifically increasing the requirements for cooling services provided to large public buildings (and indirectly the increased electricity demand caused by the switch in fuels).

There are a number of design implications and approaches to help mitigate against the increased operational costs associated with such trends. 'Passive cooling', using nighttime air to cool daytime temperatures, or the construction of 'green buildings' are all possibilities to help cool buildings in an environmentally friendly and economic way. This will be especially important in terms of the increasing frequency and duration of extreme warm events throughout Canada's southern regions, but may be also important in Canada's North where buildings usually do not have cooling systems in place.

Another significant design implication relates to building stability of structures situated in Canada's North. Due to accelerated climate warming, Arctic temperatures are rising much faster than in the south. This is melting permafrost which previously had been used to support building foundations. The risk to public buildings has not been quantified and literature on this is not readily available. However, engineers and designers, managers and operations personnel, as well as owners of both present and future building stock will all be faced with the challenge of changes in permafrost conditions in the North. A number of technical solutions exist to help mitigate against these challenges, namely the use of thermosyphons to help keep ground surface temperatures below freezing.

Climate change will also have implications for the choice of materials used in buildings. Concrete formulations will have to be assessed for new atmospheric conditions, while plaster and other building façade material will have to be developed that can withstand different climatic characteristics. Important climate thresholds are changing in various geographical regions in Canada, such as across the Ottawa to Quebec City corridor where winter time temperatures have warmed, and freeze thaw cycles increased as a result. This has implications for cracking and physical weathering of concrete, chemical weathering of steel support, etc.

Another design implication that stands out in the literature that is particularly relevant to large public buildings is the need for an integrated approach to design. Namely, the cross spectrum of participants that are involved in the construction of a building, from electrical engineers, structural engineers, architects, etc, must take a unified approach to the design and construction of a building, with all building components matching at the appropriate scale and service level. If efforts are taken that significantly change the thermal characteristics of a building, for example, this has to be reflected in the choice of heating and cooling systems installed.

In terms of the process of literature review, a number of lessons stand out. First, at present, there is limited literature related to climate change impacts and adaptation specific to the public buildings sector in Canada. Seeing the likely significant impacts that changes in climate conditions will have, whether related to structure, materials, or even the requirements for relocation, this indicates am area where further attention should be placed.

6 Recommendations

A series of recommendations emanate from the literature review.

- All climatic data relevant to codes and standards, and specifically the National Building Codes, should be updated and the mechanisms should be put in place to ensure that these are kept current. This process should be publicly reviewed and should involve the active participation of infrastructure professionals.
- Guidelines and standards for designing for climate change should be commissioned so designers can design with the future in mind
- Climate zoning maps for Canada need to be created for different design tasks. This should include maps which reflect changing risks and climate loadings associated with climate change. This could include:
    - Hygrothermal maps
    - Wind-driven rain maps
    - Wind maps
    - HDD CDD maps
    - Soil and foundation vulnerability
    - Permafrost degradation maps
- Further development and refinement of global and regional climate modeling resources that would allow climate analysis and future predictions at the regional and local level.
- Development of methodologies and toolsets for extrapolating climate data into the future for design values. This include a variety of tools such as regional climate models and trend analysis, but require first of the establishment of a working group of associated climate experts and infrastructure professionals. Eventually this should result in the publishing of a guide for infrastructure professionals (including engineers, but also suitable for managers and planners).

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