Impact of Climate Change on Civil Infrastructure – A State-of-the-Art Review

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Abstract

This paper summarizes the impact of climate change on Canada's civil infrastructure and many related engineering, and policy and funding considerations. It is recommended that the Federal Government assume the lead in getting together all interested parties from the public and private sectors to review the present and future needs in the area of infrastructure. This could consist of a long-range infrastructure policy, along with ten- or 15-year regional and local plans, with assured funding, which can be provided by a national infrastructure bank, funded and managed by both the public and private sectors.

Keywords: infrastructure assets, climate change, impact, damage, adaptation, infrastructure policy, short-term plan, public involvement, different levels of government

Résumé

Si l'article est en français, le résumé français sera le premier. (New translation !)

Mots clés : conférence, article, modèle, dix mots maximum (New translation!)

1. Introduction

The impending climate change will continue to increase the vulnerability of the various infrastructure facilities, such as buildings, bridges and transportation infrastructure, water supply and wastewater infrastructure, energy infrastructure. This would necessitate upgrading of the existing deteriorated infrastructure and to increase its resilience to the different manifestations of climate changes in different regions of Canada. The most effective way of combatting climate change would be to first attempt to mitigate this serious global problem and then develop and implement suitable adaptation measures to plan, develop and then implement these plans to ensure satisfactory future infrastructure performance. This would require development and implementation of new and innovative technologies and skills, public involvement, and effective communication amongst all concerned parties.

"Climate change is the shift in the average weather occurring in a given region, normally based on the average weather pattern for a specific region. Global climate change implies change in the climate of the earth and it occurs naturally, gradually and very slowly" [1]. Presently, climate change is raising concern around the globe; often termed global warming, climate change is the process by which greenhouse gas emissions (GHG) are causing changes in the Earth's climate system. The changes due to the effect of temperature increases and abnormal precipitation patterns, are already being experienced around the world. Canada has been very active in climate change research, in the development of extreme climate change scenarios, and has been among leading countries to cooperatively establish targets to reduce GHG emissions. In 2009, the Government of Canada signed an agreement under the Copenhagen Accord, under which

Canada would decrease its GHG emissions to 17% below 2005 levels by the year 2020, which is basically aligned with the U.S. target [2].

The weather conditions of Canada vary greatly with the time of the year and from coast to coast. It is extremely complex to generalize the current and future potential climate impacts on infrastructures of Canada because of geographical, temporal, socioeconomic and other diversities involved. Due to the significant socioeconomic differences, few communities have a higher capacity to adapt to the impact of climate change due to greater wealth, higher levels of education, more diverse skill sets and easier access to technology and institutions, as compared with the communities that have limited economic resources and access to services [3].

Table 1 Positive and negative effects of climate change on infrastructure [4, 5].

Phenomenon	Positive/Negative Effect	Urban Infrastructure
Inundation and flooding	Negative	Damage to roads, railways, airports, electric power supply and telecommunication systems
Sea-level rise	Negative	"Sinking" of harbor facilities, coastal structures, drainage facilities, breakwaters, and tidal embankments
Rise in sea water temperature	Positive	Reduction of freezing in harbor areas in winter season
Change of rainfall pattern	Negative	Increased demand on storm-water systems
	Negative or positive	Change of water demand and supply
Decrease in freezing	Negative	Ice roads no longer safe
	Positive	General improvement of transportation conditions
	Positive	Reduction of pavement costs
Reduction of snow	Positive	Improvement of transportation conditions
	Positive	Reduction of investment in snow removal facilities
Loss of permafrost	Negative	Damage to structures and infrastructure in these areas
Increase in storm intensity	Negative	Increased wear and tear, and overloading on all infrastructure facilities

Climate change impacts can be beneficial, disadvantageous, or both simultaneously. Melting glaciers, for example, would open water channels in the North which can be beneficial for trade and development; however, these new open channels and the easier access into the country from the North can also result in a national security threat, requiring construction of new infrastructure. Also, some species, such as polar bears would face extinction because of changes to their natural habitats and their inability to survive in the changing conditions. At the same time, the Northern populations need to adapt to a new way of life, which would involve several difficulties. Warmer temperatures would promote longer profitable tourism seasons. These warmer temperatures are causing changes in evaporation and precipitation patterns, leading to changes in water chemistry, sea levels and soil moisture levels, and negatively impacting the agricultural and fishing sectors. Shorter winters and longer summers would also mean a decrease in heating demands, yet this benefit would be counteracted by an increased demand for air conditioning in the warmer summer months. A shorter duration of ice covered waters would mean longer and profitable shipping season, which would enhance international competitiveness and would contribute to nation building. Table 1 provides examples of positive and negative effects of climate change on different types of infrastructure.

The available information available on the subject clearly suggests that the adverse consequences of the climate change crisis far outweigh the apparent advantages. While climate change is a worldwide problem, it will impact different countries in different ways. Canada is a vast country, and different regions would face different risks and would need to cope with the climate change effects in a variety of ways, to shift from “remediation, response and recovery to mitigation and prevention” [6].

Canada’s infrastructure is severely deteriorated because of lack of quality control in construction, severe climate, and negligence and deferred maintenance; close to $300 billion are needed simply to bring the distressed infrastructure up to an acceptable level. In addition, another $200 billion are needed to fulfill the new infrastructure needs throughout Canada. The Auditor General, Sheila Fraser, in her “parting speech” on May 25, 2011 to the Canadian Club of Ottawa, emphasized that Canada’s infrastructure was suffering from “age and obsolescence” and needed major upgrading, along with significant climate change adaptation policies. The impact of climate change is only going to worsen the current infrastructure situation, with the ability of some communities to adapt to climate change varying with the local difficulties and issues involved. In 2010, the Environment and Sustainability Commissioner reiterated that despite the Federal Government commitment to develop an “adaptation policy” to combat the various impacts of future climate change, no strategy was formulated to help with “more effective and efficient ways of managing climate change risks” [7].

A brief review of the issues affecting civil engineers and infrastructure planners and managers follows.

2. Engineering considerations

Climate change would impact engineers and infrastructure planners and managers in a variety of ways, such as:

- The current climate extremes considered in design are derived from the past climatic data, and are not representative of the predicted future weather patterns. The design climate extremes need to be modified urgently to represent the future operating conditions if the infrastructure assets are to be designed for safety, serviceability, sustainability and efficiency throughout their service lives.

- As climate data is an important environmental loading parameter in design of infrastructure assets, the codes and standards would need changes to reflect the increased risks posed by the future climate change, and it should be reviewed and updated periodically to account for the progress in weather extremes research [8].

- Disaster management should be assigned a high priority. A backup plan should be developed to ensure effective functioning of all infrastructure assets important to the quality of life of any community with zero or minimal damage.

- Links should be drawn between extreme weather events and acceptable infrastructure damage threshold levels [9]. These forensic studies can be performed in the North where climate change has already caused considerable damage to the existing deteriorated infrastructure assets; these can provide valuable information for the urgently needed preventive actions elsewhere.

- Existing infrastructure assets would have to be evaluated in terms of the risks posed by any future climate change for their structural integrity and performance levels;

- As recommended by the Technology Road Map (2003) and Mirza (2007,2013), a detailed inventory of all existing assets needs to be developed urgently, to facilitate accurate evaluation of the assets that are most at risk. From the list of at risk assets, engineers must assess whether these can be retrofitted for preventive action against the impact of climate change [9, 10, 11, 12].

- There is a need to develop specialized agencies in different regions to assist municipalities with the recommended condition assessments and to incorporate adaptation planning into their infrastructure management practices [13].

- Finally, modifications will be required in the design and construction of different infrastructure facilities. Risk assessments of the existing assets would help to establish optimal alternatives when planning to retrofit the existing assets, or to mitigate the effects of the predicted climate changes in development of new infrastructure assets. For example, if storm-water pipes are determined to be under-capacity for the predicted increase in precipitation, then the size of the existing pipes should be re-evaluated, besides provision of more green spaces to prevent the rapid draining of the storm water into catch basins. Therefore, not only should the infrastructure be retrofitted, but engineers also need to work closely with urban planners to plan for alternative sustainable and economical solutions to ensure that the existing assets remain adequately serviceable. The considerable effort required to incorporate climate change in civil engineering practice to rehabilitate and reconstruct the existing deficient infrastructure represents a formidable challenge. The solutions developed to meet the future needs arising from the climate change would create opportunities to plan for new infrastructure and to retrofit the existing deteriorated infrastructure for adaptation to future climate change extremes [9].

3. Impact of climate change on infrastructure

Climate change can impact infrastructure in many ways, for example, increasing temperature will lower the soil moisture content, and increase the evaporation rates, which, in turn, will decrease surface runoff in the Lower Lakes and South Laurentien regions. In addition, the water quality in these lakes is already jeopardized by the effluents from the various regional industries; the low water quality and low water level will impact the health and quality of life of people in this area. This would also lower the St. Lawrence River outflow by as much as 20% [14].

Most of this negative impact can be mitigated or prevented with new, or improved infrastructure, e.g., higher levels of treatment may be required to counteract the effects of lower water level on water quality. Water temperatures are typically higher at lower levels, which promote the growth of algae and bacteria. Also, dredging will be required in some areas to facilitate shipping and other marine activities; this could lead to re-suspension of toxic chemicals [14]. Furthermore, existing dams would need retrofitting, or new infrastructure would be needed for alternate sources of power generation, and to transport water to affected regions at larger distances, which can be quite expensive. By contrast, increased water levels would require construction of dikes and other flood protection schemes in some coastal regions. Other examples of the influence of expected climate change (Table 2) on infrastructure in the various regions are summarized briefly:

(a) Periods of drought would result in reduced water quality and lower water levels; higher temperatures would increase the levels of bacterial, nutrient and metal contamination (NRC 2004), requiring more stringent and innovative water treatment practices.

(b) Increased precipitation would require new infrastructure for flood mitigation. Increased flooding could "increase the flushing of urban and agricultural waste into source water systems", needing higher levels of water treatment. The large amounts of rainfall could overwhelm the capacity of the storm water systems, causing overflow, with large quantities by-passing the treatment plants before being disposed into fresh water sources [15, 16, 17]. In the case of combined sewers, the overflows would again contaminate the various water resources. Many existing transportation systems have not been designed for the extreme precipitation patterns. In

The case of concrete bridges and pavements, the resulting drainage problems, especially with the use of deicing salts, can accelerate the corrosion of the embedded steel reinforcement leading to serious and costly deterioration problems, resulting in reduced safety and serviceability.

(c) The rise of seawater level due to melting of glaciers, increased precipitation and expansion of ocean waters due to higher temperatures would require flood protection infrastructure to protect the coastal communities, especially those that are just above the sea level, as is the case for many communities along the western coast of Canada, especially, the Delta in southwestern British Columbia

Increased precipitation can also trigger slope instability and landslides, which could be a serious problem along the Pacific coast, with damage to transportation systems in mountainous areas and other infrastructure in the local communities. Similar problems will be faced by communities with sloping embankments, with road closures accompanied by inadequate service, and reduced water quality due to ingress of silt and clay in the reservoirs, which reduces the disinfecting ability of the chlorination process [15, 16, 17]. Significant research and development work will be needed for alternative slope stabilization and soil reinforcement techniques, along with enhanced safety and stability of earth retaining structures and appropriate hydrological mitigation strategies [15, 16, 17].

Canada has the most coastal land compared with any other country, and the sea levels are projected to rise by 10 to 100 cm above the current levels over the next 100 years. The rising sea levels could result in increased erosion of coastal areas and the waterfront infrastructure. Several offshore structures designed for lower sea levels, such as offshore oil platforms would be threatened and need appropriate protective measures. New dykes would have to be constructed to prevent inundation by storm surges in low lying areas [15, 16, 17]. The increased precipitation could cause spilling of toxic compounds from the existing tailings ponds into local water systems [14, 18, 19], requiring construction of appropriate defensive barriers. The enhanced spring runoffs from increased winter precipitation would place a "greater demand on reservoirs to even out electric supply" [20], besides spilling toxic compounds into local water systems. The water table will rise in some countries, increasing the probability of ground water contamination and requiring large investments for purification [15, 16, 17].

High risk of coastal storms of high intensity causing wave surges and tropical storms would increase the risk of damage to coastal and offshore structures, offshore oil platforms and ships. Tsunamis, caused by underwater earthquakes or volcanic eruption could further aggravate the damage risk [1].

Table 2 Expected climate change events in Canada's main climatic regions [15, 16, 17]

Climate Change Event	Pacific Coast	North & South Mountain	West & East Arctic	Prairie	North Interior	North Laurentian	Lower Lakes & South Laurentian	Atlantic
Increased storm severity							✓	
Intense rainfall events							✓	
More sheet runoff							✓	
Less sheet runoff							✓	
Increased flood events	✓						✓	✓
Increased evaporation							✓	
Increased evapotranspiration				✓				
Increased periods of drought				✓			✓	
Decreased duration of lake ice cover							✓	
Lower lake water levels							✓	
Less snow							✓	
Increased winter precipitation	✓	✓	✓		✓	✓	✓	
Shorter winters					✓	✓		
Increased fall precipitation			✓		✓	✓		
Rising temperatures	✓	✓	✓	✓	✓	✓	✓	✓
Melting permafrost			✓		✓	✓		
Increased sea levels	✓		✓					✓
Increased incidence of storm surges								✓
Decreased snow cover		✓						✓
Elimination of wetlands and sloughs				✓			✓	
Decreased water levels				✓			✓	
Decrease in duration of snow cover				✓				
Decreased summer soil moisture				✓	✓		✓	
Earlier snowmelt and ice breakup					✓			
Less thick and less permanent sea ice					✓			✓
Milder winters			✓		✓	✓		
Longer summers			✓		✓	✓		
Increased snowfall						✓		
Increased rain-on-snow events		✓						
Increased risk of avalanches		✓						
Increased rate of snowmelt		✓						
Decreased summer stream flows		✓		✓				
More risks of landslides	✓							
Glacier retreat and disappearance	✓							
Higher impacting river flows	✓							
Risks of forest fires	✓			✓	✓			
Insects and possible spread of disease	✓			✓				

(d) Increased runoffs due to excessive precipitation could be greater than the infiltration capacity of the local land, resulting in large quantities of sediment, nutrient, pesticides and other possible waste entering the surface waters. Again, this would require supplementary purification systems at significant costs. Providing large green spaces for temporary storage of these runoffs would be an appropriate sustainable solution.

Changing water flow patterns could cause more erosion in offshore and waterfront infrastructure and increase the risk of scouring of foundations. These can be countered by using hydraulic (rip-rap or sheet piles), and/or structural modifications (e.g., modifying a structure influenced by erosion, e.g., implementing changes in pile geometry and alignment, and reinforcing the foundation), along with regular monitoring (visual and with appropriate fixed instrumentation).

(e) Increased temperatures and humidity levels could result in higher rates of pavement softening and deterioration of other infrastructure facilities, including buckling of railway tracks. Moreover, higher temperatures would increase the rate of chemical reaction, leading to faster degradation of the various construction materials, and requiring considerably higher levels of maintenance, along with preventive measures. The increase in temperature would decrease the number of freezing and thawing cycles acting on structures, especially in southern parts of Canada. However, in the northern parts, the number of freezing and thawing cycles would increase, resulting in increased deterioration due to scaling and disintegration of concrete. Higher temperature would reduce dissolved oxygen in fresh water resources, causing longer stratification and resulting in algal bloom, which would lead to lower quality of water, besides influencing its taste and odor [21, 24, 25], and increasing salinization, requiring considerably improved water treatment [15, 16, 17]. In addition, the existing water storage facilities would not be able to cope with long drought periods; water supply and sewage disposal systems in some areas, basically in the Prairie Provinces may not be able to meet the demands of the communities.

The length of the seasons would change along with the intensity of extreme temperatures; in particular, the summers will be longer, warmer and drier, with an increased in the number of hot days and would result in an increase in the frequency and intensity of thunderstorms. By contrast, the winters will be shorter with a decrease in the number of cold days. The existing HVAC systems would need to be upgraded to deal with the resulting temperature extremes.

(f) Ice jams can negatively influence the local or regional hydrology. Waterfront infrastructure, dams, bridge piers and other assets could be subjected to significant erosion and considerable damage due to impact of large “icings”. Protective systems, such as fenders could be installed on existing and new assets to mitigate the damaging impact of these large icings.

In addition, increased duration of ice-on-snow periods, could result in heavier loads on building roofs and other assets, increasing the risk of collapse under increased loads which would be considerably higher than that for the design loads. Several such collapses have been noticed in the recent snow storms in the eastern Atlantic coast states and the Atlantic Provinces. The current design loads need careful consideration and revision to eliminate these dangerous situations.

(g) Deteriorated infrastructure facilities can contribute to climate change in several ways. Some examples are:

Table 3 Examples of costly climate change impact on infrastructure in Canada [3, 18, 19].

Climate hazards	Region	Estimated costs (CAD)	Infrastructure damaged
Manitoba and Saskatchewan, June, 2014	Eastern Prairies	>$1 billion	• Closure of a hundred highways, including a stretch of the TransCanada east of Regina • Dozens of bridges, culverts and utilities were washed away
Toronto's Torrent, July 8, 2013	Southern Ontario	>$1 billion	• Major transit halts and delays • Several roads and underpasses under water • About 500,000 households without power ranging from few hours to several days • About 3,000 basements flooded, causing major damages.
Calgary Flood, June 19, 2013	Southern Alberta	> $6 billion	• 3,000 buildings were flooded in downtown Calgary • 1,000 km of destroyed roads • Hundreds of washed-away bridges and culverts • Thousands of homes demolished and damaged by backed-up sewers • Calgary Zoo moved many of its exotic animals to its ranch south of the city
Toronto Flood, August 19, 2005	Ontario	>$500 million	• 30 m of Finch Avenue West (a major arterial street) was washed out • Damage to two high-pressure gas mains, and a portable water main • Damage to telephone, hydro and cable service lines
Southern Alberta Floods, 2005	Prairies	>$400 million	• Sewer backup • Roads, parks, sewers, bridges, buildings, agriculture
Peterborough Flood, July 15, 2004	Ontario	$200 million	• 500 homes were flooded • 1,000 homes had gas lines disconnected • Sewer systems and roads were inundated
B.C. Wildfires, 2003	British Columbia	$700 million	• Destroyed 334 homes and many businesses
Hurricane Juan, 2003	Atlantic	$200 million	• Homes, businesses, energy systems, roads, pipelines damaged
Ice Storm, 1998	Ontario, Quebec, Atlantic Canada	$5.4 billion	• Power lines causing loss of electricity for more than 4 million people for periods ranging from a few days to several weeks • 1,000 steel electrical pylons, and 35,000 wooden utility poles were crushed by the weight of the ice • Approximately $790 million in damage to homes, cars and other property
Saguenay Flood, 1996	Quebec	$1.7 billion	• Roads, bridges, railways, aqueduct and sewage networks needed complete restoration • 20 businesses destroyed and another 25 damaged

- Increasing number of potholes, extensive emergency road repairs and inability of the transportation system to fulfill the service demand will contribute to high levels of road congestion and accompanying increase in greenhouse gases.
- Increasing vehicle use resulting from low capacity and increasing deterioration of the transit system, especially in city cores.
- Increasing purified water leakage from pipes, leading to inefficient treatment plant operations and energy losses.
- Partial or complete lack of recycling requires use of newly manufactured materials, increasing the resulting GHG emission and energy consumption.
- The techniques for repair and rehabilitation of older structures utilize excessive amount of water and energy. The area needs further research and development.

Table 3 summarizes few examples severe weather events in Canada and their quantitative impacts on civil infrastructure. However, these costs are estimated at the time of the particular event, not considering the long-term associated costs, as well as interdependency between the different infrastructure systems. For example, in July 2013, more than 100 mm of rain fall in about two hours in Greater Toronto Area (GTA), causing more than $1 billion damage. At about the same time of the year, Southern and Central Alberta, including Calgary, experienced the most severe flooding in the province’s history, with estimated cost of damage of more than $6 billion. Consistent with projections that the frequency and severity of extreme weather events are likely to increase in most parts of Canada in the future due to climate change, it can be anticipated that the economic costs associated with such events will also only grow in the absence of planned adaptation efforts [3, 18, 19].

4. Where do we go from here?

As mentioned earlier, the current state of severe deterioration of Canada’s Infrastructure will get considerably worsened by the impact of the impending climate, requiring considerable resources beyond what can be provided by the different levels of government and the private sector. In fact, the frequency and intensity of natural and man-made disasters have increased considerably over the past 25 years. The Federal Government must take the lead in getting all parties together to review the current and the future projected situation, and determine appropriate solutions, which can be implemented in the near future. This would involve establishing a long-range infrastructure policy to fulfil all needs of the society now and into the future [22], along with a ten- or 15-year plan for each region and each community to ensure that Canada’s infrastructure continues to remain in a good state of health. This would need assured funding form both the public and private sectors. The concept of a national infrastructure bank has been proposed by Mirza (1998, 2013) and others [11, 12, 22, 23]. It is urgent that all interested parties agree on a course of future action to ensure that our infrastructure does not continue to deteriorate and the burden of ameliorating the badly deteriorated infrastructure is not left to the future generations. They must receive the infrastructure in at least as good a condition as the previous generations left for us. **The time to act is now**, and with a federal election this fall, the subject should be discussed by all political parties.

5. Summary and conclusion

The impact of climate change on Canada’s civil infrastructure and many related engineering, and policy and funding issues are examined briefly in this paper. The climate extremes needed to be considered in developing a disaster management plan for a given asset in a given climatic region of Canada are summarily reviewed. The presently available guidelines, designed codes and standards need to be modified and strengthened to mitigate the effects of predicted climate changes and extreme weather on the various infrastructure assets. It is recommended that the Federal Government assume the lead in getting together all interested parties from the public and private sectors to review the present and future needs in the area of infrastructure. This could consist of a long-range infrastructure policy, along with ten- or 15-year regional and local plans, with assured funding, which can be provided by a national infrastructure bank, funded and managed by both the public and private sectors.

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8. Biography

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Dr. Ali is Postdoctoral Fellow in the Department of Civil Engineering and Applied Mechanics at McGill University. He received his Ph.D. degree in Civil Engineering from McGill University, and Bachelor of Science in Civil and Master of Sciences in Structural Engineering degrees from the Engineering University Lahore, Pakistan. His research work deals with sustainability and durability of civil infrastructure.

Professor M. Saeed Mirza

Professor Mirza is regarded "an outstanding engineer with a unique vision for the future, and an excellent researcher and educator who has made a tremendous impact on many infrastructure issues". He has lobbied strongly for renewal of Canada's deteriorating infrastructure and related technical, environmental, socio-economic, and financial, management and policy issues. Winner of several awards for outstanding teaching, research and professional contributions, he is considered a world authority on structural concrete behaviour and design of sustainable infrastructure.