IEc

Costing Climate Change Impacts on Canada's Infrastructure:

Results for "Deep Dive" Statistical and Process-based Models

Final Report | 31 December 2020

prepared for:

Canadian Climate Institute

prepared by:

Industrial Economics, Incorporated

2067 Massachusetts Avenue

Cambridge, MA 02140

IEc

TABLE OF CONTENTS

ACRONYM LIST

ACE	Air Cooled Embankments
ADR	Annual Damage Ratio
DEM	Digital Elevation Model
CAD	Canadian Dollars
CCI	Canadian Climate Institute
CIRA	Climate Change Impacts and Risk Analysis
CMA	Census Metropolitan Area
CO_2	Carbon Dioxide
DEM	Digital Elevation Model
FDD	Freezing Degree Days
FDI	Freezing Degree Index
FEMA	U.S. Federal Emergency Management Authority
GCM	General Circulation Model
GHG	Greenhouse Gas
GIC	Ground Ice Content
GWh	Giga-watt hour
IPCC	Intergovernmental Panel on Climate Change
IPSS	Infrastructure Planning and Support System
M&I	Municipal and Industrial
MWh	Megawatt hour
NCPM	National Coastal Property Model
NRCan	Natural Resources Canada
NRTEE	National Round Table for the Environment and the Economy
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
SLR	Sea Level Rise
TDD	Thawing Degree Days
TDI	Thaw Degree Index
TWh	Terawatt hour
USD	U.S. Dollars
USEPA	U.S. Environmental Protection Agency
VKT	Vehicle Kilometers Traveled

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The report provides the results of an analysis of the economic impacts of climate change across Canada. The approach relies on a two phased approach to developing thematic impact estimates. First, we applied a new, published screening level approach to characterizing multi-sectoral climate impacts in North America based on reduced-form damage functions, which were derived from a set of existing process-model runs. Application of these functions to the Canadian context, because they were originally developed for the U.S. Environmental Protection Agency, required infrastructure and climate data inputs that have been collected by CCI and our own research, from both government and commercial sources. The methodologies and results of this screening analysis are documented in a separate IEc report to CCI.[1]

Based on the results of the reduced-form analysis and peer reviewer input, we apply process-based modeling approaches to a subset of the infrastructure categories to develop more in-depth results. These selected categories, which are the focus of this report, include coastal properties, inland flooding, roads, rail, permafrost, winter roads, the electrical grid, and hydropower generation. In addition, we consider delay costs, which are motorist and freight delays associated with out-of-service or underperforming infrastructure attributable to changes in climate. Each of these process-based modeling approaches is an adaptation from peer-reviewed work that our team conducted in the U.S.

ES.2 TECHNICAL APPROACH

The spatial and temporal resolutions of the process-based modeling activities vary considerably depending on data availability and model configuration. By temporal resolution, we are referring to the modeling time step of the analysis. Damages are estimated for two "eras": the 2050s (2040 to 2069) and the 2080s (2070 to 2099). In some cases, as in the permafrost and electrical grid analyses, an earlier era (2020 to 2039) is presented for context on those effects. Our analyses consider seven General Circulation Models (GCMs) and two greenhouse gas emissions scenarios (i.e., 14 scenarios total), selected to represent a range of potential Canadian climate futures. The results presented in this report focus on the average and range of damages from the seven GCMs for each emissions scenario. For the six infrastructure categories with adaptation alternatives, we present the reactive adaptation damages as the primary "status quo" scenario. We also present a "proactive adaptation" scenario, where adaptation investments are forward-looking, considering anticipated climate change.

Damage estimates for infrastructure primarily represent the increased costs of protection, repair, or replacement of infrastructure under a changing climate. Damage models for these categories are

[1] The screening-level approach builds on a recent study by Neumann et al. (2020) that econometrically identifies relationships between commonly available climate projection variables (i.e. temperature, precipitation, and sea level rise) and damage, by analyzing the results of consistently parameterized, process-based, econometric, or combination damage model runs for the contiguous United States under varying climate scenarios.

developed using damage estimates scaled by the regional infrastructure network inventory (i.e., road miles, vulnerable bridges, rail miles, coastal property value, or urban area). Brief descriptions of each category follows.

- The **coastal properties** study estimates the potential future property value damages as a result of sea-level rise combined with storm surge attributed to climate change. Damages are estimated for properties (land and structure) in coastal regions.
- The **inland flooding** study estimates the potential increase in flooding damages as a result of more frequent and severe high river flow events associated with climate change.
- The **roads** study estimates the cost of road repair, user costs (vehicle damage) and road delays due to degrading road surface quality as a result of climate change.
- The **rail** study estimates repair, equipment, and delay costs due to rail track buckling or the threat/risk of buckling associated with elevated temperatures.
- **Permafrost thaw** represents an important climate stressor for Northern Canada that will impose costs on multiple types of infrastructure, including roads, buildings, and runways.
- The **winter roads** analysis quantifies costs under climate change assuming winter roads become impassable during a given month if the monthly average temperature exceeds a threshold.
- The **electric transmission and distribution** study estimates damages to the electric transmission and distribution infrastructure due to climate change, and considers extreme temperature, extreme rain, vegetation growth, and coastal flooding.
- The **hydropower** analysis provides a high level, initial estimate of the potential effects of climate change on hydropower generation. This category is not monetized and is therefore not included in the summary of findings below.

ES.3 SUMMARY OF FINDINGS

Table ES-1 summarizes the costs of climate change by the eight infrastructure categories presented in this report, and delay costs resulting from road and rail impacts. Under the reactive strategy, inland flooding has the highest annual costs with mid-range estimates between $5 billion and $8 billion per year, which is 15 to 135 percent larger than the next highest category, depending on RCP and era.[2] Road-related costs are next, then resulting delay cost effects in the 2080s, then impacts to the electrical grid, which collectively range between $600 million and $7 billion per year. The next tier includes impacts to coastal properties, driven by permafrost thaw, and to winter roads in the 2050s under RCP8.5 range between $120 million and $450 million. Effects on winter roads in the 2080s and 2050s under RCP4.5, and to rail are generally lower, ranging from $7 million to $60 million.

Adopting a proactive adaptation strategy generally has dramatic benefits, driving reactive costs down 76 to 98 percent for roads, rail, and delay costs; 45 to 77 percent for coastal properties; and 38 to 47 percent for the electrical grid. Cost reductions for permafrost thaw and inland flooding impacts are more modest. In the case of permafrost thaw, this is because of the challenge of adapting to this climate hazard –

[2] Note that mid-range estimates are an average across GCMs. The range of GCM specific results for each impact category is reported in the relevant sector chapters of this report.

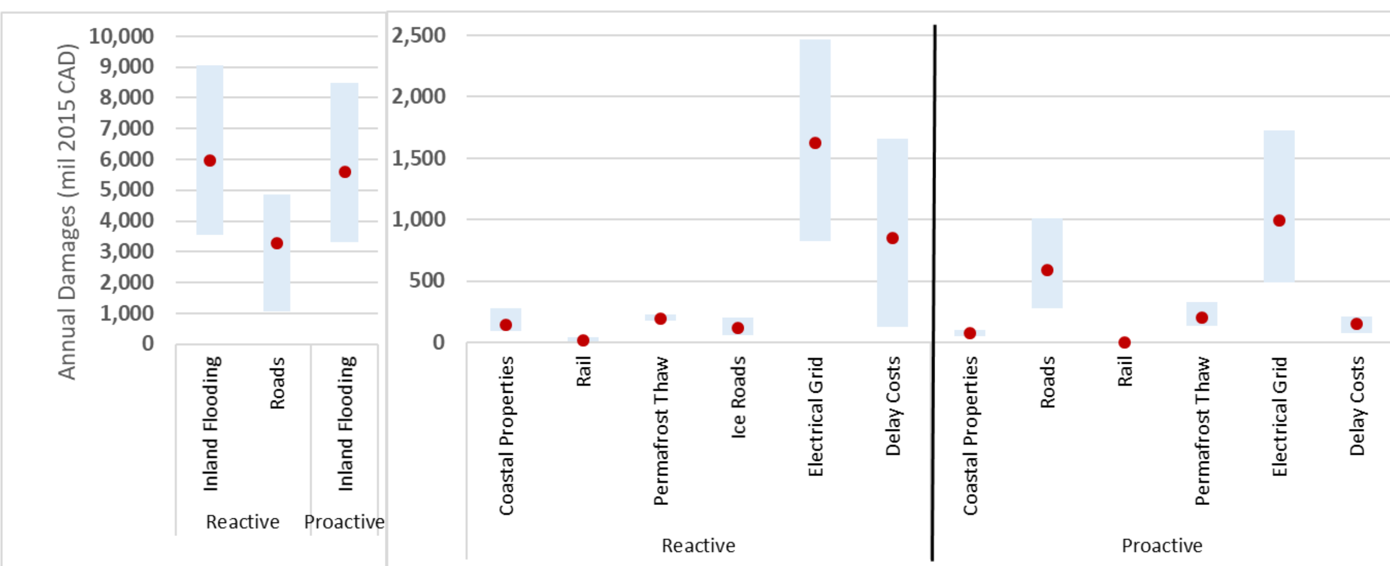
generally costs can be delayed but not avoided, which is why a proactive strategy increases costs in the 2050s and 2080s under RCP 8.5. For flooding, the proactive costs consider only a single adaptation response – abandoning or relocating the most vulnerable properties to flood-free areas – so these adaptation savings are best seen as a partial estimate.

TABLE ES-1. SUMMARY OF ANNUAL NATIONAL COSTS AND ADAPTATION SAVINGS ($MIL 2015 CAD)

	Reactive				Proactive				Proactive Reduction in Costs			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Category	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s
Coastal Properties	$131	$240	$146	$453	$71	$90	$78	$104	-45%	-62%	-47%	-77%
Inland Flooding	$5,269	$5,011	$5,961	$8,289	$4,922	$4,684	$5,579	$7,751	-7%	-7%	-6%	-6%
Roads	$2,242	$3,117	$3,270	$7,229	$532	$295	$591	$118	-76%	-91%	-82%	-98%
Rail	$6.7	$6.7	$18	$61	$1.2	$1.3	$1.2	$1.3	-83%	-81%	-93%	-98%
Permafrost Thaw	$193	$206	$196	$172	$152	$174	$200	$211	-22%	-16%	2%	23%
Winter roads	$38	$29	$117	$51	-	-	-	-	-	-	-	-
Electrical Grid	$1,223	$582	$1,621	$1,467	$663	$307	$997	$790	-46%	-47%	-38%	-46%
Delay Costs	$545	$768	$853	$2,478	$98	$86	$152	$275	-82%	-89%	-82%	-89%

Figure ES-1 presents the variability in total costs across GCMs under the RCP 8.5 scenario, in the 2050s. The reactive costs are split onto two vertical axes to accommodate the large difference in costs between the flooding and roads impacts, and all remaining categories of reactive and proactive costs. Generally, costs vary much more significantly across GCMs for the flooding, roads, the electrical grid, and delay cost categories than the others. This is because impacts in these four categories are driven partly by precipitation projections, which vary much more across GCMs than temperature projections.

FIGURE ES-1. VARIATION IN AVERAGE ANNUAL COSTS ACROSS GCMS, RCP 8.5 SCENARIO, 2050s ($MIL 2015 CAD)



Note: The red dot for each category is the average across GCMs; the blue box surrounding the dot shows the range.

The distribution of these costs over provinces and territories varies considerably across the infrastructure damage categories. Table ES-2 provides an example of this distribution for RCP 8.5 in the 2080s, where the size of bars within the cells reflects the magnitude of values wthin a given infrastructure category rather than across all categories. Some categories, such as roads, rail, the electrical grid, and delay costs, tend to scale roughly based on population (i.e., Ontario has the highest impacts, and British Columbia, Quebec, and Alberta tend to have large effects). Although there are notable exceptions, such as the low flooding impacts in Quebec and the high rail impacts in Saskatchewan. Other impacts are also driven based on geography, such as coastal property, permafrost, and winter road effects.

In particular, the combined impacts of permafrost thaw and winter road effects are pronounced for the three territories (about $170 million per year), considering their combined population is roughly 100 times lower than that of Ontario (i.e., 120,000 versus 14.5 million).

TABLE ES-2. AVERAGE ANNUAL COSTS BY PROVINCE/TERRITORY AND INFRASTRUCTURE DAMAGE CATEGORY, RCP 8.5 SCENARIO, 2080s ($MIL 2015 CAD)

Province/Territory	Coastal Properties	Inland Flooding	Roads	Rail	Permafrost Thaw	Ice Roads	Electrical Grid	Delay Costs
Alberta	-	$968	$1,580	$8.5	$0.1	$3	$169	$383
British Columbia	$276	$1,209	$916	$7.0	$1.5	$0	$120	$370
Manitoba	-	$592	$582	$5.6	$6.4	$17	$90	$173
New Brunswick	$63	$156	$256	$0.8	$0.0	$0	$56	$53
Newfoundland and Labrador	-	$135	$66	$0.3	$0.0	$0	$27	$20
Northwest Territories	-	$5	$21	$0.1	$54	$12	$5.2	$2.8
Nova Scotia	$59	$209	$155	$0.0	$0.0	$0.0	$42	$34
Nunavut	-	$1.3	$1.4	$0.0	$54	$0.1	$5.2	$0.1
Ontario	-	$4,111	$1,510	$15	$0.3	$16	$446	$679
Prince Edward Island	$16	$7	$104	$0.0	$0.0	$0.0	$21	$17
Quebec	$39	$780	$1,574	$10	$2.1	$0.0	$408	$418
Saskatchewan	-	$103	$447	$13	$0.2	$3.6	$74	$325
Yukon	-	$12	$18	$0	$54	$0.0	$5.2	$2.6
TOTAL	**$453**	**$8,289**	**$7,229**	**$61**	**$172**	**$51**	**$1,467**	**$2,478**

Note: the size of bars within cells reflect the magnitude of values within a single infrastructure impact category (i.e., table column), rather than across all categories.

ES.4 RECOMMENDATIONS FOR FUTURE WORK

This study provides a partial estimate of the potential economic impacts of climate change to Canada and the possible benefits of adaptation. Areas of ongoing research, modeling, and data collection will open avenues to consider a wider range of damages. Below, we provide several recommendations for future work in the specific categories we analyze in this study.

- **A more comprehensive update to a National coastal risk analysis**, incorporating sea-level rise and storm surge threats, could be useful in guiding GHG mitigation, adaptation, and economic development policy.

- **Potentially important omissions in the sectoral scope of the coastal sector analysis** that may be worth considering for enhancement in future work include intensification of wind damage from coastal storms; accelerated loss of coastal wetlands and other natural areas that provide ecosystem service flows such as flood protection and commercial fish nursery grounds; effects of sea-level rise on the extent of high-tide flooding and other high frequency/low consequence coastal events; and the potential for disproportionate impacts of coastal vulnerability and adaptation decision on socially vulnerable populations.
- **Disproportionate impacts of inland and coastal flooding on small and disadvantaged communities** that rely critically on access to coastal or riverine resources, particularly in Northern Canada, should be assessed with specialized methods that consider both the unique nature of the climate stressors (e.g., loss of winter ice pack in the Arctic Ocean and Hudson's Bay) and the relatively larger economic reliance on these resources among these communities.
- **Refining hydrologic and hydraulic modeling.** There appears to be continued effort across Canada, mostly at the urban scale, to further refine the hydrologic and hydraulic modeling basis to assess impacts of inland flooding. We recommend use of the national-scale analyses presented here, which by necessity rely on more simplified hydrologic and hydraulic modeling methods, to guide geographic priorities for refining hydrologic, hydraulic, and infrastructure impact modeling under future climatic conditions.
- **More comprehensive consideration of benefits of climate change in the roads and rail analysis** will be important to develop a more complete view of impacts to those sectors. Currently, we exclude the benefits to rail of fewer extreme cold temperature breaks, and the benefits to asphalt maintenance of higher minimum temperatures.
- **A process-based permafrost modeling approach**, similar to the Melvin et al. (2017) study of Alaska's infrastructure, would allow for a much more refined analysis of permafrost impacts. Although no such model is currently available for Canada, the Permafrost Partnership Network for Canada is currently developing projected permafrost conditions under a range of climate models that could be leveraged once available.
- **Considering the costs of electric power outages** from more frequent damaging weather events such as ice storms, lightning strikes, and wildfires. Although data and modeling needed to conduct such research in Canada is currently limited, a starting point could be adapting the Interruption Cost Estimate (ICE) Calculator from Lawrence Berkeley National Labs (LBNL) to the Canada context. This research will be particularly important as electrification initiatives for transport and home heating advance.
- **More detailed analysis of hydropower impacts** that allows for analysis of firm power effects. Boehlert et al. (2016) found that although annual hydropower generation rises in the U.S. under climate change, firm power declines. Most importantly, this assessment will require a more detailed hydrological dataset so that rainfall runoff models can be properly calibrated to low flows, and more detailed data on hydropower generation facilities.

CHAPTER 1 | INTRODUCTION

The report provides the results of an analysis of the economic impacts of climate change across Canada. The approach relies on a two phased approach to developing thematic impact estimates. First, we applied a new, published screening level approach to characterizing multi-sectoral climate impacts in North America based on reduced-form damage functions, which were derived from a set of existing process-model runs. Application of these functions to the Canadian context, because they were originally developed for the U.S. Environmental Protection Agency (U.S. EPA 2017), required infrastructure and climate data inputs that have been collected by CCI and our own research, from both government and commercial sources. The methodologies and results of this screening analysis are documented in a separate IEc report to CCI.[3]

Based on the results of the reduced-form analysis and peer reviewer input, we apply process-based modeling approaches to a subset of the infrastructure categories to develop more in-depth results. The selected categories, which are the focus of this report, include coastal properties, inland flooding, roads, rail, permafrost, winter roads, the electrical grid, and hydropower generation. In addition, we consider delay costs, which are motorist and freight delays associated with out-of-service or underperforming infrastructure attributable to changes in climate. Each of these process-based modeling approaches is an adaptation from peer-reviewed work that our team conducted in the U.S.

Climate projections were from the Pacific Climate Impacts Consortium, which has generated statistically downscaled and bias corrected scenarios for a range of General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs), or emissions scenarios.[4] Sea level rise projections are derived from Natural Resource Canada. Results across all infrastructure categories are presented for a 1986-2005 baseline, and two 30-year eras that CCI intends to use for their overall cost of climate impacts study (2050s: 2041-2070 and 2080s: 2071-2100).

In the remainder of this report, Chapter 2 reviews the technical approach of the study, including analytical frameworks for the reduced form and process modeling approaches. Chapter 3 summarizes the methods and results for each of the eight categories considered in this work, as well as delay cost effects. This chapter also includes the limitations and caveats of each approach. Chapter 4 summarizes the results and provides recommendations for future work.

---

[3] The screening-level approach builds on a recent study by Neumann et al. (2020) that econometrically identifies relationships between commonly available climate projection variables (i.e. temperature, precipitation, and sea level rise) and damage, by analyzing the results of consistently parameterized, process-based, econometric, or combination damage model runs for the contiguous United States under varying climate scenarios.

[4] See https://pacificclimate.org/data/statistically-downscaled-climate-scenarios.

CHAPTER 2 | TECHNICAL APPROACH

As described above, this study uses a set of process-based modeling approaches to develop estimates of the costs of climate change to Canada. This chapter describes our analytical framework, then describes the infrastructure categories we estimate. Further details about the individual modeling approaches are provided in Chapter 3, additional details about selection of climate change scenarios are provided in Appendix A, and documentation of the climate projections is in Appendix B.

2.1 DAMAGE ESTIMATION FRAMEWORK

2.1.1 SPATIAL AND TEMPORAL SCALE

The spatial and temporal resolutions of the process-based modeling activities vary considerably depending on data availability and model configuration. By temporal resolution, we are referring to the modeling time step of the analysis. The methodological details of these modeling approaches are provided in Chapter 3. Damages are estimated for the 2050s and 2080s eras described above. In some cases, as in the permafrost and electrical grid analyses, an earlier era (2020 to 2039) is presented for context on those effects.

2.1.2 CLIMATE SCENARIOS

Our analyses consider seven GCMs and two RCPs, selected to represent a range of potential Canadian climate futures. See Appendix A for the procedure that CCI and IEc used to select the set of seven GCMs, and Appendix B for a more detailed review of the climate projections employed than provided here. Each of the GCMs (CCSM4, GFDL-CM3, GFDL-ESM2M, HadGEM2-AO, HadGEM2-ES, MIROC-ESM-CHEM, and MRI-CDCM3) is applied for RCP4.5 and RCP8.5 greenhouse gas (GHG) emissions scenarios. The results presented in this report focus on the average and range of damages from the seven GCMs for each RCP; damage estimates for each individual GCM are also available.

For illustration of regional differences, Table 2-1 presents the average projected changes in temperature and precipitation for each region, era, and RCP employed in this analysis. Projections vary by GCM, with the GCMs projecting a range of increases in temperature over time. On average across GCMs, all Provinces and Territories are projected to have increasing rainfall, with British Columbia showing the largest increases. Individual GCMs do show drying conditions in some areas. Details are presented in Appendix B.

TABLE 2-1. AVERAGE PROJECTED CHANGE IN TEMPERATURE AND PRECIPITATION FROM BASELINE

Province/ Territory	Change in Mean Temperature (°C)				Change in Precipitation			
	RCP 4.5, 2050S	RCP 4.5, 2080S	RCP 8.5, 2050S	RCP 8.5, 2080S	RCP 4.5, 2050S	RCP 4.5, 2080S	RCP 8.5, 2050S	RCP 8.5, 2080S
Alberta	2.76	3.36	3.62	5.9	3%	6%	5%	13%
British Columbia	3.06	3.71	4	6.52	14%	17%	18%	26%
Manitoba	2.52	3.05	3.33	5.38	5%	7%	8%	12%
New Brunswick	2.97	3.47	3.77	5.84	3%	5%	6%	12%
Newfoundland and Labrador	2.35	2.89	3.15	5.1	5%	7%	7%	10%
Northwest Territories	2.97	3.45	3.79	5.87	5%	7%	6%	10%
Nova Scotia	2.73	3.22	3.53	5.54	2%	5%	5%	10%
Nunavut	2.99	3.46	3.81	5.91	7%	9%	8%	12%
Ontario	2.78	3.3	3.62	5.72	4%	6%	8%	13%
Prince Edward Island	2.48	2.99	3.29	5.26	0%	2%	2%	5%
Quebec	2.87	3.4	3.71	5.87	4%	6%	7%	14%
Saskatchewan	2.72	3.28	3.56	5.73	2%	5%	5%	11%
Yukon	3.18	3.94	4.14	6.86	6%	10%	11%	19%

Note: Temperature and precipitation values are averages across the seven GCMs. See Appendix B for detailed results.

2.1.3 ADAPTATION ALTERNATIVES CONSIDERED

For the six infrastructure categories with adaptation alternatives, we present the reactive adaptation damages as the primary "status quo" scenario. We also present a "proactive adaptation" scenario, where adaptation investments are forward-looking, considering anticipated climate change. More details on the definitions of these adaptation scenarios with regards to coastal properties, inland flooding, roads, rail, permafrost, and electrical grid categories are presented in Table 2-2. A "no adaptation" option is also presented for reference for some categories, although this is not considered in the analysis.

TABLE 2-2. ADAPTATION OPTIONS CONSIDERED

	REACTIVE ADAPTATION	PROACTIVE ADAPTATION
COASTAL PROPERTY		
Costs Include	• The property values of abandoned properties (due to inundation or when the expected value of damage exceeds the property value), structure damage from flooding, and costs of elevating structures.	• The property values of abandoned properties, the costs of coastal flood protection where it is warranted, and residual damage from flooding.
Costs Do Not Include	• Direct measure of damage to public infrastructure. • Indirect costs associated with flooding (i.e. delay costs or secondary impacts of loss of critical infrastructure).	• Direct measure of damage to public infrastructure. • Indirect costs associated with flooding (i.e. delay costs or secondary impacts of loss of critical infrastructure).

	REACTIVE ADAPTATION	PROACTIVE ADAPTATION
Avoided Costs Include	• N/A	• Structural damage avoided by coastal flood protection
INLAND FLOODING		
Costs Include	• Structure and content damage from pluvial and fluvial flooding.	• Structure damage from pluvial and fluvial flooding.
Costs Do Not Include	• Damages outside the structure such as vehicles or agricultural land.	• Damages outside the structure such as vehicles or agricultural land.
Avoided Costs Include	• N/A	• One tenth of the damage in the most vulnerable census subdivisions through relocation: moving out of the floodplain.
ROADS		
Costs Include	• Repair costs • Costs of delays due to repairs	• Upfront capital costs of proactive strengthening • Repair costs • Costs of delays due to proactive strengthening and repairs.
Costs Do Not Include	• Routine (non-climate driven) maintenance costs	• Routine (non-climate driven) maintenance costs
Avoided Costs Include	• N/A	• Reduced repair, capital, and delay costs due to proactive strengthening and repairs
RAIL		
Costs Include	• Costs of replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones • Costs of delays that occur due to track buckling and repair, as well as delays associated with blanket speed reductions	• Costs of purchasing, installing, and maintaining the track temperature sensors, and related software infrastructure • Costs of delays associated with risk-based speed reductions
Costs Do Not Include	• Costs of derailment that may result from track buckling • Costs of developing and implementing the speed orders • Costs of routine (non-climate driven) track maintenance	• Costs of routine (non-climate driven) track maintenance
Avoided Costs Include	• N/A	• Delay costs related to track buckling and repair
PERMAFROST THAW		
Costs Include	• Repairing building foundations and repairing cracks in paved roads and runways • Regraveling and regrading gravel roads • Rehabilitating roads • Rebuilding/reconstructing buildings and roads • Relocating	• Repairing building foundations and repairing cracks in paved roads and runways • Regraveling and regrading gravel roads • Thermosiphon installation for buildings • Base upgrades for roads • Rebuilding/reconstructing roads and runways with air-cooled embankments

	REACTIVE ADAPTATION	PROACTIVE ADAPTATION
Costs Do Not Include	• Routine (non-climate driven) maintenance costs	• Routine (non-climate driven) maintenance costs
Avoided Costs Include	• N/A	• Structural damages avoided by thermosiphon and air-cooled embankment installation • Reduced operations and maintenance costs from base upgrades
ELECRICAL GRID		
Costs Include	• Building replacement transformers and transmission ampacity upgrades based on recent climate. • Steel reinforcement of wood poles, as needed, based on recent climate. • Increasing operations and maintenance costs for vegetation management.	• Building replacement transformers and transmission ampacity upgrades based on projected climate. • Steel reinforcement of wood poles, as needed, based on projected climate. • Increasing operations and maintenance costs for vegetation management.
Costs Do Not Include	• Routine (non-climate driven) maintenance costs	• Routine (non-climate driven) maintenance costs
Avoided Costs Include	• N/A	• Expenditures on transformers, transmission lines, and wood poles

2.2 DESCRIPTIONS OF DAMAGE CATEGORIES

This analysis covers damages to the Canadian economy across eight infrastructure categories. In addition, delay cost effects are estimated for roads and rail disruption. In the following paragraphs, we describe the main modeling characteristics of each category. Damage estimates for infrastructure primarily represent the increased costs of protection, repair, or replacement of infrastructure under a changing climate. Damage models for these categories are developed using damage estimates scaled by the regional infrastructure network inventory (i.e., road miles, vulnerable bridges, rail miles, coastal property value, or urban area). Certain categories also include additional costs in damage estimates — roads and rail include the costs of increased travel time associated with service outages. By contrast, the Grid Infrastructure category considers the interaction of electrical grid infrastructure and climate from the opposite angle — damages for this category are the costs associated with repair and replacement of grid infrastructure damaged by increasingly frequent and severe extreme weather, or necessitating replacement due to reduced capacity in higher air temperatures. As both of these categories are directly dependent on demand for electricity, reduced form models are developed based on damages scaled by regional population.

For each category of damages, we apply current data on the size and, where applicable, condition of the infrastructure stock. Although the stock of infrastructure may change over time, the extent of such change is uncertain and, in some cases, will depend on policy changes implemented at different levels of government. Rather than introduce further uncertainty into the analysis in the form of forecasted changes in the infrastructure stock, we use data on current infrastructure to ensure transparency and provide clarity regarding analytic limitations.

In using the current infrastructure stock, we do not attempt to capture how technological change and innovation will affect the vulnerability (and resilience) of infrastructure to climate change over time. As design practices and materials evolve and new technologies are developed, some types of infrastructure may be less (or more) vulnerable to changing climatic conditions. While this may somewhat complicate how policymakers use this analysis to inform strategic or operational decisions, the conclusions drawn from this analysis regarding the cost-reducing impacts of proactive adaptation will still provide important insights into potential opportunities to reduce climate change costs through proactive action. As new technologies come to market and existing technologies evolve, infrastructure managers can assess whether such technologies are likely to diminish (or enhance) these opportunities and prioritize their adaptation actions accordingly.

2.2.1 HOMES, BUILDINGS, AND REAL ESTATE

The **coastal properties** study estimates the potential future property value damages as a result of sea-level rise combined with storm surge attributed to climate change. Damages are estimated for properties (land and structure) in coastal regions. Storm surge damage is modeled based on changes in a historical flood frequency and severity profile, based on local tide gauge data, increased vertically by the extent of relative SLR at that point in the simulation. S**t**ructural damage from storm surge is based on depth-damage functions and storm surge heights. The analysis is completed for each of two adaptation scenarios: proactive adaptation and reactive adaptation. The proactive scenario implements cost-effective adaptation across a broad suite of adaptation options, including beach nourishment, hard structures (back bay or open ocean), and structure elevation, or in cases where adaptation is not cost-effective, abandonment of threatened property. The reactive scenario implements only the elevation and beach nourishment options.

The **inland flooding** study estimates the potential increase in flooding damages as a result of more frequent and severe high river flow events associated with climate change. Damages are estimated using a series of connected simulation models for streamflow estimation, including the process of rainfall concentrating in river valleys to produce high flow events; simplified hydraulic models to translate high flow into an area and depth of flood event around river channels; depth damage functions to forecast damages associated with high flow events; and simplified techniques to forecast the future value of residential and commercial properties.

2.2.2 TRANSPORTATION

The **roads** study estimates the cost of road repair, road construction, and road delays due to degrading road surface quality as a result of climate change. Damages are based the cost of repairs and or delay costs associated with either road shutdowns to complete repairs or deteriorated road surfaces. This analysis considers two adaptation scenarios: reactive adaptation and proactive adaptation. Under the reactive adaptation scenario, repair budgets are increased to repair all damages in a given year, and in the proactive scenario, roads are pre-emptively strengthened to prevent damage. Note that the proactive adaptation results generally reflect a much lower damage estimate overall than reactive costs, but in some scenarios the timing of those costs may be accelerated (and actually be triggered by relatively modest levels of warming) because of optimization of the capital cost of resilience investments and the high payoff to these investments in terms of avoiding future repairs and delays. In these cases damages might be higher in the 2050s than they are later in the century.

The **rail** study estimates repair, equipment, and delay costs due to rail track buckling or the threat/risk of buckling associated with elevated temperatures. The analysis is completed for two adaptation scenarios: proactive adaptation and reactive adaptation. The proactive scenario includes attempts to adopt new technologies to prevent damages (and therefore prevent delays associated with their unexpected need for repair). The reactive scenario considers reduced train speeds at higher temperatures to reduce likelihood of track buckling.

2.2.3 NORTHERN CANADA

Permafrost thaw represents an important climate stressor for Northern Canada that will impose costs on multiple types of infrastructure, including roads, buildings, and runways. The focus of this component is not to develop permafrost projections for site-specific adaptation recommendations, but rather to understand the possible regional and national-level effects of permafrost shifts. We build on the approach developed in Melvin et al. (2017), who develop damage thresholds based on thaw levels, to identify where critical foundation damage is likely to occur. For buildings, roads, and runways located in areas where the critical thresholds are met, we estimate climate change costs under both the status quo and proactive scenarios.

The **winter roads** analysis applies the approach used by IEc in our 2010 analysis for the National Round Table for the Environment and the Economy (NRTEE) (Industrial Economics 2010). Under this approach, we estimate climate change costs for winter roads under the assumption that a winter road is impassable during a given month if the monthly average temperature exceeds -5° C. This reflects the threshold recommended by the Treasury Board of Canada for assessing the stability of winter roads. This approach is applied under both the status quo scenario and the proactive adaptation scenario.

2.2.4 ELECTRICITY AND ENERGY

The **electric transmission and distribution** study estimates damages to the electric transmission and distribution infrastructure, which makes up the electric "grid," due to climate change. This multi-dimensional analysis considers several climate stressors, including extreme temperature, extreme rain, vegetation growth, and coastal flooding. Impact receptors include transmission and distribution lines, poles, and transformers. Monetized damages for this category are the costs of repair or replacement of damaged infrastructure. While certain climate stressors do cause power outages which have associated economic costs, these costs are not included in damage estimates. This analysis considers three adaptation scenarios: proactive adaptation, reactive adaptation, and no-adaptation. Repair or replacement choices vary by adaptation scenario — the no-adaptation scenario models repair and replacement that continues in a business-as-usual fashion, without consideration for a changing climate, reactive adaptation bases decisions on the climate in the moment of repair or replacement, and proactive adaptation plans for projected climates. Repair costs are allocated based on the activity being performed. These activities include: transmission line capacity, tree trimming, wood pole decay, transmission transformer lifespan, and distribution transformer lifespan.

The **hydropower** analysis provides a high level, initial estimate of the potential effects of climate change on hydropower generation. The work follows the general approach of Boehlert et al. (2016), who analyzed the impacts of climate change on U.S. hydropower generation through 2100, using a water systems model with over 2000 river basins and a fairly detailed accounting of the U.S. hydropower system. However, this work involved a significant amount of data and modeling to capture effects at a facility level that were not possible to replicate given the scope of this analysis. Instead, we develop unitless multipliers of annual hydropower generation relative to historical generation for 184 basins across Canada where we have rainfall runoff parameters calibrated from earlier work for NRTEE (Industrial Economics 2010). These relative changes in generation over time are converted to absolute hydropower generation (GWh) by applying the shocks to observed historical generation. Within each basin, all hydropower generation and installed capacity information is lumped into a single representative facility.

CHAPTER 3 | ECONOMIC ANALYSIS: METHODS AND RESULTS

This chapter presents the methods and results of the screening level and process-based analysis of the cost of climate change to Canada's infrastructure. Sections 3.1 to 3.4 of this chapter focus on process-based modeling approaches; and Section 3.5 quantifies delay costs. For the infrastructure categories where multiple adaptation scenarios are available, we present a comparison of results by category across adaptation scenarios. For the screening analysis, tables of average damages by era, category, and region are available in Appendix A.

3.1 HOMES, BUILDINGS, AND REAL ESTATE

This section summarizes the methods and results of the coastal property and inland flooding analyses. Our division of climate risks into coastal and inland components relates to the influence of different climate stressors (sea-level risk and storm surge for coastal, extreme precipitation induced floods for inland). While the two can overlap geographically in coastal areas, we have found that proper estimation of joint risks in these areas can only be accomplished with much more temporally and geographically detailed analysis that is beyond the scope of the current study.

3.1.1 COASTAL PROPERTY

Although much of the development in Canada is concentrated in areas away from the coast (e.g., around Toronto, ON), certain key high-value areas, particular around Vancouver, BC, are at risk to coastal flooding ranging from permanent inundation from sea level rise to less frequent but high impact storm surge events. Stanton et al. (2010) estimates that annual costs range from \$2.6 to \$5.4 billion by the 2020s, and \$7.3 to \$48.1 billion by the 2080s for a "no adaptation" scenario. This work reflects careful and highly spatially resolved modeling of permanent property inundation from sea-level rise, but unfortunately for periodic storm surge damage, relies on an approach which assumes surge of any height would result in total loss/damage of coastal properties (including agriculture and forest lands) as frequently as once per year.[5] The Stanton et al. (2010) approach is inconsistent with contemporary

[5] See text on page 46 of Stanton et al. (2010): "Unlike with sea-level rise damages, which are the annual increase to damaged property, storm-surge damages are the full value of dwellings inundated in each year – as if homes were rebuilt after each flood. In model calculations, storm-surge damage frequency is capped at one per year, based on the assumption that rebuilding of homes could happen no more than once per year. Agricultural and forested lands storm-surge damages follow the same logic – as if the owners of this land paid reclamation costs equal to the value of the land after each flooding (where flooding can occur no more than once each year)." A table follows this text, showing input values for storm surge severity and frequency of up to about 1.2 meters, occurring as frequently as once per year, in some locations. The aggregate economic damage results from Stanton et al. (2010) (page 72 of the report) therefore show storm surge damage two orders of magnitude (approximately a factor of 100 times) in excess of the sea-level rise inundation results, which is inconsistent with other literature and probably not realistic.

analyses of storm surge damage (see JBA Risk (2019) and Neumann et al. (2014), for example), which assess structure damage using depth-damage functions rather than assuming total loss from all floods, and which also provide a mechanism to model abandonment in situations of frequent repeat-loss.

Methods

The objective of this analysis is to provide an estimate of property damage from sea level rise and storm surge risks in the coastal areas of Canada. Absent a detailed inundation model for Canada, we use damage ratio curves, which indicate how damage progresses with sea level rise, from the U.S. National Coastal Properties Model (NCPM).[6] The analysis follows five steps, which are described briefly here. More detail follows.

1. **Pair coastal regions in Canada with U.S. regions:** First we group the coastal areas in Canada into five targeted (smaller) areas and three regions. Each of these are paired to representative U.S. areas that have some similarities in location (and therefore, rate of SLR as well as storm surge exceedance curve) and coastal development and settlement patterns.
2. **Identify sea level rise scenarios and storm surge:** Develop sea level rise estimates for all coastal areas in Canada at the dissemination area level, from NRCan estimates, and assign storm surge heights to our targeted Canadian locations based on the literature.
3. **Estimate an elevation-property value curve:** Estimate the property value at incremental elevation contours for both the U.S. locations and for all dissemination areas in Canada. This is used to develop elevation damage ratio curves (#4) for the U.S. locations and apply those curves to coastal areas in Canada (#5).
4. **Compile damage Ratio Curves for U.S. areas:** Separately for sea level rise and storm surge, calculate the annual damage ratio by sea level, for all U.S. study areas, from the detailed results from Neumann et al. (2014) and recent updates (e.g., USEPA 2017, Lorie et al. 2020). These represent the portion of the annual vulnerable property value that is periodically damaged (from storm surge) or permanently lost (inundation from sea level rise).
5. **Estimate Damages**: Use sea level rise and storm surge from #1, the Damage Ratios by sea level from #4 for the US study areas, and elevation property value curves from #3 to estimate damages.

Pairing coastal areas in Canada with U.S. areas

Impacts to coastal properties from sea level rise and storm surge are particularly site-specific. Local characteristics such as elevation and proximity to tidally influenced waterbodies can greatly affect

Note also that Withey et al. (2015) adopts the Stanton et al. results; no new damage modeling is conducted in Withey, only processing of direct costs through a general equilibrium framework.

[6] It is reasonable to ask whether the JBA Risk Management estimates of the extent of storm surge for various storms (e.g., 100-year, 10-year, etc.) could be useful for this analysis. While these would likely provide some insight into the baseline storm surge damage estimates, they are static in time. The NCPM uses a dynamic and deterministic approach as sea levels rise each year (and, as a result, the storm surge floods reach properties at higher elevations), as well as an approach for estimating costs with cost-effective adaptation.

damage assessments and, in particular, adaptation decisions and effectiveness. It is often the case that damages from coastal flooding vary on small spatial scales. For this reason, deterministic models of the impacts of coastal flooding on properties simulate impacts at near site-level spatial scales like the U.S. NCPM (Neumann et al. 2014). Since building a coastal properties impact model like the NCPM is outside the scope of this project, we rely on results from the U.S. NCPM to provide patterns of damage ratios (damage over vulnerable property) by sea level. These ratios are used alongside value-elevation curves of Canadian coastal properties to estimate costs. To do so, we need to pair Canadian study areas with US areas that are comparable in terms of coastal topography, flooding mechanisms and settlement patterns.

The NCPM is a well-established model, developed over multiple iterations over two decades, that was designed for national-scale analysis of coastal flooding in the Contiguous U.S. (Neumann et al 2014; Lorie et al. 2020). The model determines inundated areas at the 150m grid resolution for each coastal county along a sea level rise trajectory for two types of coastal flood hazards—permanent inundation from sea level rise and storm surge—and estimates property losses and expected damage. Inundation is modeled using a modified bathtub approach that ensures a hydraulic connection as sea levels rise. The model assumes complete loss of structure value once the mean high or higher water level reaches the property, and loss of land value equivalent to a representative inland parcel, thereby implicitly assuming inland transfer of the amenity value of proximity to the coast over time. Storm surge damage is modeled across a portfolio of storm surge heights from the 2- to 500-year event. Damage from surge inundation is determined using a variety of depth-damage curves that depend on structure type. Rather than modeling actual storm surge events, the NCPM uses the probabilities of each event and estimates an average annual expected damage.

To pair coastal areas in Canada with U.S. analogues, we first identify important cities along the coast of Canada that are geographically diverse and where we expect high impacts from sea level rise and storm surge. These are listed in Table 3-1. In general, we pair cities with similar population size, development patterns, and coastal hydrologic characteristics. The rest of coastal Canada is split into three larger geographic regions (see Table 3-2). There are five targeted areas and three regions. The Census Division where each city in Table 3-1 resides for the targeted areas are paired with U.S. counties, while the regions in Table 3-2 are paired with groups of counties in the U.S.

In the Pacific, most of the vulnerable property value is in and around Vancouver, BC. We also include the Province Capital, Victoria, BC. Vancouver and Victoria are paired with nearby U.S. cities on the other side of the Salish sea that have relatively similar populations, property values, and development patterns. For the Atlantic, we selected Halifax in Nova Scotia, Charlottetown on Prince Edward Island, and Quebec City, at the mouth of the St. Lawrence River. Halifax and Charlottetown are paired with cities with similar characteristics in Maine. Since Quebec City is located on the tidally influenced St. Lawrence River, further inland from the open ocean compared to the other sites, we pair it with Albany, NY, which is located further inland on the tidally influenced Hudson River, and is relatively similar in size and development.

For the rest of coastal Canada, we use three broad regions for the pairing. For the Pacific Region, we use the remaining counties in the state of Washington. Coastal areas in Quebec along the tidally influenced St. Lawrence River are separated from the rest of the Atlantic Coast and paired with U.S. counties along the Hudson River, which is also tidally influenced. The Maritime Provinces are grouped with coastal areas in

Quebec east of Quebec City to form the Atlantic Region, which is paired with U.S. Counties in Maine and New Hampshire. Note that other areas of Canada are not modeled, either because relative sea level is expected to fall in those locations; the value of coastal property in those locations, as estimated in Stanton et al. (2010) is relatively low; or both. The modeled areas in Tables 3-1 and 3-2 account for more than 95 percent of the national permanent inundation damages reported in Stanton et al. (2010).[7]

TABLE 3-1. TARGETED STUDY AREAS AND U.S. CITY ANALOGUE

Targeted Study Area	U.S. City Analogue (County listed)
Vancouver, BC	Seattle, WA (King County)
Victoria, BC	Port Angeles, WA (Clallam County)
Halifax, NS	Portland, ME (Cumberland County)
Charlottetown, PEI	Bar Harbor, ME (Hancock County)
Quebec City	Albany, NY (Albany County)

TABLE 3-2. REGION STUDY AREAS AND U.S. REGION ANALOGUE

Region	Provinces Included	U.S. Region Analogue
Pacific	British Columbia	Washington State
Atlantic	Maritime Provinces, Quebec (east of Quebec City)	Maine and New Hampshire
St. Lawrence River	Quebec (west of Quebec City)	Counties in New York State along the Hudson River

Sea level rise scenarios and storm surge

Gridded sea level rise projections from 2006 to 2100 were provided by NRCan at a tenth of a degree for all coastal areas in Canada. The projections start in 2006 with sea levels provided for each decade (2010, 2020, etc.) up to 2100 and are relative to a 1995 mean sea level. These were spatially aggregated to dissemination areas in Canada, where property value information is available. Projections include two greenhouse gas mitigation scenarios—RCP 4.5 and RCP 8.5—and three uncertainty levels—lower, median, and upper.

Historical storm surge heights were gathered from literature sources. Xhai et al. (2015) provides estimates of the 50-year return period storm surge by analyzing 22 tide gauge measurements along the Atlantic Coast of Canada. Similarly, Abeysirigunawardena et al. (2011) developed estimates of storm surge heights for a variety of return periods along the Pacific Coast. Table 3-3 provides a summary of these

[7] As indicated in the introduction to this chapter, we rely solely on the more reliable permanent inundation components of Stanton et al. (2010). We omit consideration of the periodic storm surge results from that work, because they are inconsistent with contemporary storm surge damage estimation methods.

surge heights for a representative 50-year event for the targeted areas and regions. For the targeted areas, we take the average surge height for all gauges in the area and for the regions, we take the average of all gauges in the region. Surge heights in the Atlantic Region are further disaggregated by Province. Generally, 50-year event surge heights are lowest in the Pacific Region, varying from 0.84 to 0.95 meters; highest in the St. Lawrence Region, up to 4.5m; and intermediate in the Atlantic Region, varying from 1.9 to 2.9 meters.

TABLE 3-3. STORM SURGE HEIGHTS FOR THE 50-YEAR EVENT

Target / Region	50-year (m)
Vancouver, BC	0.95
Victoria, BC	0.82
Halifax, NS	1.74
Charlottetown, PEI	2.12
Pacific Region	0.91
Quebec City and St. Lawrence Region	4.45
Atlantic Region	
Prince Edward Island	2.12
Nova Scotia	1.89
New Brunswick	2.94
Quebec - Atlantic	2.66

Elevation-Property Value Curve

The goal of this step is to represent how property values change by elevation and is used to determine the property value vulnerable to sea level inundation or storm surge damage at a variety of elevations. To do this, we combine areas below select elevations with a property value dataset for each Census dissemination area. For the topography, we use the CoastalDEM30 product by Climate Central instead of DEMs available from the Government of Canada, which would require patchwork of LiDAR DEMs of varying resolutions that may not provide a full coastal coverage. CoastalDEM30 is a 1 arcsecond (~30 meter) horizontal resolution digital elevation model that uses satellite radar and machine learning techniques to correct for inaccuracies in the original uncalibrated satellite measurements that significantly reduces biases and errors when comparing with LiDAR measurements (Kulp and Strauss, 2018). This provides a consistent resolution and approach for all coastal areas in Canada with a sufficient vertical resolution for inundation modeling. The DEM is used to calculate the portion of building area in 0.1 m contours of elevation above sea level for all dissemination areas using spatial analysis tools. For building footprints, we use the Canadian Building Footprints dataset developed by Microsoft in collaboration with StatCan.[8]

It is important to note that the NCPM includes an initiation period that effectively determines existing protection. In order to compare across various adaptation scenarios, it is important for the model to start

[8] https://github.com/Microsoft/CanadianBuildingFootprints

from a common and stable state. Effectively, this means that the NCPM must use a potentially aggressive, economically optimal adaptation build simulation for existing protection, a likely overestimate of existing protection for all simulations, even one without adaptation. As a result, estimates from the NCPM are likely an underestimate of costs. For this baseline adaptation simulation, we assume no property value should be present at elevations below 0.5m above the mean higher high water level, which is the typical NOAA minor flood (or "nuisance" flood) level for U.S. coastal areas (Sweet et al. 2018). Minor flood events typically impact traffic on roadways or underground infrastructure and rarely damage valuable property, at least at current sea levels.

The 2016 Census provides the average of the self-reported residential dwelling value for each dissemination area as well as the number of dwellings. These values include both property and structure. While sea level rise impacts include the loss of structure and land value, storm surge only affects structures in the NCPM (damage to land from episodic flooding is not considered). Structure values are decoupled from land value using the representative ratios of building value to total value, estimated from the data available. For urban areas, we apply estimates of decoupled assessed values from Vancouver and Kamloops (~36 percent attributed to structure by averaging portion from the two cities) and for rural areas we use the average ratio from a USEPA analysis of coastal flood risks (USEPA 2017) (~50 percent attributed to structure).

Similarly, non-residential value is estimated using the ratio of residential value to total value of all property uses (including, e.g., commercial, institutional, and industrial value). Urban areas are assigned the average ratios from four cities in Canada with detailed value assessments (56 percent residential)—namely, Vancouver, Calgary, Regina, and Kamloops—and rural areas are assigned the average ratio from the U.S. used in USEPA 2017 (69 percent residential). Content damages are assumed to be valued at an additional 50 percent of the structure damage for residential structures and 100 percent of the structure damage for commercial structures. This assumption is used in the FEMA HAZUS Flood Technical Manual.[9] Also, we use a housing price index from Statistics Canada (Table: 18-10-0205-01) to convert from 2016 CAD to 2015 CAD.

Property values below each 0.1 m elevation contour are estimated by calculating the proportion of total dissemination area building area below each contour. The total property value in the dissemination area is then scaled by that proportion to give the property value below the contour. Table 3-4 shows the total property value in each province in the model, as well as values below 1 and 2 meters using the methods described above. Note that because this assessment depends on U.S. estimates of damage, we restrict the model to the area within 400km of the U.S. border as areas further north cannot be assumed to have coastal geographies and settlement patterns that are analogous to those in the U.S.

[9] Available online at www.fema.gov/plan/prevent/hazus – see Table 14.6.

TABLE 3-4. PROPERTY VALUES (BILLIONS OF 2015 CAD)

Province	Total Property Value	Value below 1m	Value below 2m
British Columbia	$1,226	$20.06	$73.44
New Brunswick	$53	$0.28	$1.37
Nova Scotia	$74	$0.27	$1.35
Prince Edward Island	$11	$0.05	$0.33
Quebec	$847	$0.07	$0.63

In the following assessment, we follow the convention used in the NCPM by assuming permanent inundation from sea level rise results in complete loss of both structure and land value while flooding from storm surge only damages the structure.

Damage Ratios Curves for U.S. areas

Damage ratios curves provide a mapping between incremental sea level changes and damage as a portion of vulnerable property. The general equation for the Damage Ratio (DR) is simply

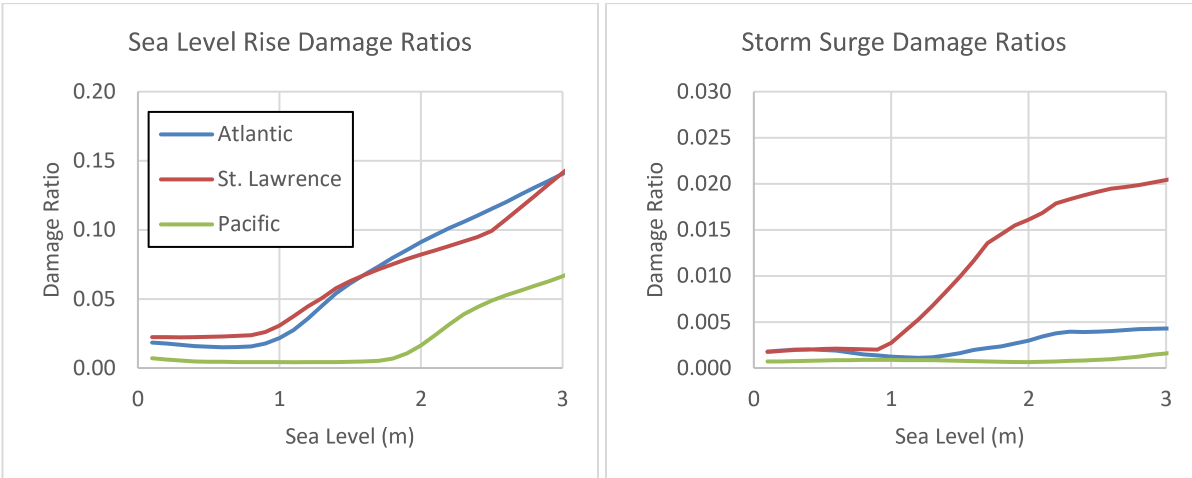
$$DR = (Damage)/(Vulnerable\ Property)$$

where *DR* is the damage ratio at specified relative sea level changes, *Damage* is the damage from changes in sea level from either permanent inundation or storm surge, and *Vulnerable Property* is the sum of all property value that is estimated differently for permanent inundation than for storm surge flooding.

For permanent inundation the *Damage* is the sum of all abandoned property loss and the *Vulnerable Property* is the sum of value below the current sea level for each year of sea level rise. For storm surge, the *Damage* is the annual flood damage from storm surge. Since storm surge primarily impacts properties between the sea mean sea level and the height of the surge, we calculate *Vulnerable Property* using the value between the sea level and the surge height of the 50-year event, which matches what is available for across Canada.

As an example, Figure-3-1 shows damage ratios from permanent sea level rise and annual storm surge damage for the three regions. With a simple bathtub approach and without consideration of existing protection, damage ratios from sea level rise would be 1. Since the NCPM uses the modified bathtub approach and an estimate of existing protection, ratios are less than one. Ratios are generally higher as sea levels increase as existing protection becomes less viable. The storm surge damage ratios are more complex because damages in the NCPM are based on depth-damage functions across a range of surge events and associated likelihood.

FIGURE 3-1. DAMAGE RATIOS FOR PERMANENT INUNDATION FROM SEA LEVEL RISE (LEFT) AND ANNUAL STORM SURGE DAMAGE (RIGHT) FOR THE THREE REGIONS



Estimate Damages

The damage for Coastal areas in Canada with this approach is estimated by solving for the *Damage* in the *DR* equation above, using the product of the Damage Ratio Curve from the U.S. analogue areas and the Property Elevation Curve from each Census Subdivision in Canada. The same definitions for the property that is vulnerable to either permanent inundation or surge flooding also apply here.

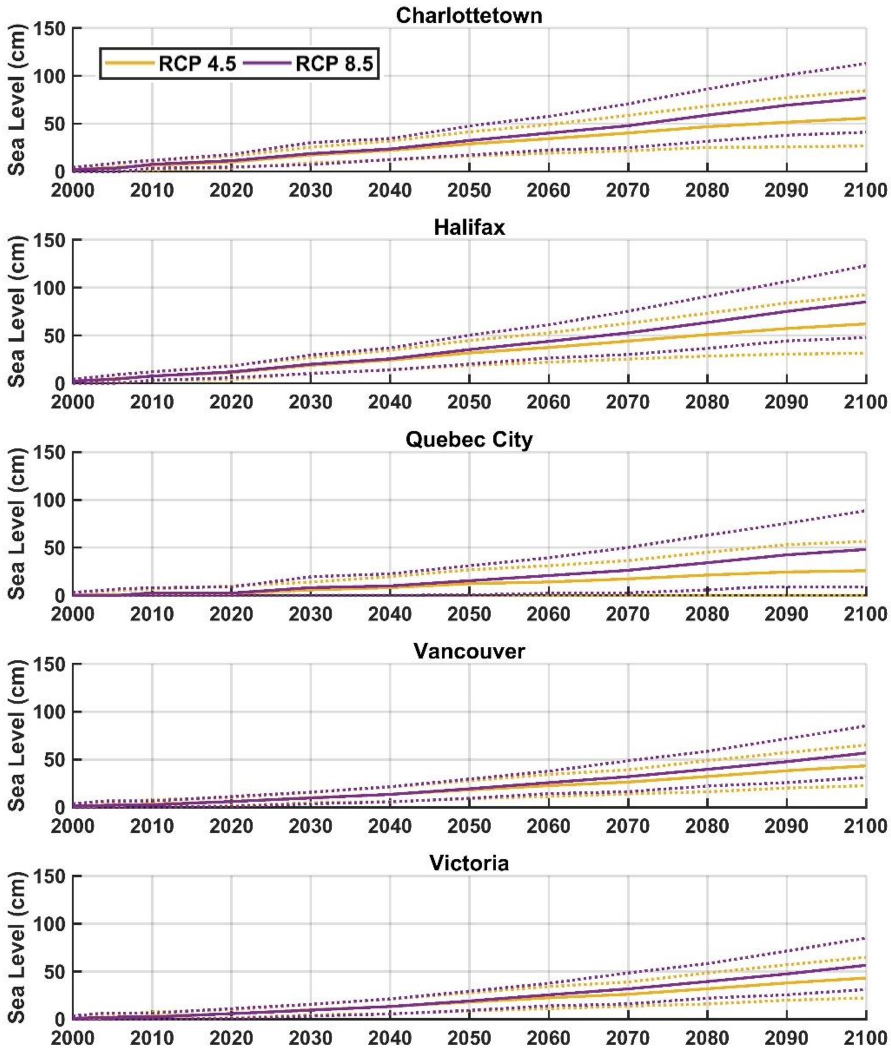
Results

The following section shows the results from the analysis starting with the sea level rise scenarios for target areas followed by costs across the scenarios, eras, and impact types (sea level rise and storm surge).

Sea level rise scenarios

Figure 3-2 shows the relative sea level rise scenarios (which incorporate the net effect of both land subsidence/uplift, and local sea level changes) for five target areas. For all target areas, differences between RCP4.5 and RCP8.5 by 2050 are less than 5cm, which is typical of sea level rise scenarios, where the mitigating benefits of GHG emissions reductions are more pronounced later in the century. Most scenarios are well below 1 meter of rise although the Upper scenario of RCP8.5 does rise above 1 meter by the 2090s for Halifax and Charlottetown, which have the highest projections. The median projections for Halifax and Charlottetown reach above 50cm by the end of the century for RCP4.5 and above 75cm for RCP8.5, while the range of the upper and lower projections are about 60cm for RCP4.5 and slightly higher for RCP8.5 at about 70cm. While the median projections for Quebec City are lower than the Atlantic sites, reaching about 26cm in RCP4.5 and 48cm in RCP8.5, the range across the upper and lower scenarios is comparable at 56cm for RCP4.5 and 80cm for RCP8.5. The Pacific sites have smaller differences between RCPs, with the median reaching 43cm for RCP4.5 and 57cm for RCP8.5. The upper and lower scenarios range from 23cm to 65cm for RCP4.5 and 41cm to 85cm for RCP8.5.

FIGURE 3-2. SEA LEVEL RISE SCENARIOS FOR THE FIVE TARGET AREAS. SOLID LINES SHOW THE MEDIAN AND THE DOTTED LINES SHOW THE LOWER AND UPPER SCENARIOS.



Costs from sea level rise and storm surge

Figure 3-3 shows the national annual costs of permanent inundation from sea level rise, plus total costs (including baseline) for episodic storm surge damage. Baseline costs (i.e., before sea level rise starts) from storm surge are roughly 57 million CAD / year, which are included in the costs shown. In the 2050s era, median costs are $131 and $146 million/year, which is about $73 and $88 million/year above the baseline for RCP4.5 and RCP8.5, respectively. Annual costs range from $86 to $203 million across the upper and lower bound for RCP4.5 and are slightly larger for RCP8.5 ranging from $97 to $280 million. While the lower and median costs only increase marginally from the 2050s to the 2080s for RCP4.5, the upper scenario reaches $700 million /year. RCP8.5 2080s median annual costs are roughly triple the 2050s cost at $450 million and range from $210 million to $1.1 billion across the lower and upper scenarios indicating a signficant greenhouse gas mitigation benefit in both the costs and as a reduction in the uncertanty of damage in the later half of the century.

FIGURE 3-3. NATIONAL ANNUAL COSTS ($MIL 2015 CAD) WHERE THE BLACK DOTS SHOW THE MEDIAN SCENARIO COSTS AND THE BOXES SHOW THE RANGE OF THE UPPER AND LOWER SCENARIOS

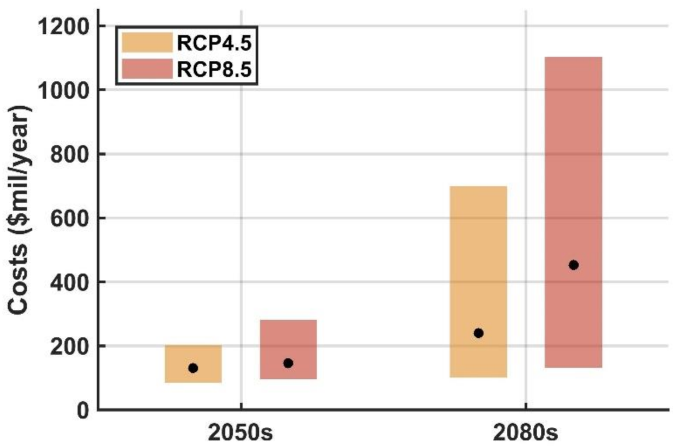
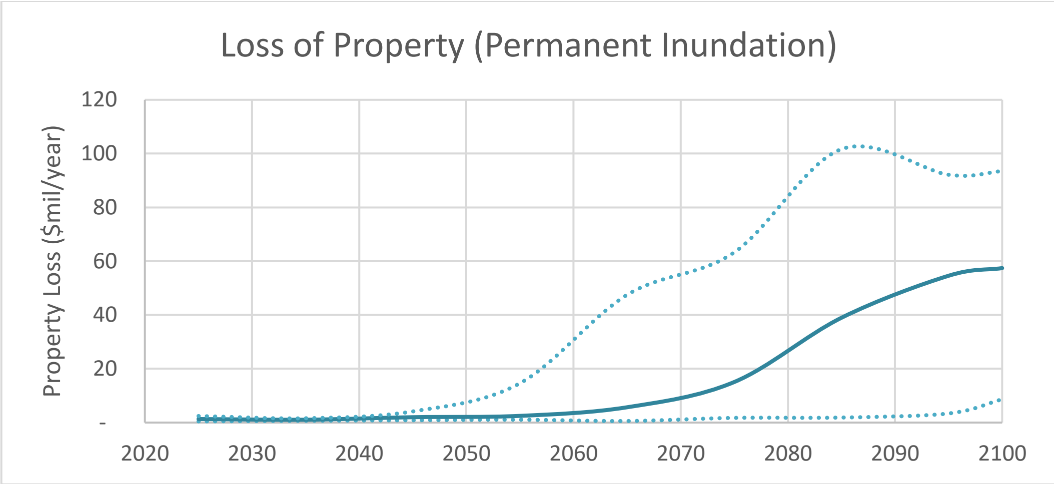


Figure 3-4 shows the annual property loss from permanent inundation (top) and annual storm surge damage (bottom) for RCP 8.5. Sea level rise is a small portion of the total costs in all scenarios until around 2060. After that, sea level rise costs rise rapidly for the upper sceanario, rising above $100 million / year in the 2080s. The median starts to rise quickly around 2075 reaching $57 million/year by the end of the century. The lower scenario never rises above $9 million/year. Storm surge accounts for over 90% of the total costs for all scenarios and years, with 2050 costs ranging between $97 and $226 million / year and end of century costs ranging from $160 million/year to $1.1 billion/year and a median of $750 million /year.

FIGURE 3-4. NATIONAL ANNUAL COSTS ($MIL 2015 CAD) FROM PERMANENT INUNDATION (TOP) AND STORM SURGE DAMAGE (BOTTOM) SHOWING THE MEDIAN (SOLID LINE) AND UPPER AND LOWER SCENARIOS (DOTTED LINES) FOR RCP 8.5



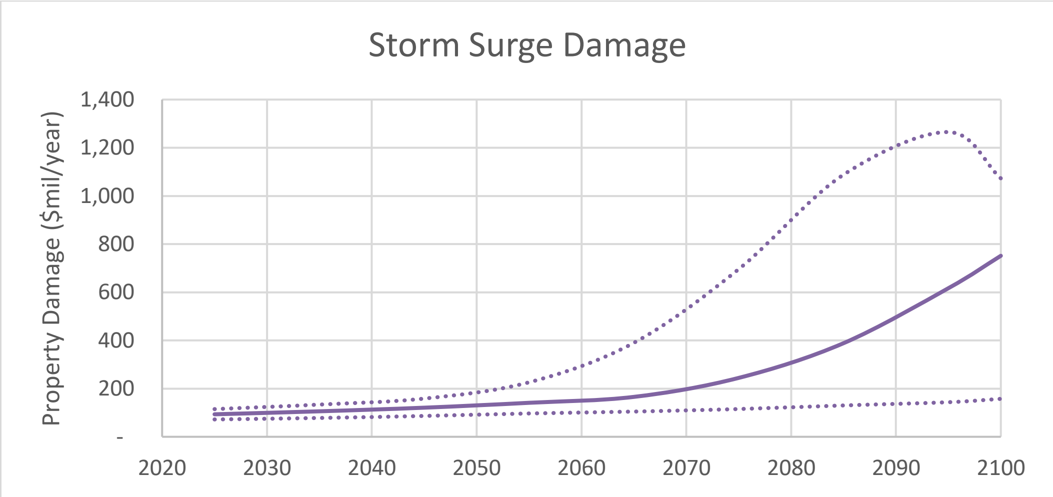


Table 3-5 shows the total annual costs per era for each province. The values inside the parentheses show the lower and upper scenarios, respectively. As British Columbia accounts for about 95 percent of the total value below 2 meters, it is not surprising that British Columbia has the highest costs in all scenarios and eras, including the baseline. However, due in part to lower sea level rise projections and storm surge heights for British Columbia, damages only make up about 30 to 47 percent of total annual costs for 2050 across all scenarios. By the 2080s, annual costs span across a large range from $38 to $766 million. For the upper scenario, RCP 8.5 British Columbia accounts for 70 percent of the national costs suggesting significant uncertainty in the later half of the century.[10] The areas along the Atlantic Coast have higher

[10] For their most extreme scenario (corresponding to the older A2 SRES GHG scenario) Stanton et al. (2010) estimate that British Columbia accounts for about 55 percent of permanent inundation damage, and 95 percent of total damage from SLR and storm surge.

costs relative to vulnerable property (value below 2 meters) because of higher sea level rise scenarios and storm surge heights. New Brunswick, which only accounts for 1.8 percent of the total property below 2 meters accounts for about 19 to 27 percent of the national costs for all eras and scenarios except the three highest in the 2080s. Nova Scotia and Prince Edward Island are similar. Nova Scotia, with about 1.8 percent of the value below 2 meters, represents 16 to 24 percent of national annual costs for the majority of scenarios and eras; and PEI accounts for 0.4 percent of the value below 2 meters but represents 5 to 6 percent of the national annual costs in most scenarios. Vulnerable property value in Quebec represents about 0.8 percent of the total and accounts for 5 to 17 percent of national costs across all scenarios and eras. Most of the costs in Quebec are from storm surge damages in areas along the St. Lawrence, which have the highest surge heights.

TABLE 3-5. ANNUAL COSTS (MILL 2015 CAD) BY PROVINCE FOR THE BASELINE AND FUTURE ERAS (TOP VALUES ARE THE GCM MEAN AND VALUES IN THE PARENTHESES ARE THE RANGE ACROSS GCMS)

Province	Baseline	2050s		2080s	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
British Columbia	$26	$39 ($33 - $77)	$43 ($34 - $132)	$115 ($38 - $479)	$276 ($43 - $766)
New Brunswick	$13	$33 ($23 - $45)	$37 ($24 - $52)	$46 ($27 - $80)	$63 ($34 - $121)
Nova Scotia	$11	$29 ($20 - $39)	$32 ($22 - $45)	$41 ($25 - $74)	$59 ($32 - $105)
Prince Edward Island	$3	$8 ($5 - $10)	$9 ($5 - $13)	$11 ($6 - $19)	$16 ($8 - $31)
Quebec	$4	$22 ($5 - $32)	$25 ($12 - $38)	$27 ($5 - $48)	$39 ($15 - $79)
National	**$57**	**$131 ($86 - $203)**	**$146 ($97 - $280)**	**$240 ($101 - $700)**	**$453 ($132 - $1,102)**

Table 3-6 shows the number households impacted and the annual costs per household across eras and RCPs for the median sea level rise scenario. Note that the household counts include the households in dissemination areas at elevations below the 50-year storm surge height, adjusted by the sea level rise of each year and scenario. Nationally, the number of households impacted increases from 95 thousand in the baseline to 164 and 174 thousand by the 2080s for RCP4.5 and RCP8.5, respectively. Costs per household are $604 in the baseline but increase by more than 4-fold by the 2080s under RCP8.5. British Columbia has the highest number of households impacted in all scenarios. Quebec has the second lowest number of households impacted in the baseline but the second highest in all future eras and scenarios. While sea level rise projections are some of the lowest along the St. Lawrence River in Quebec, storm surge from extreme events are the highest. While higher-valued properties near the St. Lawrence River are relatively safe in the baseline period, increases in storm surge height, driven by even small increases in sea level, start to damage these properties as early as the 2040s.[11]

In the baseline, impacts per household are highest in Nova Scotia and Quebec. While the costs in Quebec per household decline from the increases in the number of households impacted, the costs per household in Nova Scotia remain the highest of all provinces except for RCP8.5 in the 2080s era. While total costs are highest in British Columbia, those costs are spread over a larger number of households than in other provinces resulting in a lower cost per household in the 2050s era. In the 2080s era, costs rise higher for British Columbia than the number of households with costs per household reaching almost $4,000 / year for RCP8.5.

TABLE 3-6. ANNUAL NUMBER OF HOUSEHOLDS ("HHs" IN TABLE) IMPACTED AND COSTS (2015 CAD) PER DWELLING ("$/HH" IN TABLE) FOR THE MEDIAN SEA LEVEL RISE SCENARIOS

Province	Baseline		RCP4.5 - 2050		RCP8.5 - 2050		RCP4.5 - 2080		RCP8.5 - 2080	
	HHs	$/HH	HHs	$/HH	HHs	$/HH	HHs	$/HH	HHs	$/HH
British Columbia	45,891	$577	57,780	$676	59,151	$732	65,628	$1,757	69,738	$3,957
New Brunswick	25,332	$531	27,698	$1,201	28,048	$1,316	29,016	$1,587	30,186	$2,094
Nova Scotia	12,406	$857	14,609	$1,984	14,894	$2,179	15,583	$2,622	16,387	$3,615
Prince Ed. Is.	5,068	$569	6,235	$1,216	6,420	$1,335	6,903	$1,579	7,482	$2,073
Quebec	6,489	$624	46,004	$472	46,836	$528	47,510	$575	50,255	$776
NATIONAL	95,186	$604	152,327	$857	155,348	$940	164,641	$1,460	174,047	$2,602

Table 3-7 shows the annual costs for the target areas, which are Census Divisions that include the city listed. Greater Vancouver includes 93 percent of the total value below 2 meters in Canada and has the highest overall costs of all Census Divisions across all scenarios and eras. On the lower end, costs are just above $30 million / year and on the higher end they reach almost $760 million / year. Quebec City and Victoria both have low costs overall at about $1 million / year. The ranges across the upper and lower scenarios for these two target areas are relatively small compared to other target areas because of low sea level rise projections and relatively flat elevation-value curves. Charlottetown, which lies in the Census Division with the lowest total property value of the five target areas, has the third highest costs of the target areas and fourth highest of all Census Divisions suggesting a significant burden to the area. Halifax is the Census Division with the third highest costs overall (Gloucester, NB is the second) where costs tripple from the baseline in the 2050s era and are 4 to 6 times higher in the 2080s era.

[11] This may also be an artifact of the NCPM's approach to estimating the effectiveness of existing protection discussed previously. Meaning that, it may be the case that existing protection, which will have the most impact to the baseline period, causes an underestimate of baseline storm surge damage.

TABLE 3-7. ANNUAL COSTS (MILL 2015 CAD) FOR THE TARGET AREAS FOR THE BASELINE AND FUTURE ERAS (TOP VALUES ARE THE GCM MEAN AND VALUES IN THE PARENTHESES ARE THE RANGE ACROSS THE UPPER AND LOWER SCENARIOS)

Target Area	Baseline	2050s		2080s	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Charlottetown	$1.5	$4.6 ($3.1 - $6.4)	$5.2 ($3.3 - $7.6)	$6.7 ($3.8 - $12.4)	$9.8 ($4.9 - $19.5)
Halifax	$4.0	$11.4 ($8.0 - $15.1)	$12.7 ($8.7 - $17.9)	$16.2 ($9.9 - $30.3)	$24.1 ($12.7 - $40.8)
Quebec City	$0.0	$1.3 ($0.0 - $1.3)	$1.3 ($1.3 - $1.3)	$1.3 ($0.0 - $1.3)	$1.3 ($1.3 - $1.3)
Vancouver	$24.8	$37.2 ($31.0 - $75.1)	$41.3 ($31.9 - $129.5)	$113.2 ($35.8 - $475.4)	$273.4 ($41.4 - $760.5)
Victoria	$0.9	$0.9 ($0.9 - $0.9)	$0.9 ($0.9 - $1.0)	$0.9 ($0.9 - $0.9)	$0.9 ($0.9 - $0.9)

Adaptation

We apply the same approach described above using results from a simulation of least-cost decisions based on a benefit cost test performed for each grid cell on an annual basis for sea level rise and on a decadal basis for storm surge. The cost-benefit test in the NCPM compares an estimate of discounted avoided damages over the next 30 years with the cost of each adaptation option. The decision rule is based on an estimate of expected annual damages and expected annual benefits of adaptation, and assumes a 3% annual discount rate, consistent with estimates of the real social rate of time preference for individuals who might be in the position to make a decision to protect or abandon a property. The costs of adaptation include initial capital costs as well as annual maintenance costs. The benefits of adaptation include the avoided damages that would likely occur without protection. Note that discounting of expected benefits of protection, and expected costs of protection, is used in the decision rule to allow the model to select the lowest-cost adaptation option, where the expected annual benefit exceeds the cost of that option. This represents a traditional cost-benefit test for optimal risk-reduction investment at an individual property level. The model results, however, represent the outcome of implementing that decision – the model results themselves are presented as undiscounted.

Grid cells with higher benefits than costs are protected and protection costs, including annual maintenance costs are tallied for the remainder of the simulation. Properties can be protected by hard structures like sea walls, which protects from sea level inundation and storm surge up to the 100-year surge height, elevation of structures, which protects from storm surge only, and beach nourishment, which is similar to hard structures but is only effective up to a certain height. Hard structures and nourishment protect not only the properties but are also built to protect properties further inland. The costs of protection are estimated by site-specific characteristics like if the property is in the back bay or ocean facing, which requires additional costs for sea walls to protect from wave action, or the building density, which affects the cost of elevating those buildings. The model chooses the protection type that is the cheapest for that grid cell.

A detailed model like the NCPM is not available for Canada, so we apply a similar model transfer for protection costs and adaptation effectiveness used in the preceding analysis, but using the proactive adaptation results from NCPM application.in U.S. cities. This involves using cost-elevation curves to estimate the protection costs, similar to those for loss and damages shown in Figure 3-1, and the study site pairings discussed above.

Table 3-8 shows annual costs (in millions) for each province with adaptation. Nationally, adaption reduces annual costs between 45 percent for lower sea level rise scenarios and 88 percent for higher sea level rise scenarios. Costs are roughly reduced by half by the 2050s era for most provinces except British Columbia where adaptation reduces costs by about 20 percent for the lower and median scenarios but by 50 percent and 70 percent for the upper scenario under RCP4.5 and RCP8.5, respectively. The relative benefits of adaptation become more apparent in the 2080s era, reducing costs by 60-80 percent in most cases. Note that these results are more dependent on the U.S analogue sites because the process of estimating these costs are more complex and depend on more site-specific characteristics.

TABLE 3-8. ANNUAL COSTS (MILL 2015 CAD) FOR THE ADAPTATION SCENARIO FOR THE FUTURE ERAS (GCM MEAN, VALUES IN PARENTHESES ARE THE RANGE ACROSS GCMS)

	2050s		**2080s**	
Province	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
British Columbia	$32 ($25 - $38)	$33 ($26 - $40)	$40 ($30 - $49)	$45 ($34 - $58)
New Brunswick	$14 ($9 - $18)	$15 ($9 - $19)	$11 ($11 - $20)	$19 ($14 - $22)
Nova Scotia	$12 ($8 - $15)	$14 ($9 - $17)	$10 ($10 - $17)	$17 ($14 - $20)
Prince Edward Island	$4 ($2 - $5)	$4 ($3 - $5)	$3 ($3 - $6)	$6 ($4 - $7)
Quebec	$10 ($2 - $14)	$11 ($6 - $17)	$2 ($2 - $19)	$17 ($7 - $23)
National	**$71 ($47 - $90)**	**$78 ($53 - $97)**	**$56 ($56 - $111)**	**$104 ($72 - $130)**

Main takeaways

The main takeaways from this analysis are:

- Results indicate that costs are relatively low compared to other damage categories considered in this study by the 2050s but rise significantly under the upper scenario by the 2080s. This suggest that costs are sensitive to higher sea levels, including those in the mid-century period that are less likely but still within the uncertainty bounds.
- Costs are concentrated in specific local coastal communities such as those in the Maritime Provinces where costs are high relative to average costs in other less vulnerable locations. Sea

level rise projections are especially high in these areas along with a high number of low-lying properties that are at risk.

- Permanent inundation to property from sea level rise is not a major threat nationally until later in the century and primarily under higher end sea-level rise scenarios. Storm surge, however, is a significant threat currently and will likely worsen without investments in property protection or well-planned managed retreat.
- Although sea level rise projections and storm surge heights are lower on the Pacific Coast, Greater Vancouver contains 94 percent of the total property value potentially vulnerable to coastal damage. It is likely that most of the higher value buildings and property could be protected but some communities may need to be relocated.
- Adaptation is extremely effective in reducing costs for most provinces, especially those in the East where costs are about 5 to 7 times lower based on cost-effectiveness in similar analog locations in the Eastern U.S. In British Columbia, adaptation may be less effective for most scenarios but does reduce costs significantly for the high-end scenarios indicating a significant reduction in uncertainty.

Limitations and Caveats

The major caveats and limitations to this approach are noted below.

- As mentioned, developing a detailed inundation model is outside the scope of this analysis so we use analogue US areas to fill in the relationship between damage and vulnerable property for each incremental increase in sea level. While we attempt to model the effect of local features using a damage ratio, built into the costs from the U.S. sites are site-level attributes such as existing protection, local topography and settlement/development patterns that are not necessarily representative of the Canadian coast and property development.
- The 2016 Census provided average residential home value estimates provided by the census participants. From that we derive non-residential value and decouple structure value from the total value using ratios from four cities in western Canada as well as ratios derived from the U.S. While these two property value adjustments provide required data to estimate comprehensive effects, and to recognize intermittent flooding impacts on structures alone exclusive of land, actual ratios of structure value to total value throughout the full Canadian spatial domain likely differ in an unknown manner.
- The building footprint database provides important information for distributing property value for the elevation-value curves, yielding a more accurate estimate of property potentially vulnerable to flooding or inundation. We find that in coastal areas, buildings are typically concentrated in areas that are outside zones regularly flooded under current or historic climatic and sea-level conditions. With sea level rise, however, these areas that have proven to be safer historically can experience high levels of damage in the latter half of the century without aggressive protection plans. We have also found that estimates generated with simplifying assumptions that do not take into account building footprint location data, such as uniform allocation of property value across dissemination areas, result in biased estimates, including overestimation of damage in nearshore areas historically flooded, and underestimation of damage in higher elevation areas where building data indicate clustering of property value.

- The U.S. NCPM estimates the locations of existing protection by simulating a least-cost build strategy. While this provides a necessary starting point for comparisons across protection strategy scenarios, it is likely an overestimate of existing protection, which results in a conservative estimate of damages throughout the century. The conservative nature of the NCPM likely propagates to this estimate for Canada, especially without adaptation.
- Simulating adaptation effectiveness ideally requires a detailed coastal inundation model, built to be reliable at the project scale. We include an estimate of the effects of adaptation, which relies heavily on U.S. site analogues, but there is more uncertainty in this estimate than the estimate without adaptation due largely to the complexity of the adaptation process which is both path-dependent and includes a least-cost adaptation decision tree to simulate the potential cost-effectiveness of adaptation projects.

3.1.2 INLAND FLOODING

Flood events pose the highest risk to properties than any other weather-related disaster in Canada (Burn and Whitfield 2015) and water-related losses have surpassed fire and theft as the principal source of property insurance claims (Public Safety Canada 2015). Land use change and climate change threaten to worsen this risk in the future. The Disaster Financial Assistance Arrangements (DFAA) reports substantial increases in liabilities from 2009 to 2015 with an annual average of $2.4 billion in damages from non-hurricane flood events, which is about half the total costs that also include hurricanes, winter storms, and convective storms (PBO 2016). No comprehensive analysis of increased inland flooding risk from climate change has been conducted at the national scale, but regional and local analyses suggest that risks will increase. Roy et al. (2001) evaluate changes in seasonal floods in the Châteauguay River Basin in southern Quebec for 24-hour events run through a hydrology-hydraulics model. They find significant increases in extreme flows between 2 and 3 times historical flows for the 20- and 100-year events, which result in a 250 percent increase in flood depths. Thistlethwaite et al. (2018) use the G-CAT flood model (Guy Carpenter 2015) to evaluate flood risks in Halifax, Nova Scotia. They find that damage from a 100-year flood would increase from $7 million CAD to $67 million in a world with 4 °C of warming globally by 2100 and that average annual losses increase to three times the baseline costs.

Methods

The objective of the analysis is to estimate changes in future flood damages from climate change across Canada given the available data and resources. The analysis follows four overall steps, which are described briefly here. More detail follows.

1. **Calculate baseline period damages:** Estimating baseline damage is the backbone of the analysis as the projected damages are meant to provide a nudge or shift from the baseline. This step is data driven and relies primarily on three datasets: detailed map of Annual Damage Ratios (ADRs) from flood catastrophe models obtained from JBA Risk Management; a geolocated building footprint database; and self-reported home value data collected for the 2016 Census and aggregated to dissemination areas.
2. **Estimate distributions of extreme precipitation events:** Future projected damages from climate change are scaled using shifts in the statistical properties of extreme-value precipitation. This step

estimates those shifts in statistical properties by fitting an extreme value distribution to maximum annual 24-hour precipitation for both the baseline and future eras.

3. **Calibrate damage curves to fit baseline ADRs:** Relying on the baseline ADRs from JBA, this step calibrates four precipitation-driven damage functions, address both residential and commercial as well as both fluvial and pluvial flood events.
4. **Estimate future damages:** Projected ADRs are estimated by multiplying the damage curve from step 3 and the distributions of extreme precipitation from Step 2, which provides estimates of annual damage ratios for each projection and the two future eras. Damages are then calculated by multiplying structure and content value by the projected ADRs.

Pluvial flood (from rainfall, usually locally) and fluvial floods (from rivers) are evaluated differently using spatial scales that better represent the contributing area. Fluvial flooding is evaluated across 184 basins in Canada and pluvial flooding is evaluated with a half-degree grid. While flood events are likely to occur on smaller spatial scales, the GCMs that provide the drivers of change in precipitation patterns and statistics run at larger spatial scales. As such, river basins and half degree grids provide a comfortable balance between the scale of the impact and the scale of the projection. Figure 3-5 shows the basins and dissemination areas across Canada and Figure 3-6 shows the same for Southern Ontario with the half-degree grids overlaid, including a map of an area in Toronto with ADRs (in blue) and the building footprints.

FIGURE 3-5. BASINS AND DISSEMINATION AREAS IN CANADA

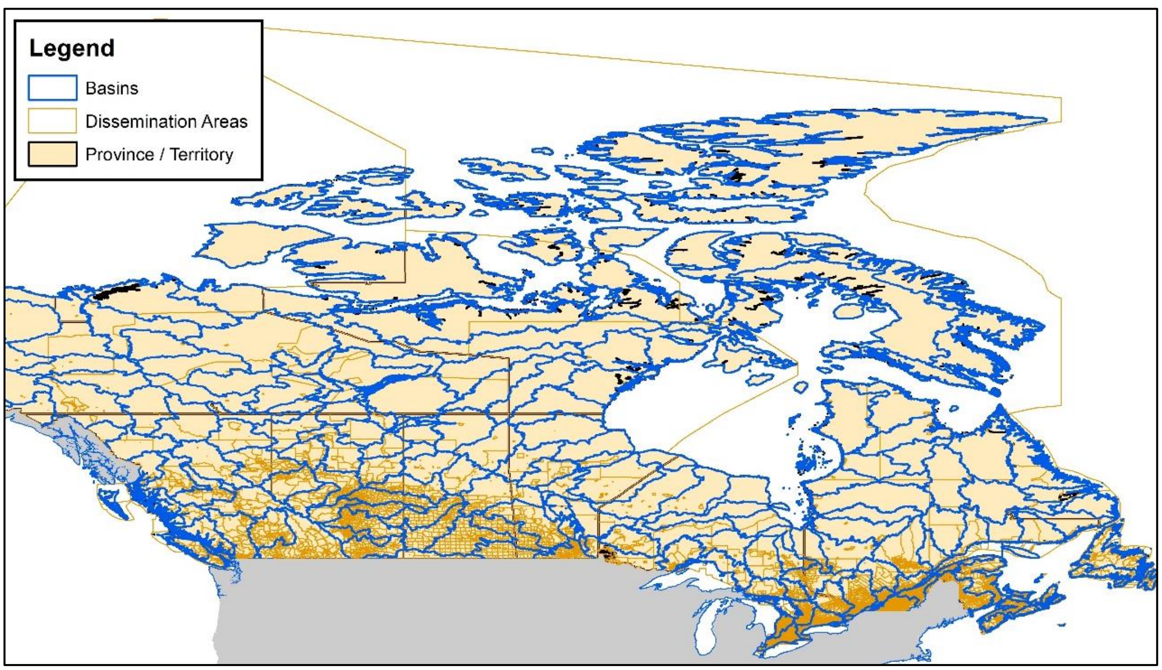
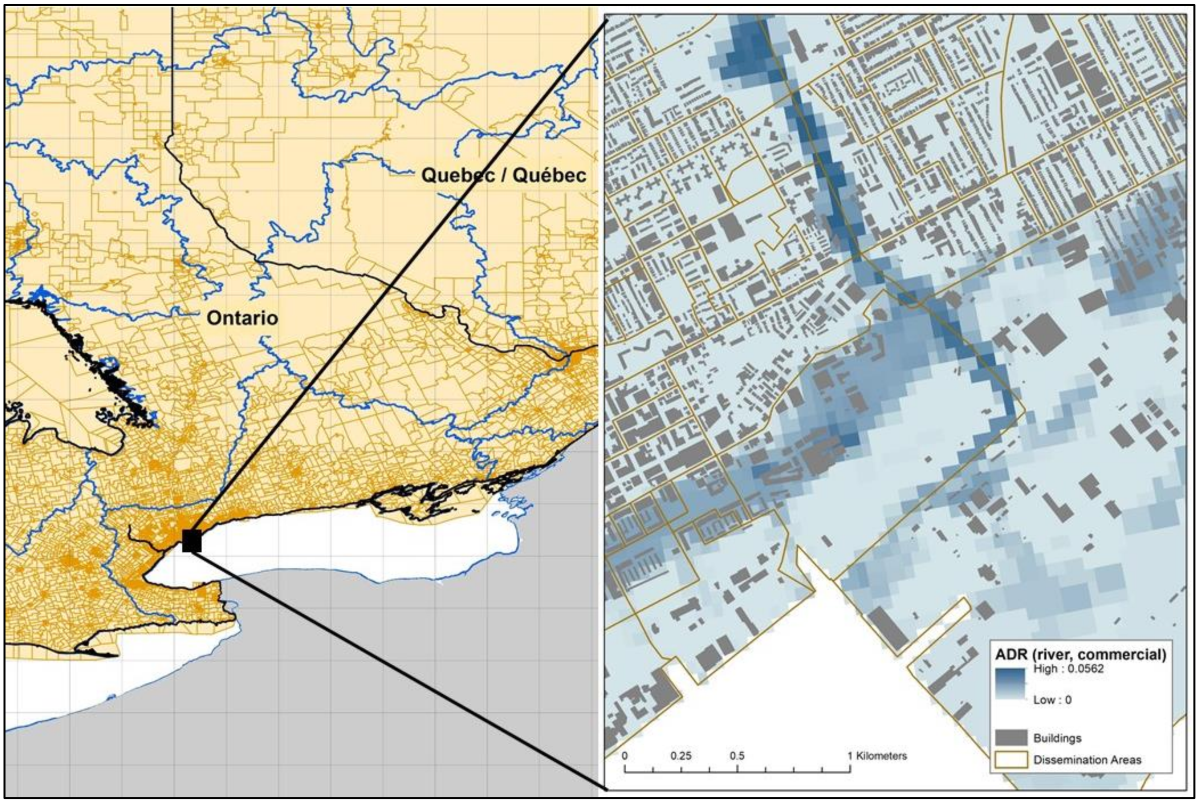


FIGURE 3-6. BASINS, DISSEMINATION AREAS, AND HALF DEGREE GRIDS (GREY LINES) IN SOUTHERN ONTARIO, AND AN AREA IN TORONTO (RIGHT) WITH ADRS AND THE BUILDING FOOTPRINT DATA



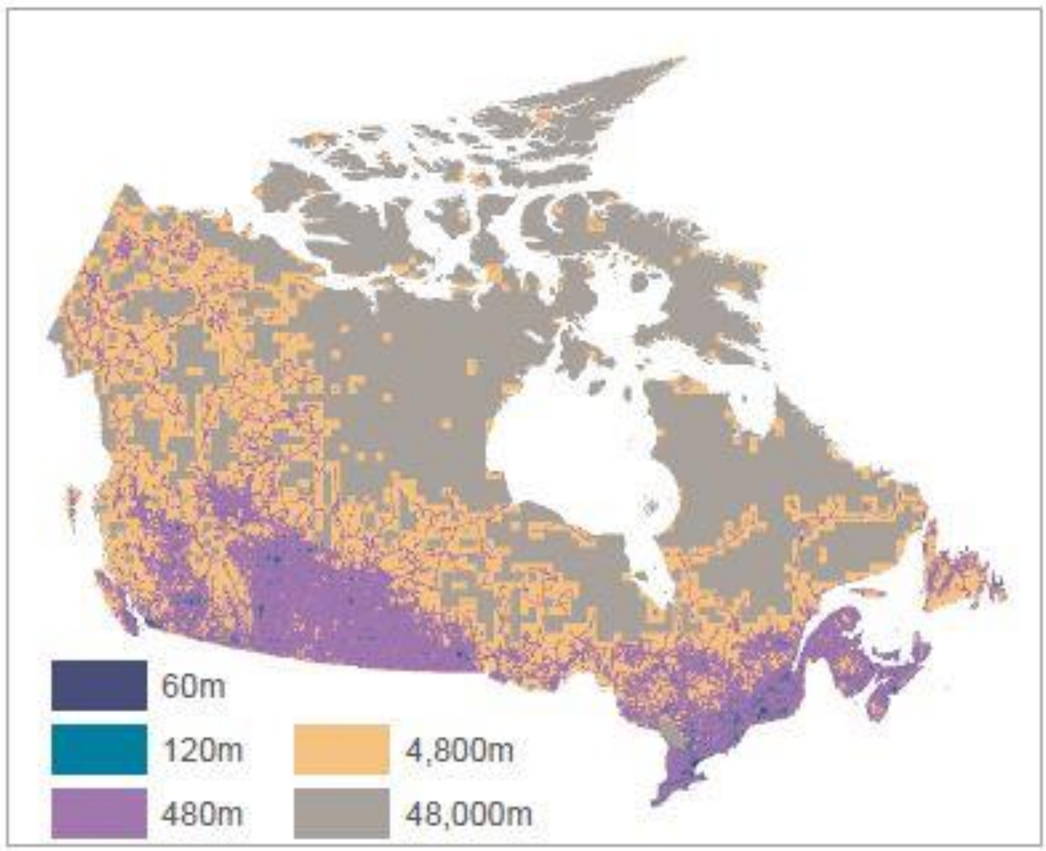
Calculating baseline period damages

This analysis relies on a dataset of flood risk developed by JBA Risk Management, who developed detailed flood risk and damage maps across Canada. These risk maps are developed using a proprietary 2D hydrodynamic flood model often used to assist in pricing premiums for individual properties (JBA Risk Management 2018). The model incorporates federal government data on streamflows and water levels (Hunter et al.2007; Lamb et al. 2009; Faulkner et al. 2016).

The specific product used here is the historical Annual Damage Ratio (ADR) map, which provides ratios of expected damage as a fraction of structure and content value and serves as the baseline of this analysis. The ADR was estimated with a gridded hydrologic/hydraulic flood model combined with a generic depth-damage relationship for a standard structure type from the U.S. Army Corps of Engineers. The hydrologic flood model uses a Variable Resolution Grid (see Figure 3-7) and represents the average damage from a 10,000 year simulation. The ADR is informed by insurance claims data from past flood events. The latest version of the dataset (2015) used in this study incorporates claims data from the Alberta and Toronto 2013 flood events. While the ADRs do include the effect of existing protection where data is available, the product does not include the effects of storm drainage systems. The bias this introduces is not clear as storm drainage systems are designed to protect local infrastructure by moving stormwaters away quickly, which has the potential to flood infrastructure downhill or downstream. For this analysis, we use the

ADRs that include both structure and content damage. These ADRs reflect the risk mitigation effects from most major existing flood protection infrastructure.

FIGURE 3-7. JBA VARIABLE RESOLUTION GRID OVER CANADA (SOURCE: JBA RISK – CANADA VRG ADR INFORMATION – LEGEND SHOWS GRID DIMENSION)



Baseline expected annual damage is the product of the ADRs and the sum of structure value and content value. ADRs are only evaluated in areas with within a building footprint. These building specific ADRs are averaged for each dissemination area, weighted by building area. In effect, this assumes each square meter of ground-floor building area has the same value within each dissemination area. For building footprints, we use the Canadian Building Footprints dataset developed by Microsoft in collaboration with StatCan.[12] Property values are constructed using the same data and approach described in Section 3.1.1 for coastal properties. We use the decoupled structure-only values, assuming land value is not affected, for both residential and commercial assets, which use different depth-damage functions in the ADR estimates. Content damages are assumed to be valued at an additional 50 percent of the structure damage for residential structures and 100 percent of the structure damage for commercial structures. This assumption is used in the FEMA HAZUS Flood Technical Manual.[13]

[12] https://github.com/Microsoft/CanadianBuildingFootprints

[13] Available online at www.fema.gov/plan/prevent/hazus – see Table 14.6.

Estimate distributions of extreme precipitation events

Using the baseline daily precipitation (1986-2005) and the projected daily precipitation for the two eras (2050s: for the era 2041-2070 and 2080s: for the era 2071-2100), we fit an extreme value distribution to characterize the statistical properties of maximum annual precipitation over these time periods. The Gumbel distribution, also known as the Generalized Extreme Value Distribution Type-I, is commonly used for extreme precipitation (Wilks 1993; Wotling et al. 2000; Ehmele and Kunz 2019), and is used here as well.

One of the limitations of our approach is that without a hydrologic flood model of Canada, we cannot estimate future flood depths – instead we need to develop damage curves based on precipitation as a proxy for flood depth. As an attempt to partially correct for the non-linear relationship between? precipitation and flood depth, before fitting these distributions, we use a transformation on precipitation to produce what we are calling "equivalent depth," which is the square root of precipitation. This relationship is derived from general hydraulic geometry theory, which indicates that flood depth is related to the square root of runoff (see Leopold and Maddock (1953) for the formulation of the theory and Singh (2003) for a review and updates based on experimental data as well as Allen et al. (1994) for a direct application of this specific approach). Note that this transformation only accounts for the relationship between flood depth and runoff. We do not attempt to account for differences from precipitation and runoff since these are more nuanced and site-specific and would require a detailed hydrologic flood model, which is outside the scope of this national-scale analysis. The effect of this depends on antecedent moisture conditions in soils. In dry conditions, rain is often absorbed in the soil or lost directly through evapotranspiration and there is little to no runoff generated but in wet conditions, such as flood events, the ratio of runoff to precipitation is much higher, especially when the ground is fully inundated. While it is not clear exactly how this omission will impact the analysis, it is more likely the damage estimates would be higher if these effects were considered, but given the scale of the analysis and other sources of uncertainty it is still appropriate given the objectives of the analysis.

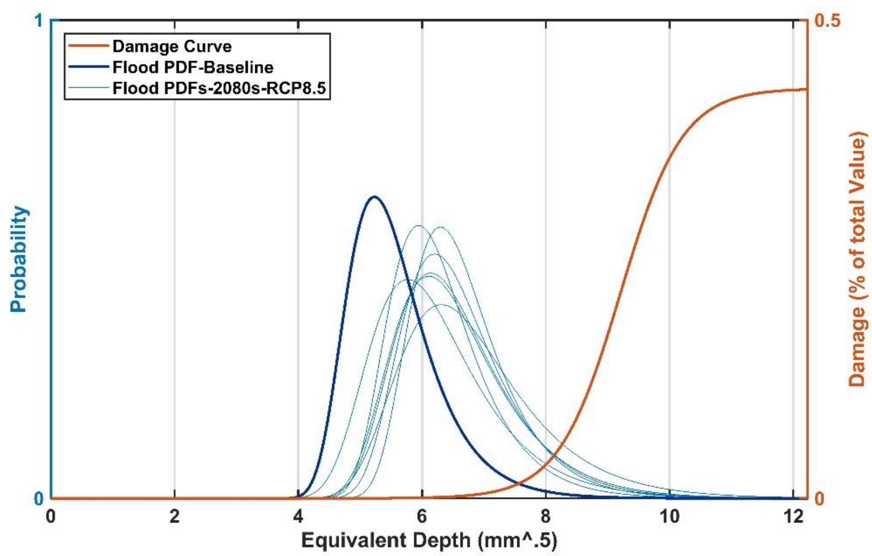
Calibrate damage curves to fit baseline Damage Ratios

While depth-damage functions are commonly applied in flood damage assessments, including the JBA Risk Management flood assessment used to characterize baseline risks in this analysis, due to the data and resource limitations, we develop equivalent-depth damage functions that provide damage ratios for various equivalent depth levels at a given location. Generally, depth-damage curves follow an S-curve such that at certain depths damage is zero (e.g., lower than the baseline floor or crawl space). Then as depth increases beyond the zero-damage threshold, damages accelerate with depth, then decelerate to a plateau at a theoretical maximum damage level. Due to regulations and some common sense, most valuable structures such as a home or business are not built in areas that are damaged often (e.g., every year) so it is the tail of the distribution of maximum annual events (e.g., above the 50-year event) where most flood damage is incurred. Using this general knowledge and the shape of the various depth-damage functions developed by the U.S. Army Corps and others (CITE), we use a logistic function to represent the equivalent-depth damage curves. This function has the following form:

$$DR = c/(1 + ae^{-b*EQ})$$

where DR is the damage ratio of the event, EQ is the equivalent depth, and a, b, and c, are parameters. Calibrating the ADRs to all three parameters would result in many possible solutions, many of which would violate the general logic of depth-damage curves, so it is necessary to hold some parameters constant. For b, we use a value of 2, which maintains the general shape of existing depth-damage functions, and we relate the parameter, c, to ADR such that c = 10*ADR. As a result, we calibrate the parameter, a, such that the sum of the product of the equivalent depth distribution and the damage function is equal to the ADR of the grid or basin. As an example, Figure 3-8 shows the distribution of equivalent depth for the baseline and the solved damage curve for residential pluvial flooding in the basin that includes Toronto city center. Note that the damage curve uses the right vertical axis and the flood density functions use the left vertical axis. Damages are effectively the area under the intersection of the damage curve and Probability Density Function (PDF). In this example, the extension of the tail of the distribution from the future scenarios in the 2080s era compared to the baseline increases damages substantially by increasing that intersected area. As shown in the results section, this pattern is prominent throughout Canada, especially in areas with high building and contents value.

FIGURE 3-8. EXAMPLE OF THE DAMAGE CURVE AND EQUIVALENT DEPTH DISTRIBUTIONS (BASELINE AND FOR THE RCP8.5 2080S ERA) FOR RESIDENTIAL PLUVIAL FLOODING IN TORONTO



Estimate future damages

Similar to baseline damage, projections of future damage for the two eras are the sum of the product of the damage function and equivalent depth distributions. Since the damage curve is the same for the projections and the baseline, changes in damage are driven by shifts in the distribution of equivalent depth, especially changes in the upper tail. The adjustments to damage ratios are re-aggregated from half degree or river basins to the dissemination areas using a spatial weighting. Annual expected damages are then the product of the revised damage ratio and the structure and content values developed in Step 1.

Results

The sections below summarize the baseline flooding damages, how precipitation extremes are projected to be affected under climate change, and the resulting projected flooding damages.

Baseline Damages

Figure 3-9 shows the total baseline damage by province or territory for the four damage types. Total expected annual damage is roughly $1.2 billion CAD for the baseline. About 56 percent of the damage is from fluvial flooding in residential buildings, 25 percent from fluvial flooding in commercial buildings, and the other ~19 percent from pluvial flooding. 86 percent of the flood damage occurs in four provinces: Ontario (41 percent), British Columbia (21 percent), Quebec (13 percent), and Alberta (11 percent). Table 3-9 shows the number of households and value in the floodplain of JBA's 10,000-year flood model simulation, which are estimated using the portion of building area in the floodplain multiplied by the total number of households for each dissemination area. New Brunswick and Newfoundland and Labrador are the provinces with the highest annual damage ratios at $3.34, and $2.98 per thousand CAD of total asset value.

FIGURE 3-9. TOTAL BASELINE FLOOD DAMAGE BY PROVINCE OR TERRITORY

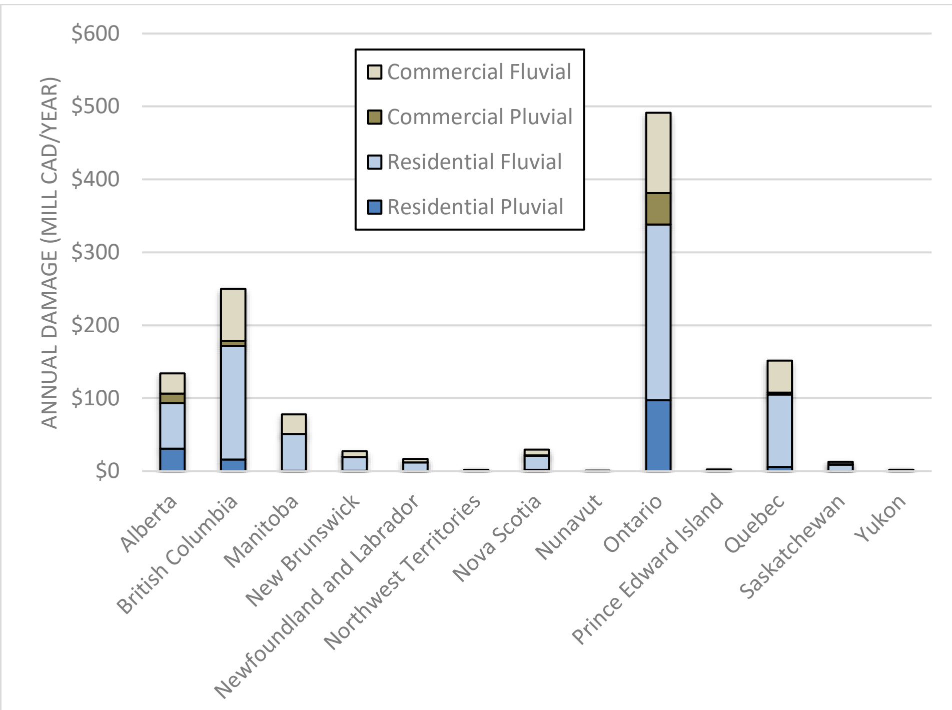


TABLE 3-9. BASELINE HOUSEHOLDS AND VALUE IN THE FLOODPLAIN BY PROVINCE / TERRITORY

Province / Territory	Households in Floodplain (thousands)	Building Value in Floodplain ($millions)
Alberta	383	$68,054
British Columbia	374	$92,683
Manitoba	330	$39,147
New Brunswick	100	$8,136
Newfoundland and Labrador	48	$5,606
Northwest Territories	3	$314
Nova Scotia	115	$12,121
Nunavut	2	$96
Ontario	1,095	$205,876
Prince Edward Island	15	$1,424
Quebec	767	$78,997
Saskatchewan	80	$10,111
Yukon	4	$626
National	**3,316**	**$523,191**

Changes in Extreme Precipitation

Figure 3-10 shows the change in the value-weighted empirical 10-year event. These are estimated by taking the third highest annual maximum rainfall from the 30-year era and weighting those by property value in each half-degree grid. The advantage of this graphic is that it avoids the errors that may be introduced from fitting a distribution and relies only on the half-degree precipitation. The figure shows that all projections indicate an increase in the 10-year empirical event except for a couple of scenarios in Novia Scotia, RCP4.5. The increases are generally higher for RCP8.5 than RCP4.5 and intensify in the 2080s era compared to the 2050 era. While there is an agreement in the sign of change, nationally the magnitude varies from 11 to 24 percent in the 2050 era and 26 to 68 percent in the 2080s era. Similarly, Figure 3-11 shows the change in intensity for the 100-year event, weighted by property value.

FIGURE 3-10. VALUE-WEIGHTED CHANGE IN THE 10-YEAR PRECIPITATION EVENT BY PROJECTION AND ERA COMPARED TO THE BASELINE

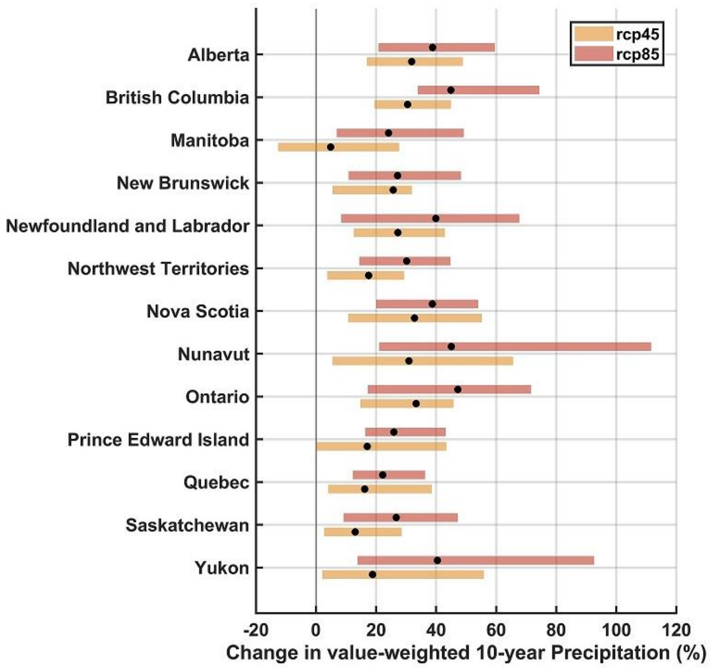


FIGURE 3-11. VALUE-WEIGHTED CHANGE IN 100-YEAR PRECIPITATION EVENT BY PROJECTION AND ERA COMPARED TO THE BASELINE

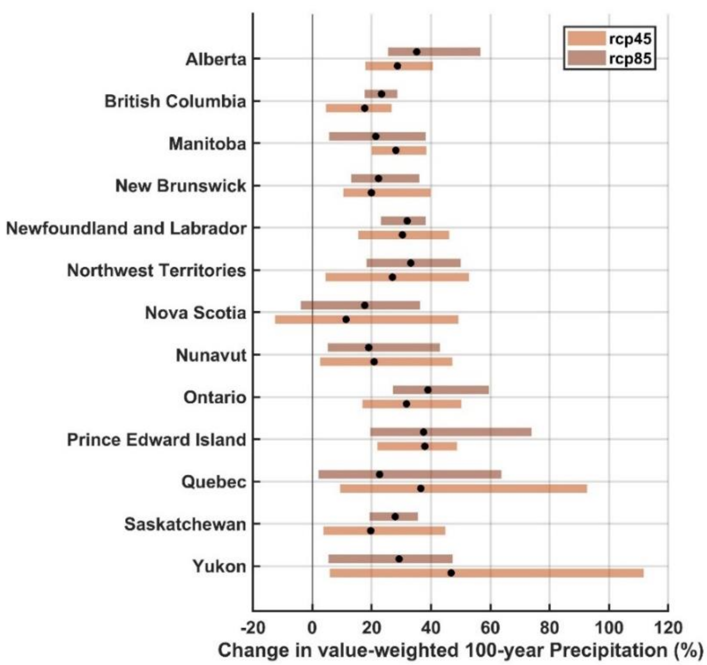


Table 3-10 shows the change in frequency of the historical 100-year event in the 2080s era for fluvial flooding in select cities with high asset value and high baseline damages. Fluvial flooding accounts for about 90 percent of the baseline damages so these frequencies are important. As shown, under RCP8.5, the 100-year event is likely to occur between 3 and almost 7 times more often given the median projection. Under RCP8.5 conditions worsen to 9 times more often for Toronto and 14 times more often for both Edmonton and Calgary.

TABLE 3-10. FREQUENCY OF THE HISTORICAL 100-YEAR EVENT (IN YEARS) FOR THE MEDIAN GCM AND BOTH MINIMUM AND MAXIMUM FOR BOTH RCPS IN THE 2080s ERA FOR FLUVIAL FLOODING IN SELECT CITIES

	RCP4.5			RCP8.5		
City Name	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
Toronto	29	14	59	11	6	22
Edmonton	15	7	36	7	5	43
Calgary	21	6	31	7	6	16
Vancouver	22	12	59	17	9	21

Future Damages

Figure 3-12 shows the total national damages for the future eras organized by RCP. Note that these are damages in absolute terms are not relative to the baseline, which is roughly $1.2 billion / year. Flood damages are about four times higher than the baseline for both 2050s and 2080s eras under RCP4.5. Under RCP 8.5, damages are 5 times higher than the baseline in the 2050s era and 7 times higher in the 2080s era. While the range across GCMs vary by about +/- 20 to 60 percent of the mean, even the lowest projection from RCP4.5 in the 2050s era is about 2 times higher than the baseline.

FIGURE 3-12. TOTAL NATIONAL DAMAGES FOR TWO FUTURE ERAS. BOXES SHOW THE RANGE OF GCM OUTPUTS AND DOTS SHOW THE MEAN. BASELINE IS ROUGHLY $3 BIL CAD / YEAR.

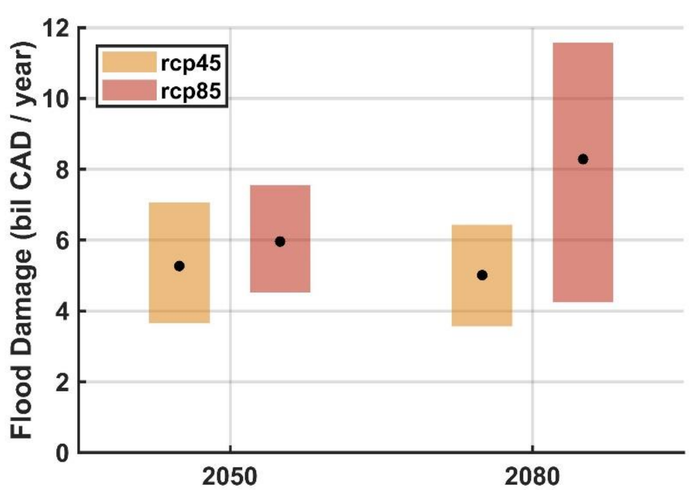


Table 3-11 and Table 3-12 show damage and ratios of the change in damage from the baseline, respectively. Ontario has the highest future damage in all scenarios, followed by British Columbia.

However, the provinces with the highest change in damage are Ontario, New Brunswick, Newfoundland and Labrador, and Nova Scotia, where all RCPs and eras indicate a GCM mean increase in damage around 5 times the baseline or higher. Table 3-13 shows the 10 census subdivisions with the highest damages in the 2080s for RCP 8.5. In total, these represent about a third of the damages for RCP8.5 in the 2080s. Note that many of these are near each other. For example, both Georgina and Mississauga are near Toronto.

TABLE 3-11. FLOOD DAMAGE IN MILLIONS OF 2015 CAD / YEAR BY PROVINCE FOR THE BASELINE AND FUTURE ERAS. TOP VALUES ARE THE GCM MEAN AND VALUES IN THE PARENTHESES ARE THE RANGE ACROSS GCMS

Province / Territory	Baseline	RCP4.5 - 2050	RCP8.5 - 2050	RCP4.5 - 2080	RCP8.5 - 2080
Alberta	$134	$609 ($390 - $1,068)	$783 ($557 - $1,312)	$594 ($268 - $977)	$968 ($299 - $1,389)
British Columbia	$250	$696 ($413 - $1,087)	$785 ($463 - $1,050)	$822 ($599 - $1,252)	$1,209 ($940 - $1,669)
Manitoba	$78	$354 ($120 - $537)	$293 ($87 - $407)	$394 ($88 - $693)	$592 ($97 - $1,471)
New Brunswick	$27	$147 ($98 - $250)	$143 ($71 - $252)	$126 ($71 - $210)	$156 ($115 - $228)
Newfoundland and Labrador	$17	$83 ($49 - $134)	$93 ($35 - $208)	$83 ($38 - $137)	$135 ($80 - $247)
Northwest Territories	$1	$3 ($2 - $6)	$4 ($2 - $8)	$4 ($2 - $7)	$5 ($2 - $10)
Nova Scotia	$29	$170 ($70 - $243)	$190 ($96 - $279)	$152 ($52 - $281)	$209 ($110 - $283)
Nunavut	$0	$1 ($0 - $1)	$1 ($1 - $1)	$1 ($0 - $2)	$1 ($1 - $2)
Ontario	$491	$2,690 ($1,118 - $4,380)	$3,092 ($1,938 - $4,703)	$2,281 ($1,401 - $3,334)	$4,111 ($1,899 - $6,554)
Prince Edward Island	$2	$7 ($1 - $13)	$5 ($2 - $11)	$4 ($1 - $11)	$7 ($3 - $14)
Quebec	$152	$426 ($247 - $674)	$500 ($256 - $726)	$481 ($236 - $922)	$780 ($374 - $1,240)
Saskatchewan	$13	$76 ($52 - $109)	$64 ($24 - $90)	$63 ($23 - $91)	$103 ($27 - $211)
Yukon	$2	$7 ($3 - $12)	$8 ($3 - $17)	$7 ($4 - $14)	$12 ($4 - $28)
National	**$1,196**	**$5,269 ($2,561 - $8,515)**	**$5,961 ($3,535 - $9,064)**	**$5,011 ($2,783 - $7,931)**	**$8,289 ($3,951 - $13,346)**

TABLE 3-12. CHANGE IN FLOOD DAMAGE (RATIOS WHERE VALUES ABOVE 1 ARE INCREASES IN DAMAGE FROM THE BASELINE) BY PROVINCE FOR THE BASELINE AND FUTURE ERAS. TOP VALUES ARE THE GCM MEAN AND VALUES IN THE PARENTHESES ARE THE RANGE ACROSS GCMS

Province / Territory	Baseline	RCP4.5 - 2050	RCP8.5 - 2050	RCP4.5 - 2080	RCP8.5 - 2080
Alberta	$134	4.5 (2.9 - 8.0)	5.9 (4.2 - 9.8)	4.4 (2.0 - 7.3)	7.2 (2.2 - 10.4)
British Columbia	$250	2.8 (1.7 - 4.4)	3.1 (1.9 - 4.2)	3.3 (2.4 - 5.0)	4.8 (3.8 - 6.7)
Manitoba	$78	4.6 (1.5 - 6.9)	3.8 (1.1 - 5.2)	5.1 (1.1 - 8.9)	7.6 (1.3 - 18.9)
New Brunswick	$27	5.4 (3.6 - 9.2)	5.3 (2.6 - 9.3)	4.6 (2.6 - 7.7)	5.8 (4.2 - 8.4)
Newfoundland and Labrador	$17	5.0 (2.9 - 8.0)	5.6 (2.1 - 12.5)	5.0 (2.3 - 8.2)	8.1 (4.8 - 14.8)
Northwest Territories	$1	2.1 (1.3 - 4.2)	2.6 (1.5 - 5.2)	2.4 (1.2 - 4.7)	3.5 (1.5 - 6.9)
Nova Scotia	$29	5.8 (2.4 - 8.2)	6.4 (3.2 - 9.4)	5.1 (1.8 - 9.5)	7.1 (3.7 - 9.6)
Nunavut	$0	2.3 (1.3 - 3.4)	2.9 (2.3 - 4.0)	2.6 (1.5 - 5.3)	3.9 (2.2 - 6.5)
Ontario	$491	5.5 (2.3 - 8.9)	6.3 (3.9 - 9.6)	4.6 (2.9 - 6.8)	8.4 (3.9 - 13.3)
Prince Edward Island	$2	3.1 (0.6 - 6.1)	2.2 (0.8 - 5.1)	1.8 (0.5 - 5.1)	3.4 (1.3 - 6.6)
Quebec	$152	2.8 (1.6 - 4.4)	3.3 (1.7 - 4.8)	3.2 (1.6 - 6.1)	5.1 (2.5 - 8.2)
Saskatchewan	$13	5.9 (4.0 - 8.4)	5.0 (1.8 - 7.0)	4.8 (1.8 - 7.1)	7.9 (2.1 - 16.3)
Yukon	$2	3.6 (1.8 - 6.5)	4.4 (1.8 - 8.8)	3.8 (1.9 - 7.7)	6.5 (2.2 - 14.7)
National	**$1,196**	**4.4 (3.1 - 5.9)**	**5.0 (3.8 - 6.3)**	**4.2 (3.0 - 5.4)**	**6.9 (3.5 - 9.7)**

TABLE 3-13. CENSUS SUBDIVISIONS WITH HIGHEST DAMAGES IN RCP8.5, 2080S SHOWING THE BASELINE AND FUTURE ERAS, MEAN OVER GCMS

			Flood Damages ($mill/year)				
CSD Name	Province	Households in Floodplain	Baseline	RCP4.5 2050	RCP8.5 2050	RCP4.5 2080	RCP8.5 2080
Toronto	Ontario	146,798	$97	$547	$581	$538	$556
Winnipeg	Manitoba	250,918	$53	$280	$235	$254	$319
Calgary	Alberta	105,441	$36	$189	$191	$189	$230
Mississauga	Ontario	38,341	$24	$159	$163	$154	$162
Edmonton	Alberta	108,171	$34	$129	$106	$127	$141

CSD Name	Province	Households in Floodplain	Flood Damages ($mill/year)				
			Baseline	RCP4.5 2050	RCP8.5 2050	RCP4.5 2080	RCP8.5 2080
Georgina	Ontario	4,846	$16	$120	$106	$115	$129
Ottawa	Ontario	75,514	$43	$112	$90	$107	$112
Chatham-Kent	Ontario	32,076	$11	$106	$94	$91	$105
Haldimand County	Ontario	9,015	$10	$100	$89	$86	$99
Innisfil	Ontario	4,612	$10	$79	$71	$75	$85

Table 3-14 shows the annual damage per household for the baseline and the GCM-mean across eras and RCPs. Note that the number of households in the floodplain is estimated by multiplying the portion of building area with a non-zero ADR by the number of households in each dissemination area. In the baseline, costs per household are highest in British Columbia, Northwest Territories, Yukon, and Ontario but likely for different reasons—high in Northwest Territories and Yukon because of lower household counts and high in British Columbia and Ontario because values per dwelling are high in the areas most impacted. The highest changes in impact in the 2080s compared to the baseline cost are for Ontario, Newfoundland and Labrador, and Saskatchewan where costs are almost eight times higher in the 2080s under RCP8.5. The lowest changes in costs per dwelling are in the Northwest Territories and Prince Edward Island with 3.5 and 3.4 times higher costs, respectively, for RCP8.5 in the 2080s era.

TABLE 3-14. DAMAGES PER HOUSEHOLD

Province / Territory	Households in Floodplain (thousands)	Baseline	2050s		2080s	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alberta	383	$350	$1,591	$2,046	$1,552	$2,529
British Columbia	374	$667	$1,860	$2,098	$2,196	$3,228
Manitoba	331	$234	$1,070	$883	$1,189	$1,788
New Brunswick	100	$272	$1,467	$1,430	$1,260	$1,563
Newfoundland and Labrador	48	$347	$1,724	$1,926	$1,729	$2,800
Northwest Territories	3	$546	$1,172	$1,395	$1,313	$1,928
Nova Scotia	115	$257	$1,478	$1,647	$1,315	$1,819
Nunavut	2	$96	$322	$398	$362	$543
Ontario	1,087	$448	$2,456	$2,824	$2,083	$3,754
Prince Edward Island	15	$141	$440	$317	$255	$482
Quebec	767	$198	$556	$652	$627	$1,017
Saskatchewan	80	$161	$952	$803	$782	$1,279
Yukon	4	$493	$1,760	$2,153	$1,854	$3,225
National	3,308	$362	$1,593	$1,802	$1,515	$2,506

Adaptation

Adapting to an increase in flood damage may take many forms from hard structures such as engineered storm drainage systems, retention ponds, or so called "green solutions" like wetlands designed to slow and hold water long enough to seep into deeper groundwater reserves. The streamlined approach used here does not lend itself to a simulation of these effects, which are complex and better for project-level analyses. Instead we apply an example that is meant to inform the efficacy of an adaptation response that targets the properties that are most vulnerable. The exact response is not prescribed per se, but it may be easiest to think in these terms: the most vulnerable property in the most vulnerable locations are abandoned or relocated to flood-free areas. To get a sense of how a strategy like this will impact total damage, we first identify the dissemination areas with the highest potential damage by ranking each using the ADR from the projection that yielded the highest damage in the 2080s era. We use the 90th percentile, which is an ADR of about 1.6 percent, and any dissemination areas with an ADR higher than that we flag as "most vulnerable." We then assume these dissemination areas are able to completely protect 10 percent of the asset value from flood damage. Since the dissemination areas with ADRs above the 90th percentile contain roughly 10 percent of the total asset value, this strategy protects about 1 percent of the total asset value nationally (not just the asset value in the floodplain). Table 3-15 shows the asset value in the most vulnerable locations by province or territory that is completely protected (i.e., 10 percent of the total value in the most vulnerable locations). As shown, the asset value is not evenly distributed. In Manitoba and New Brunswick, almost 2 percent of the asset value is protected but that is the case for only 0.2 percent of the value in Prince Edward Island.

Table 3-15 also shows the reduction in damage, in percent, using the average across the projections in the 2080s era. Nationally, damages are reduced on average 6.5 percent for both RCP4.5 and RCP8.5. Not surprisingly, provinces or territories with a higher portion of protected asset value are also the ones with the highest damage reduction. Damages are reduced 9 percent in Manitoba but only 1.2-1.3 percent in Prince Edward Island.

TABLE 3-15. VALUE PROTECTED AND DAMAGE REDUCTIONS FROM TARGETED ADAPTATION

Province / Territory	Value Protected ($mill)	Value protected (% of total asset value, $2.4 trillion)	Damage Reduction from Adaptation (2080s)	
			RCP4.5	RCP8.5
Alberta	$1,885	0.6%	-6.0%	-6.0%
British Columbia	$2,996	0.6%	-6.2%	-6.2%
Manitoba	$1,019	1.9%	-9.2%	-9.1%
New Brunswick	$493	1.9%	-6.5%	-6.4%
Newfoundland and Labrador	$434	1.7%	-6.9%	-6.8%
Northwest Territories	$10	0.6%	-7.7%	-7.8%
Nova Scotia	$567	1.4%	-4.7%	-4.7%
Nunavut	$2	0.5%	-2.9%	-3.4%
Ontario	$11,094	1.1%	-6.7%	-6.6%
Prince Edward Island	$8	0.2%	-1.3%	-1.2%
Quebec	$2,049	0.6%	-5.4%	-5.6%
Saskatchewan	$330	0.6%	-6.8%	-6.7%
Yukon	$52	2.3%	-7.6%	-7.5%
National	**$20,939**	**0.9%**	**-6.5%**	**-6.5%**

Main Takeaways

The from the analysis are:

- While there is uncertainty in estimating flood damages (discussed in the Limitations and Caveats section below), there is high confidence that flood intensities will get worse in the future based on these projections since almost all GCMs and RCPs indicate an increase in intensities where property values are highest in the Provinces and Territories. This is true for both more frequent, less intense storms (10-year) as well as less frequent, more intense storms (100-year).
- The baseline damage estimate and other literature suggest that flooding is a major category of weather-related costs. Our results indicate that flood damage is likely to be about 4-5 times larger than it is currently by 2050 and 4 to 7 times larger by 2100.
- Damages are driven by areas near major cities like Toronto, Vancouver, Calgary, and Edmonton, where asset value is high as well as both baseline and projected damages. For example, the results show that the historical 100-year event could occur as often as every 7 and 22 years for these areas for RCP8.5. Flood protection strategies targeted to these areas could offset damages.

Limitations and Caveats

The major caveats and limitations to this approach are noted below.

Data and resource limitations

- We use equivalent depth (square root of precipitation) as a proxy for flood depth in this analysis because of data and resource constraints. While we develop unique damage curves that relate equivalent depth to damage to account for this disconnect, there are many site-specific characteristics (e.g., ground slope, ground cover, perviousness of surface and soil column, etc.) that influence the relationship between flood depth and precipitation that are not accounted for here.
- The damage functions are representations of the expected relationship between flooding and equivalent depth based on a review of damage curves as well as expert judgement. The method for developing and calibrating these damage curves was a necessary step to bridge a major data gap but the assumptions used here does influence the results and as such is not intended for project-scale analysis.
- Reduced snowpack and drier antecedent conditions have both been noted as potential factors that may reduce the risk of flood relative to extreme precipitation increases. For example, Cunderlik and Ourda (2009) find a reduction in snowmelt floods in southern Canada by analyzing streamflow records three decades prior to the study. However, Gaur et al. (2018) find that parts of Quebec and Ontario will only see a shift in snowmelt floods in the future rather than a decrease. Our analysis does not account for snowmelt or antecedent soil moisture.
- The flood model (developed by JBA) is designed to assist in pricing premiums for individual properties damage for insurance companies and uses a consistent framework nation-wide. The approach uses a generic depth-damage function. Not all buildings are damaged the same way and detailed information on building characteristics would be required to take these effects into account. Also, other assets such as vehicles are not included in these damage estimates. While we expect the future estimates of flood damage would scale more or less linearly with the baseline.
- Similar to coastal properties, we rely on the available home value estimates from the 2016 census and ratios from four cities in western Canada as well as ratios derived from the U.S to derive non-residential value and decouple structure value from the total value. While these two property value adjustments provide required data to estimate comprehensive effects, and to recognize intermittent flooding impacts on structures alone exclusive of land, actual ratios of structure value to total value throughout the full Canadian spatial domain likely differ in an unknown manner.
- The building footprint database provides important information for estimating ADRs by building, yielding a more accurate estimate of property potentially vulnerable to flooding. We find that in many urban areas buildings are built outside frequently flooded areas, likely because of building regulations in place. We have also found that estimates generated with simplifying assumptions that do not take into account building footprint location data, such as uniform allocation of property value across dissemination areas, result in biased estimates, including overestimation of damage by at least a factor of two.

Uncertainties of future change

- While future changes in flooding are abstracted to larger spatial extents (half degree or river basin) the analysis does rely heavily on the JBA ADRs that anchor the baseline flood damage.

As such, the floodplain and the households in the floodplain, are static in time and we make no attempt to project changes in the flooded areas. However, it is not likely the floodplain will change drastically without changes in topographic, bathymetric features, soils, or ground cover, all of which could be driven by climatic changes but are not usually simulated in hydrologic flood models alone.

- The analysis presented here does not account for changes in property value related to economic or population changes to the end of century.
- Certain building characteristics such as the existence of a basement or the number of floors change the relationship of flood depth to damage. These were not accounted for in this analysis where a generic damage function is applied to all buildings in the region. These factors are, however, reflected in the baseline flood damages in the JBA Risk Management model – whether damages to buildings associated with these characteristics scales with our precipitation scalar is currently unknown.
- This analysis focuses on changes in climate and does not account for changes in floods caused by land-use change or general basin degradation and health. In addition to human-induced change, natural changes in basin hydrology and topography are also common and in many cases are caused by extreme flood events. These changes are not accounted for here.

Issues of scale

- We are limited to evaluating the 24-hour flood event as that is the finest temporal resolution available. Flood events occur on various times scales from minutes to weeks that are dependent on hydrologic and climatological tendencies of the place or region. Flash floods over small watersheds, for example, that occur in hours may not be well-represented in this analysis.
- GCMs generally have better performance over aggregated space and/or time. Since flood events usually occur on smaller timescales, we rely on short temporal scales for the analysis. While the BCSD method for bias-correcting GCM results likely improves these issues of scale in the GCMs, there is still uncertainty in the underlying drivers of change from the GCMs at these shorter time scales.
- At this scale, storm drainage systems are not accurately represented in either the JBA ADRs or for the projections of change, which may reduce the damages shown here but could also have the opposite effect, as discussed earlier. Also, complex processes of urban flooding such as sanitary sewer backup in combined sewer systems, which do cause additional flood damage in Canada, are not resolved in the analysis.

3.2 TRANSPORTATION

Our process-based modeling of climate change costs for transportation infrastructure focuses on impacts to Canada's roads and its rail network. For both roads and rail, we apply methods consistent with those used for the USEPA's Climate Change Impacts and Risk Analysis (CIRA) project (U.S. EPA, 2017). We limit the application of process-based methods to these two types of transportation infrastructure because (1) sufficient Canada-specific data are available to apply an existing process-based approach to these categories and (2) existing process-based approaches may be applied within the project resource constraints for these two types of transportation infrastructure but not others. While the climate change impacts literature includes process-based modeling approaches for bridges, the application of these methods is both time- and resource-intensive and therefore not feasible within the resource and time constraints of this study. We instead rely upon the reduced-form approach described above to assess climate change costs for bridges.

To apply the process-based approaches described in this section, we will use the Infrastructure Planning Support System (IPSS), which members of our project team have previously applied for several peer-reviewed studies (e.g., Chinowsky et al. 2019, Melvin et al. 2017, Neumann et al. 2015, Chinowsky et al. 2013) and for the U.S. EPA's CIRA Project. Using IPSS, our analysis of climate change costs to roads and rail will capture costs under both the status quo (reactive adaptation) scenario and a proactive adaptation scenario.

Infrastructure Planning Support System

IPSS is a first-of-its-kind system developed by Resilient Analytics that performs engineering analysis within a broader resiliency perspective. IPSS models infrastructure vulnerability to future climate and weather conditions, considers specific adaptation scenarios, and provides a cost- benefit based risk analysis. IPSS draws its data from a range of climate science projections, engineering and materials studies, and environmental research to provide users with decision support that is based in real-world risk scenarios.

3.2.1 ROADS

Changes in temperature and precipitation patterns over the coming decades will increase the stress on Canada's road network, increasing the cost of ensuring that Canada's roads provide the same level of service as they provide at present day. This section presents our analysis of these costs for Canada's network of paved and unpaved roads for the two 30-year eras described above (2050s: 2041-2070 and 2080s: 2071-2100). The analysis examines the cost implications of three climate stressors with documented impacts on roads: (1) changes in temperature, specifically extreme heat; (2) changes in precipitation; and (3) changes in freeze-thaw cycles.[14] Consistent with the other analyses presented in this report, we examine the cost of these stressors under a status quo scenario that reflects a reactive response to changes in climate and a proactive scenario under which Canada's transportation agencies make road design and maintenance decisions based on expected changes in climate. As described in Chapter 2, our specification of these two scenarios is intended to provide infrastructure managers with insights into which climate-related risks are most significant to Canada's roads and the degree to which proactive

[14] This analysis does not consider climate change costs related to winter roads or thawing permafrost. These are included in the Canada's North section below. Also, roads that are located on permafrost are excluded from the analysis presented in this section to avoid potential double counting of impacts for the roads examined in the permafrost impact analysis below.

adaptation might reduce those risks. While technological change and innovation may affect the magnitude of climate-related costs under the reactive and/or proactive scenarios, the insights gained from this analysis still provide infrastructure managers with a starting point for understanding and evaluating climate-related risks and prioritizing adaptive actions.

Methods

Our analysis of climate change costs for Canada's road network relies on a detailed inventory of Canada's roads and engineering-based methods for translating changes in climate stress to changes in costs for Canada's road network. We describe each of these components of our analysis below.

Road Inventory

This analysis relies upon an inventory of Canadian roads obtained from DMTI, a commercial provider of geographic data specializing in Canadian spatial data. The DMTI data disaggregate the Canadian road network across multiple dimensions, including (1) paved versus unpaved, (2) road type (e.g., highways, local streets), (3) surface type (e.g., asphalt versus concrete for paved roads and gravel versus dirt for unpaved roads), and (4) number of lanes. To spatially align the DMTI road data with the climate data used for this analysis, we translated the line layer from DMTI to a half degree by half degree grid. The resulting dataset specifies the kilometers of road in each grid cell defined according to the characteristics listed above. We note, however, that DMTI includes incomplete information for some variables and locations. To fill these data gaps, we made a limited number of simplifying assumptions:

- ***Gravel vs Dirt Surface for Unpaved Roads:*** For unpaved roads, the DMTI dataset includes limited information on the distribution between gravel roads and dirt roads. Specifically, this information is in the DMTI data for less than 1 percent of unpaved road km in Canada. In cases where such information is missing from the data, we assume that half of the unpaved road length in a given grid cell is gravel and the other half is dirt.[15]
- ***Paved vs Unpaved Roads for Saskatchewan:*** For a large portion of the road segments in Saskatchewan, the DMTI data do not indicate whether the segment in question is paved or unpaved. To address this limitation of the data, we allocated the uncharacterized segments in a given grid cell between paved and unpaved based on the distribution between paved and unpaved road km for that same grid cell as specified in an alternative road inventory published by Natural Resources Canada.[16]
- ***Age of Road Stock:*** For paved roads, we evenly distribute roads in terms of age to provide a basis for estimating the replacement date of the road looking forward. Overall, this will average newer and older roads, but may skew the results if many roads are newer in age.

In addition to the above, we also assume that Canada's road network is static over the full timeframe of the analysis, in terms of both the lane-kilometers of roads and the composition of the network. To assess

---

[15] To assess the sensitivity of our analysis to this assumption, we performed test analyses where we treated these roads as gravel and a second where we treated such roads as dirt roads. For the scenarios analyzed, the results showed minimal sensitivity to this assumption.

[16] See Natural Resources Canada National Road Network – NRN- GeoBase Series, available at https://open.canada.ca/data/en/dataset/3d282116-e556-400c-9306-ca1a3cada77f.

the reasonableness of the assumption of a static road network, we reviewed historical road network data published by Statistics Canada, which showed that Canada's road network in 2013 was slightly smaller than it was in 1998 (1.3 million km in 2013 versus 1.4 million km in 1998) despite the fact that Canada's population and economy grew during that time.[17] While some changes to the road network will undoubtedly occur over the next several decades, these historical data suggest that such changes are not easily linked to changes in Canada's population and economy. Factors such as changes in land use patterns (e.g., increased development in high-density areas) and prioritization of investments in other forms of transportation infrastructure may affect growth of the road network over time as well. Because many of these factors are driven by policy decisions, we do not attempt to account for them in our analysis.

Table 3-16 summarizes the lane kilometers of roads in Canada by province and surface type. As shown in the table, paved roads make up only 33 percent of Canada's road network. This reflects reliance on unpaved roads in more sparsely populated areas across much of Canada. Quebec and Ontario, which are home to some of the largest metropolitan areas in Canada, account for nearly half of the paved road network, while also possessing significant unpaved road networks as well.

TABLE 3-16. TOTAL LENGTH OF ROAD BY ROAD TYPE AND PROVINCE (LANE-KM)

PROVINCE/TERRITORY	PAVED ROADS	UNPAVED ROADS	TOTAL
Alberta	136,460	392,008	528,468
British Columbia	111,732	203,054	314,786
Manitoba	46,912	179,583	226,494
New Brunswick	39,230	40,238	79,468
Newfoundland and Labrador	22,514	17,997	40,511
Northwest Territories	5,898	17,224	23,123
Nova Scotia	36,555	44,524	81,079
Nunavut	7	2,091	2,098
Ontario	250,794	269,921	520,716
Prince Edward Island	9,644	5,487	15,131
Quebec	196,445	336,200	532,645
Saskatchewan	49,624	334,733	384,357
Yukon	17,465	14,931	32,396
Total	**923,279**	**1,857,993**	**2,781,272**

Methods Description

As noted above, the roads analysis captures the effects of changes in temperature, precipitation patterns, and freeze-thaw cycles on paved roads and unpaved roads. The methods used for capturing the climate change costs associated with these stressors are consistent with and/or build upon those detailed in

[17] Statistics Canada, Transportation Data and Information Hub, Table 11-1: System Extent and Facilities (Kilometers), available at https://www144.statcan.gc.ca/nats-stna/tables-tableaux/tbl11-1/tbl11-1-CAN-eng.htm, accessed July 11, 2020.

Chinowsky et al. (2013) and Neumann et al. (2015), as applied in the USEPA CIRA project.[18] Under the status quo/reactive adaptation scenario, we estimate the costs of climate change for roads as the increase in maintenance and repair costs required to ensure current levels of service for Canada's road network. For the proactive adaptation scenario, we (when possible) estimate the costs to protect roads against the effects of climate change by planning for long-term climate change in road design/specification.

Table 3-17 describes the specific damages to road infrastructure associated with each climate stressor, the types of costs incurred under the status quo scenario, and the types of costs associated with the proactive adaptation scenario. For both the reactive and proactive scenarios, our approach focuses only on the physical effects of climate change on the road network and the associated costs. We do not examine potential changes in transportation demand (e.g., vehicle km traveled (VKT) per household) that might result from a changing climate and the implications of such changes on the costs of building and maintaining Canada's roads. The direction and magnitude of such changes in demand will depend on a variety of factors beyond the scope of this analysis. However, to the extent that climate change increases demand for road transportation (e.g., increases VKT), we are likely to underestimate the costs of climate change to Canada's roads, as increased use of roads will accelerate maintenance cycles. Conversely, a reduction in VKT would suggest that our analysis may overestimate climate change costs for Canada's road network.

TABLE 3-17. SUMMARY OF CLIMATE CHANGE DAMAGES AND COSTS FOR ROAD INFRASTRUCTURE

INFRASTRUCTURE TYPE	STRESSOR	DAMAGE SOURCES	STATUS QUO REACTIVE SCENARIO	PROACTIVE ADAPTATION SCENARIO
Paved Roads	Temperature	Surface degradation & increased roughness due to thermal cracking & rutting.	Increased repair costs due to climate-related damage.	Alter asphalt mix to include binder with appropriate temperature performance.
	Precipitation	Erosion of base and sub-base due to infiltration; increased cracking.	Increased repair costs due to climate-related damage.	Modify binder/sealant and increase base layer depth.
	Freeze-Thaw	Base layer degradation due to soil heaving, and increased surface damage from settling & movement.	Increased repair costs due to climate-related damage.	Modify design to increase surface density and reduce infiltration.
Unpaved Roads	Temperature	No methods for assessing damage.	N/A	N/A
	Precipitation	Surface erosion and rutting.	Increased repair costs due to climate-related damage.	Increase the base of the unpaved road to allow for greater strength and drainage.
	Freeze-Thaw	No methods for assessing damage.	N/A	N/A

[18] See USEPA (2017).

To analyze the damages and adaptation approaches summarized in Table 3-4, we applied the Infrastructure Planning Support System (IPSS) developed by researchers at the University of Colorado Boulder. A quantitative, engineering-based analysis tool, IPSS is designed to help users isolate the potential maintenance costs due to climate change on transportation, building, and energy infrastructure. IPSS broadens the criterion and methods of traditional infrastructure resiliency analysis by including both the analysis of climate change impacts and potential adaptation opportunities and associated investment costs. IPSS diverges from traditional efforts that analyze climate impacts via a top-down approach by taking a bottom-up approach to climate analysis. In this method, the impact of each climate stressor is determined at a 0.5 degree spatial scale for two 30-year eras (2040 to 2069 and 2070 to 2099) and translated to associated repair and replacement costs. For the current study, the impacts and adaptation summarized above were included to provide detailed stressor level analysis for each segment of the road network. Additional details on the approach for analyzing road category costs are presented below by stressor.

Temperature. Our analysis of temperature-related climate change costs for (paved) roads draws upon available information on the minimum and maximum temperature limits for which pavements are designed. As shown in Table 3-18, the binders used in asphalt pavement are chosen based on the expected pavement temperature where the road is located. When the temperature exceeds the design threshold for the binder used, the pavement surface may be damaged. For the purposes of this analysis, we assume that such damage would occur based on seven-day, rolling average maximum temperatures, consistent with the approach used in U.S. EPA (2017). While the choice of binder may also affect pavement cracking at extreme low temperatures, Dave et al. (2016) indicate that no criterion has been required for determining the low-temperature cracking potential of asphalt mixtures. Superpave specifications attempt to minimize thermal cracking by specifying low temperature grades for asphalt binders, but these low temperature grades do not account for the many other variables in an asphalt mixture that affect cracking under extreme cold conditions (e.g., aggregate types, use of recycled asphalt materials).

To identify the baseline binder mix without climate change, we assume that existing roads were designed according to historical climate data for the 1986-2005 period. Under the status quo scenario, we estimate climate change costs as the expenditures necessary to repair temperature-related damage and maintain the road's level of service. For the proactive adaptation scenario, we estimate climate change costs as the cost of modifying the asphalt mix to include binders appropriate for the temperature expected with climate change when roads are repaved according to their maintenance cycle.

TABLE 3-18. ASPHALT BINDER GRADES

PERFORMANCE GRADE	7-DAY MAXIMUM PAVEMENT TEMPERATURE (°C)
PG-46	46
PG-52	52
PG-58	58
PG-64	64
PG-70	70
PG-76	76
PG-82	82

Notes: These are commonly referenced binder grades. For example, see https://pavementinteractive.org/reference-desk/materials/asphalt/superpave-performance-grading/

Precipitation. For precipitation effects, our approach reflects the different effects of precipitation on paved roads versus unpaved roads. On paved roads, increased precipitation may cause rutting, which reduces the time until road resurfacing is required. On unpaved roads, increased precipitation can lead to increased erosion, making them more difficult to travel or impassable altogether. For both paved and unpaved roads, increased degradation will occur when projected maximum monthly precipitation increases by 10 cm relative to the historical baseline, with incremental increases in damages applied for each subsequent 10-cm increase (Chinowsky and Arndt, 2012 and Melvin et al., 2017). For the status quo scenario, we estimate climate change costs for both paved and unpaved roads as the increased repair costs to maintain roads' level of service. Under the proactive adaptation scenario, climate change costs for paved roads include costs to change road sealants and binders so that roads can better withstand projected increases in precipitation, as well as modifying the road base to improve drainage below the pavement surface. For unpaved roads, the proactive scenario emphasizes strengthening the base of the road when roads are rehabilitated according per their life cycle to allow for greater drainage and reduce the strength loss when the road experiences heavy precipitation.[19]

We note that the 10-cm precipitation threshold referenced above for the realization of precipitation effects may, on a site-specific basis, be an over-simplification of the physical effects of precipitation on roads. For a broad-based nationwide analysis, however, this threshold serves as a reasonable literature-based indicator of the point at which changes in precipitation are likely to lead to significant degradation of roads.

Freeze-thaw. To assess costs related to changes in freeze-thaw (for paved roads only), we examine changes in freeze-thaw cycles for each half degree grid cell, based on its annual precipitation and its Freezing Degree Index (FDI) value for each season, the latter of which is calculated as follows:

(1)
$$FDI = \sum_{x=1}^{x=days} (0 - T_{ave})$$

where

T_{ave} = average daily temperature (degrees Celsius)
days = number of days in each month

When $(0\text{-}T_{ave})$ is less than 0 when applying Equation 1, $(0\text{-}T_{ave})$ will be set to 0.

Based on Equation 1 and the annual precipitation for each area, we assign each area to one of five environmental zones:[20]

[19] See U.S. Department of Transportation (2015) and Berkshire Regional Planning Commission (2001).

[20] Note that the zones listed here do not include a no freeze-dry zone. With no freeze and dry conditions, there are no freeze-thaw-related damages.

- Deep-freeze wet: > 500 mm in annual precipitation and FDI > 400
- Deep-freeze dry: < 500 mm in annual precipitation and FDI > 400
- Moderate-freeze wet: > 500 mm in annual precipitation and FDI of 50-400
- Moderate-freeze dry: < 500 mm in annual precipitation and FDI of 50-400
- No-freeze wet: > 500 mm in annual precipitation and FDI < 50

Each of these zones represents a different level of freeze-thaw activity and correspondingly different rate of road degradation. Thus, if an area transitions from one zone to another due to climate change, its level of freeze-thaw activity and corresponding rate of freeze-thaw-related road degradation is also assumed to change. Rather than explicitly estimating the change in the number of freeze-thaw cycles, this approach relies on the FDI as an indicator of the damage caused by freeze-thaw activity, as moderate freeze areas experience more freeze-thaw cycles than deep freeze areas. For example, U.S. DOT (2006) shows that ruts forming on the road surface are 0.5 mm higher in moderate freeze areas than high freeze areas.

For areas with no change in environmental zone due to climate change, we use Equation 2 below to estimate the proportional change in freeze-thaw cycles and the proportional change in road degradation (Melvin et al. 2017), assuming that a freeze-thaw cycle occurs when there are seven consecutive days of freezing temperatures followed by a seven-day period with 30 or more thaw degree days, where the Thaw Degree Index (TDI) is greater than or equal to 30:

$$TDI = \sum_{x=1}^{x=days} (0 - T_{ave})(-1) \qquad (2)$$

where T_{ave} and *days* are as defined above and where ($0-T_{ave}$) is set equal to 0 when it calculates to greater than 0.

For the status quo scenario, we estimate climate change costs as the increased expenditures required to maintain current levels of service. For the proactive scenario, we estimate climate change costs as the expenditures associated with modifying the design of roads when they are resurfaced per their life cycle to increase surface density and reduce infiltration that occurs due to freeze-thaw.

Similar to our approach for precipitation effects, the approach for freeze-thaw effects presented here may not be sufficiently detailed to assess climate effects on a site-specific basis, as it does not account for factors such as frost front or soil moisture content. For an analysis that is national in scale, however, this approach, which is based on U.S. DOT studies of rutting in different environmental zones, provides a reasonable basis for gauging the magnitude of costs (or cost savings) associated with changes in freeze-thaw. As the literature in this area continues to develop, we would expect that future studies of road-related climate change costs will account for at least some of these other factors.

Results

Overall, the Canadian road system will experience effects from projected climate change due to both temperature and precipitation effects. However, the system will also experience some cost savings due to reductions in freeze-thaw cycles throughout the country. Under the status quo scenario, annual costs for the roads sector are approximately $2.2 billion during the 2040-2069 era based on the RCP 4.5 projections and $3.1 billion for RCP 8.5. For the 2070-2099 era, these values grow by 46 percent (to $3.3 billion) and 132 percent (to $7.2 billion), respectively. These cost values represent averages across

GCMs. As shown in the last line of Figure 3-13, the range of estimates across GCMs is fairly wide relative to each average. As context for these results, road construction expenses across all levels of government (federal, provincial, and local) were approximately $17.1 billion in 2020.[21] The highest of the average values shown in Figure 3-13 below represents slightly less than one quarter of these costs.

When adaptation options are considered across the country, the opportunity exists to significantly reduce these costs through proactive adaptation. For RCP 4.5, this reduces the average annual cost to $532 million for the 2040-2069 time period and $591 million for the 2070-2099 period (for RCP 4.5). Similarly, for RCP 8.5, average annual costs under the proactive adaptation scenario are reduced to $295 million for the first era and $118 million for the second era. The latter estimate represents a reduction of 98 percent relative to the status quo scenario.

When viewed from the perspective of the individual climate stressors, there is a significant difference in terms of level of impact that each stressor has on the overall impact total. As shown in Figure 3-13 below, temperature is the primary source of costs for the Canadian road network. Specifically, increases in temperatures are projected to cause damages including increased cracking and surface weakening that will result in increased need for repairs and more frequent road rehabilitation. Based on the average across GCMs for each RCP/era combination, temperature accounts for 78 to 95 percent of costs under the status quo.

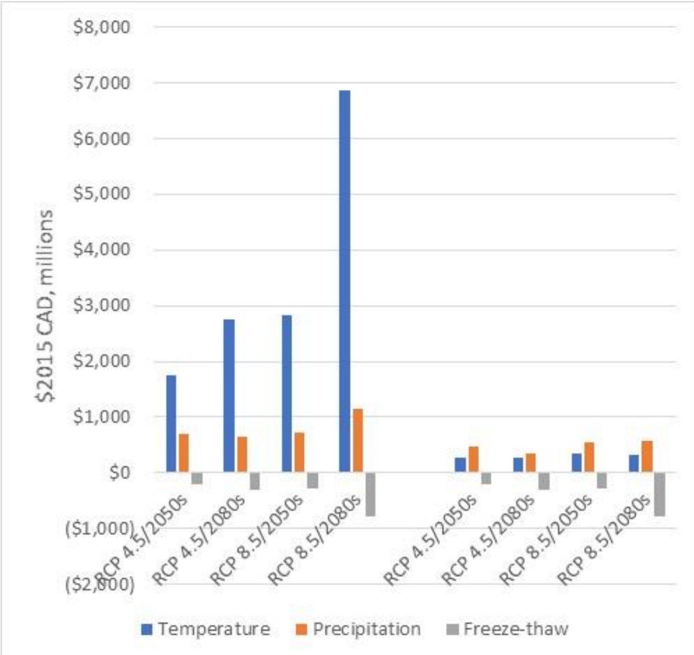
Precipitation is projected to result in significantly less damage to the road system than temperature change on a national basis under the status quo assumptions. As illustrated in Figure 3-13, we estimate that precipitation-related costs are just 26 to 40 percent of temperature-related costs under RCP 4.5 (depending on era) and 16 to 26 percent under RCP 8.5. These damages will primarily result from increased erosion as well as surface degradation occurring for both paved and unpaved roads.

The final stressor, freeze-thaw cycles, presents a small cost savings for Canada as warming temperatures will reduce the number of freeze-thaw cycles experienced in some parts of the country. As illustrated in Figure 3-13, these savings represent a small fraction of the costs associated with temperature change and precipitation under status quo conditions.

For both the precipitation and temperature stressors, the opportunity exists to implement proactive adaptation approaches that will result in reduced costs. We estimate that temperature effects can be reduced by slightly less than a full order of magnitude under RCP 4.5 and more than an order of magnitude under RCP 8.5. Similarly, annual precipitation effects can be reduced by approximately 30 percent under RCP 4.5 and 50 percent under RCP 8.5. As these changes illustrate, when proactive steps are taken to reduce road-related costs, the reduction in temperature-related costs is so significant that costs related to precipitation exceed costs related to temperature, unlike under the status quo scenario in which temperature-related costs dominate.

[21] Statistics Canada, "Infrastructure Economic Accounts, investment and net stock by asset, industry, and asset function", available at https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610060801; last modified 1 June 2021. Value reported as $18.5 billion for 2020; we adjusted for inflation using the Consumer Price Index.

FIGURE 3-13. ANNUAL ROAD COSTS BY STRESSOR ($2015 CAD, BILLIONS)



STRESSOR	Status Quo				Proactive			
	2040-2069		2070-2099		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Temperature	$1,752	$2,760	$2,818	$6,857	$262	$264	$340	$318
Precipitation	$697	$658	$733	$1,143	$479	$334	$535	$570
Freeze-thaw	($207)	($301)	($281)	($771)	($209)	($303)	($284)	($771)
Total (GCM average)	**$2,242**	**$3,117**	**$3,270**	**$7,229**	**$532**	**$295**	**$591**	**$118**
Range	$563 to $3,791	$837 to $5,049	$1076 to $4,859	$1,958 to $11,745	$287 to $949	$19 to $558	$277 to $1013	($363) to $944

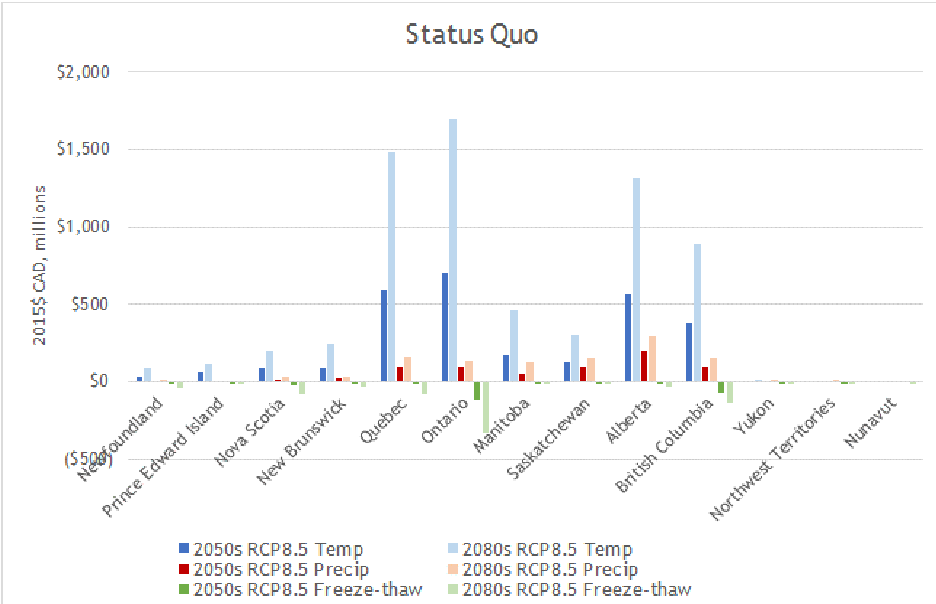
The estimated costs for the roads category also vary significantly both spatially and temporally. As indicated in Table 3-19 below, costs are projected to be highest for Alberta, Ontario, and Quebec, the three provinces with the most extensive road networks. The high costs for Alberta also reflect significant precipitation-related effects. While temperature-related costs for Alberta are comparable to the corresponding costs in Ontario and Quebec, precipitation-related costs for Alberta are approximately double those projected for either Ontario or Quebec. Table 3-19 also shows that status quo costs increase between the two eras, particularly for RCP 8.5 under which annual costs more than double between eras. Most of this increase is due to temperature effects on paved roads (see top panel of Figure 3-14 below).

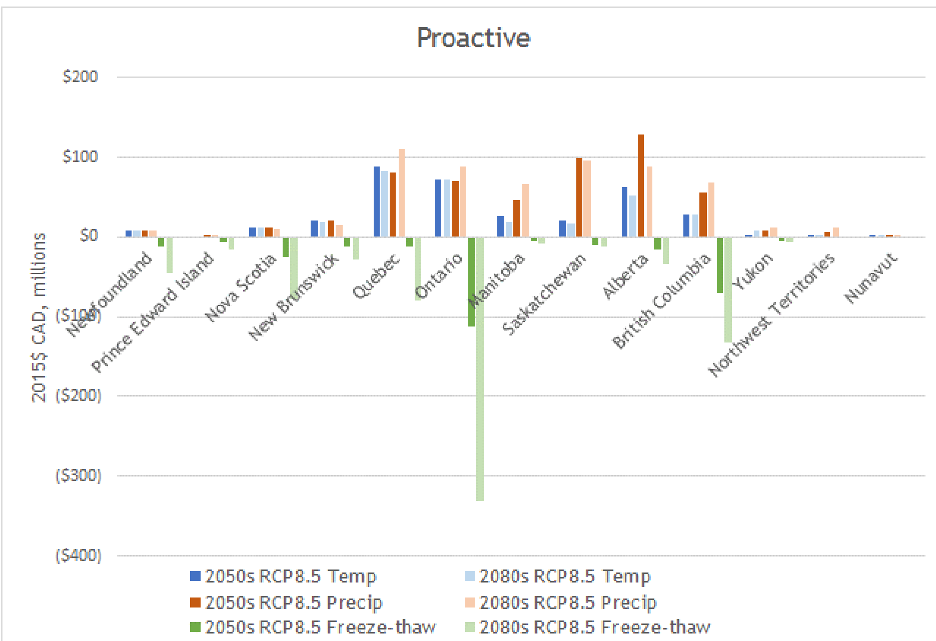
TABLE 3-19. AVERAGE ANNUAL UNDISCOUNTED CLIMATE CHANGE COSTS FOR ROADS BY PROVINCE/TERRITORY AND ERA (MILLIONS OF 2015 CAD$)

Province/Territory	Status Quo				Proactive			
	2040-2069		2070-2099		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Alberta	$553.4	$750.3	$698.9	$1,580.4	$179.6	$173.6	$62.0	$104.3
British Columbia	$295.8	$412.6	$420.2	$915.9	$25.2	$14.1	($5.3)	($37.1)
Manitoba	$162.3	$228.6	$253.4	$582.0	$52.7	$67.0	$47.9	$76.9
New Brunswick	$71.5	$112.2	$97.6	$255.8	$23.7	$29.8	$22.5	$4.3
Newfoundland and Labrador	$16.0	$28.3	$21.1	$65.7	$4.3	$3.4	($0.4)	($27.5)
Northwest Territories	$6.0	$8.5	$9.3	$20.6	$6.1	$8.1	$8.5	$13.1
Nova Scotia	$47.6	$76.8	$64.4	$154.7	($5.0)	($1.1)	($8.4)	($57.6)
Nunavut	$0.5	$0.8	$0.7	$1.4	$0.5	$0.8	$0.6	$1.4
Ontario	$460.0	$693.0	$679.1	$1,509.9	$21.7	$28.1	($10.7)	($173.4)
Prince Edward Island	$45.6	$60.7	$56.8	$103.6	($4.1)	($5.3)	($4.4)	($13.9)
Quebec	$417.7	$679.0	$610.4	$1,574.2	$136.7	$157.3	$114.9	$114.0
Saskatchewan	$160.2	$214.5	$202.1	$447.0	$85.2	$109.9	$64.6	$100.3
Yukon	$5.4	$4.8	$3.2	$18.1	$5.5	$4.8	$3.4	$12.8
TOTAL	**$2,242.0**	**$3,270.0**	**$3,117.1**	**$7,229.3**	**$532.4**	**$590.5**	**$295.1**	**$117.6**

Under the proactive scenario, however, we project that costs actually *decline* between the two eras. This reflects the combined effect of temperature and precipitation effects remaining fairly flat or slightly declining between the two eras because of the mitigating effect of proactive adaptation, while cost savings related to freeze thaw increase dramatically. Figure 3-14 shows these changes for RCP 8.5 for both the status quo and proactive scenarios. The green bars in the bottom panel of the figure show the significant growth in cost savings related to freeze thaw between the 2055 era and the 2085 era, while the blue and red bars, representing temperature and precipitation costs respectively, change minimally between the two eras. These increases in cost savings lead to the decline in annual costs under the proactive case between the two eras. In contrast, the temperature-related increases between the two eras under the status quo are much more significant than the cost savings from freeze-thaw.

FIGURE 3-14. UNDISCOUNTED COSTS BY ERA, PROVINCE, AND STRESSOR: RCP 8.5



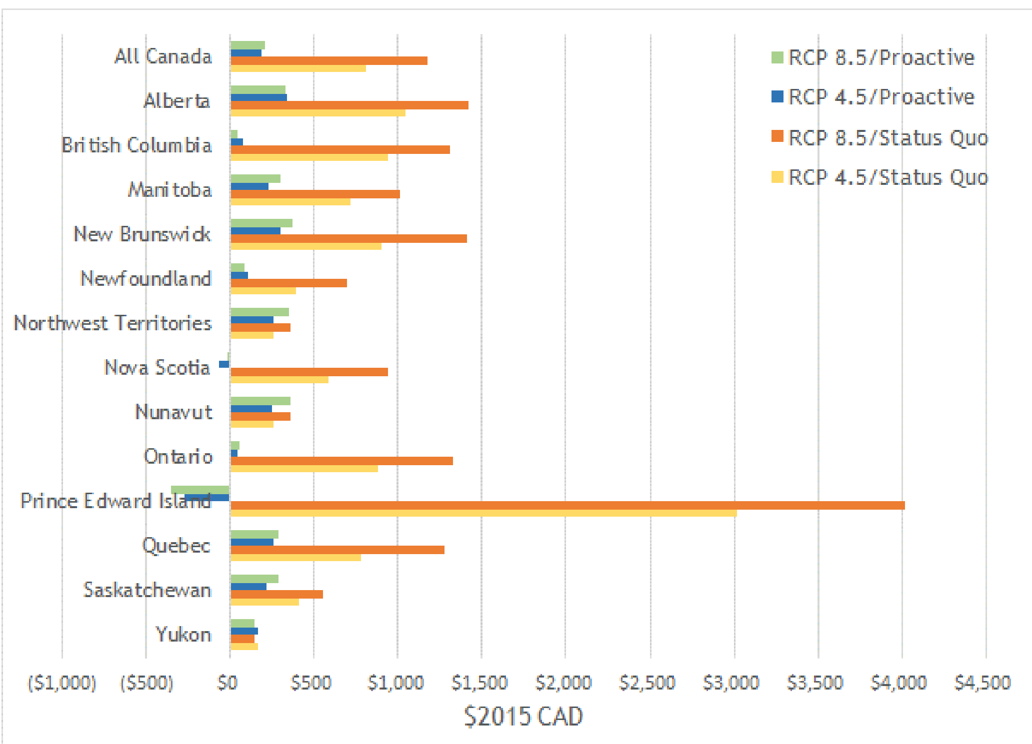


Note: Due to differences in the magnitude of costs between the status quo and proactive scenarios, the two graphs above use different ranges on their vertical axes.

As suggested by the results above, the majority of climate change costs for roads are associated with paved roads under the status quo. Cumulatively, the status quo costs for paved roads are $32 billion (average across GCMs) for RCP 4.5 and $61 billion for RCP 8.5. These figures represent more than 80 percent of estimated costs under the status quo. Under the proactive scenario, however, paved roads account for less than 15 percent of costs for RCP 4.5 and experience a cost savings under RCP 8.5. This reflects the focus of proactive adaption strategies on paved roads. For example, the introduction of proactive adaptation strategies is projected to reduce paved road costs by 97 percent for RCP 4.5 but reduce costs for unpaved roads by less than 15 percent.

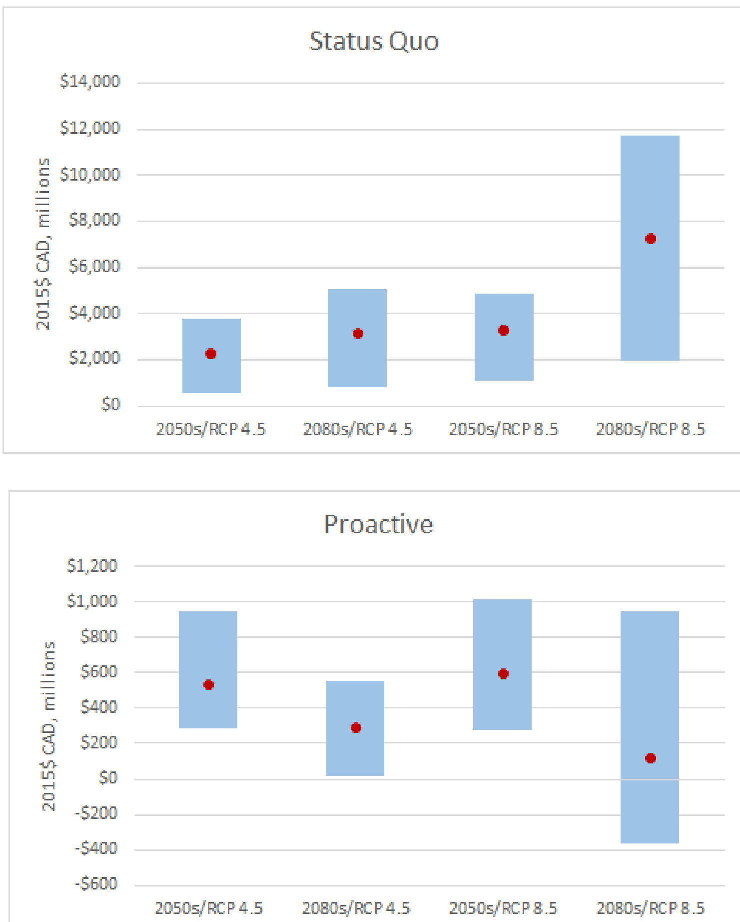
For additional insights on road-related costs at the provincial level, Figure 3-15 presents the undiscounted costs per lane km by province/territory for the first era (2040-2069) for each combination of RCP and scenario (status quo versus proactive). As the figure indicates, the costs per lane km of road are fairly consistent across Canada. For Prince Edward Island, however, costs per km are markedly high under the status quo scenario but are similar for Alberta, British Columbia Manitoba New Brunswick, Ontario, and Quebec. The high costs per km for Prince Edward Island reflect the relatively high costs for temperature-related effects, which are exclusive to paved roads, coupled with paved roads' comparatively large share of the Prince Edward Island road network (64 percent paved on Prince Edward Island versus 33 percent for all of Canada). In other words, the denominator for the cost per km in other provinces and territories mostly reflects unpaved roads, which drives down the cost per km in those areas, given that temperature-related costs for paved roads is the dominant cost. For Prince Edward Island, unpaved roads make up a smaller share of the denominator and therefore do not drive down the cost per km as much as for other provinces and territories. Figure 3-15 also shows that costs per lane km are much lower under the proactive scenario than under the status quo across all provinces, but costs per lane km in the territories are roughly the same under the two scenarios. This reflects the relatively low cost per lane km under the status quo in the territories. In addition, the results presented for the territories do not reflect roads located on permafrost, which are captured in the analysis of Northern Canada presented below.

FIGURE 3-15. AVERAGE UNDISCOUNTED COSTS PER ROAD LANE KM FOR THE 2040-2069 ERA ($2015 CAD)



While the results presented above reflect the best available information on the effects of climate change on the road network, the exact changes in climate reflected in these estimates are uncertain. For insight into this uncertainty, Figure 3-16 presents the range of undiscounted annual cost values across the seven GCMs used for this analysis for each combination of RCP and scenario. The average values across GCMs are represented by the red dots in the figure, and the blue bars represent the range between the minimum and maximum undiscounted cost estimates derived from individual GCM projections. As shown in the figure, the ranges around the average values are wider under the status quo than under the proactive scenario. This is due to the greater uncertainty in road repair costs under the status quo than in the costs of designing and building roads to be more resilient to a changing climate under the proactive scenario.

FIGURE 3-16. RANGE OF AVERAGE ANNUAL ROAD COSTS BY ERA, UNDISCOUNTED



Overall, the main takeaways from the analysis of road-related costs are:

- A proactive approach to adaptation can significantly reduce the costs of maintaining the current level of service provided by Canada's road network.

- Of the climate stressors examined, increased temperature contributes most significantly to increased costs under the status quo. When climate is proactively incorporated into road design and construction decisions, however, temperature accounts for a smaller portion of costs than precipitation and a similar portion of costs (in absolute terms) as freeze-thaw.
- While the overall effect of climate change is to increase the costs of maintaining and building roads in Canada, changes in freeze-thaw associated with climate change are projected to lead to a cost savings, partially offsetting the effects of higher temperatures and changes in precipitation patterns.

Limitations and Caveats

The major caveats and limitations to this approach are noted below.

- The stressor-response relationships applied in our analysis represent average relationships between climate and the physical conditions of roads. These relationships may vary geographically due to a number of location-specific factors not represented in our analysis such as the load on the road network in a given area and the age of the road network in different locations.
- As described above, the available information on the road network was somewhat incomplete, with road characteristic data missing for about 27 percent of road segments. While our approach for allocating these road segments to different road categories is reasonable, the incompleteness of the data represents a source of uncertainty in our analysis, though this uncertainty does not systematically bias our results in a particular direction.
- Our analysis assumes that the use of roads remains constant as the climate changes. To the extent that climate change itself or GHG mitigation policies reduce the use of roads, our analysis likely overestimates costs. Conversely, if climate change or carbon transitions lead to increased vehicle traffic, we may underestimate road-related costs.

3.2.2 RAIL

Climate change, in particular an increased frequency of extreme heat events, will impose costs on Canada's rail network. This section presents our analysis of these costs for the two 30-year eras described above (2050s: 2041-2070 and 2080s: 2071-2100). We estimate these costs under both a status quo scenario that reflects a reactive response to climate stress on the Canadian rail network and a proactive scenario in which rail owners/operators make forward-looking investments to minimize climate-related costs.

Methods

Similar to the roads analysis presented above, our assessment of the costs of climate change for Canada's rail network is based upon a detailed inventory of the Canadian rail network and stressor-response relationships that characterize how a changing climate can compromise the physical integrity of rail lines. We also draw on different engineering-based approaches for responding to such reductions in rail integrity. We describe each of these components of our analysis below.

Rail Inventory

As an initial step in our analysis, we developed a detailed inventory of the Canadian rail network based on data obtained from Natural Resources Canada (NRCan). The NRCan data split the rail network to multiple types of rail defined according to their current status and track class. Consistent with the road inventory described above, we distributed the NRCan rail inventory to a half degree by half degree grid and, for the purposes of this analysis, assumed that the rail inventory remains static over time. While the future size of the rail network is uncertain, the historical trend shows that the network shrunk by approximately 28 percent between 1990 and 2014.[22] If this trend were to continue into the future, our analysis would overestimate climate change costs for rail, all else equal. In addition, for the purposes of this analysis, we limited our assessment of climate change costs to rail lines characterized as main lines in the NRCan inventory. We excluded sidings, yard lines, spurs, and others because the traffic on these lines is typically low-speed and therefore less likely to buckle during days of extreme heat. Main lines represent approximately 72 percent of the rail-km in the NRCan inventory.

Table 3-20 shows the distribution of the rail network by province. As shown in the table, Ontario's rail network is the most extensive, followed by Saskatchewan, British Columbia, Alberta, and Quebec. The rail networks in the Maritimes and territories are much more limited.

TABLE 3-20. MAIN LINE RAIL LENGTH BY PROVINCE (KM)

PROVINCE	RAIL LENGTH (KM)
Alberta	6,646
British Columbia	7,181
Manitoba	4,829
New Brunswick	1,126
Newfoundland and Labrador	367
Northwest Territories	122
Nova Scotia	650
Nunavut	0
Ontario	11,102
Prince Edward Island	0
Quebec	6,172
Saskatchewan	8,202
Yukon	25
Total	**46,422**

Methods Overview

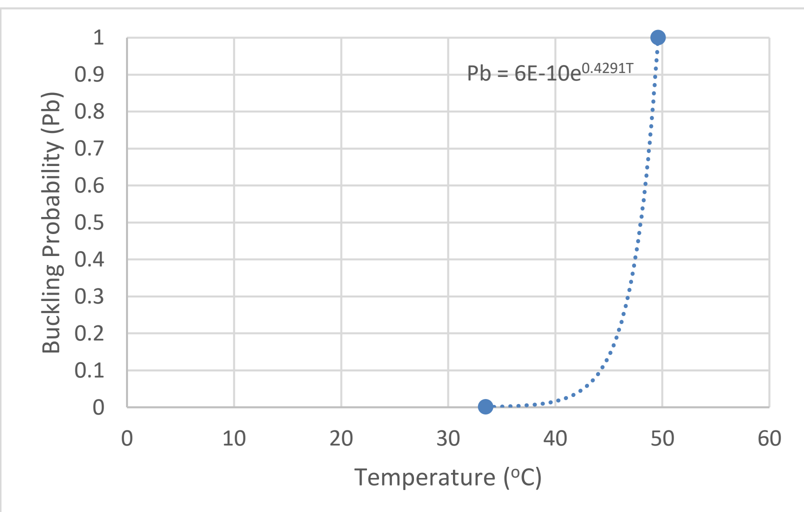
Our assessment of climate change costs for Canada's rail network draws on the methods described in Chinowsky et al. (2019), adapted for the Canadian context. These methods account for the effects of

[22] Statistics Canada, Transportation Data and Information Hub, Table 11-1: System Extent and Facilities (Kilometers), available at https://www144.statcan.gc.ca/nats-stna/tables-tableaux/tbl11-1/tbl11-1-CAN-eng.htm, accessed July 11, 2020.

track expansion and buckling during extreme heat events. During these events, tracks under heavy loads (i.e., tracks with heavy trains traveling at high speed) are subject to increased buckling risk. As described further in the limitations section below, because extreme cold may also pose risks for the rail network, rising temperatures may reduce such risk. To our knowledge however, the existing literature has not quantified the relationship between changes in cold-related climate stress and changes in rail repair, maintenance, or investment costs.

For the status quo scenario, our analysis reflects rail operators implementing temporary speed orders that result in blanket speed reductions in areas where the expected daily high exceeds a temperature that is deemed unsafe, based on current operator policies. The specific effects that we estimate at the grid cell level for the status quo scenario include the repair costs associated with track buckling and the total hours of train delays (by year).[23] With respect to the former, although blanket speed orders reduce the probability of track buckling, they do not reduce the probability to zero. Thus, consistent with Chinowsky et al. (2019), we estimate the probability of track buckling using the functional relationship established by Kish and Samavedam (2013). Under this approach, the probability of track buckling is based on the relationship between (1) the change in temperature relative to the track neutral temperature (ΔT) and (2) buckling energy (the energy required to buckle the track). At the upper critical temperature ($T_{b,max}$), a track will buckle with no external energy acting upon it and the probability of buckling is 100 percent (P_b=1). At the lower critical temperature ($T_{b,min}$), the risk of buckling is zero. Between $T_{b,min}$ and $T_{b, max}$, we assume that the probability of buckling increases exponentially as shown in Figure 3-17, based on work by the Volpe Center, Foster-Miller, Inc. (FMI), and the Federal Railroad Administration (FRA) that expanded upon Kish and Samavedam (2013).

FIGURE 3-17. RELATIONSHIP OF BUCKLING PROBABILITY TO AIR TEMPERATURE



[23] These delays are monetized according to the methods described in the delay cost section later in this document.

Using the relationship shown in Figure 3-11, it is possible to estimate the number of buckling events per year (per grid cell) using the following equation:

$$e_b = \frac{(P_b \times P_T \times n_t \times 365 \times L)}{L_t} \quad (3)$$

Where

e_b = Expected number of buckling events

P_b = Probability of buckling at rail temperature

P_T = Annual rail temperature frequency

n_t = Number of trains per day

L = Total length of track

L_t = Length of train

For each buckling, we apply a repair cost of $26,601 CAD based on Gordian (2017), adjusted to Canadian dollars based on the purchasing power parity-adjusted exchange rate.

For the proactive adaptation scenario, we assume that train operators install track temperature sensor technology that allow them to implement a risk-based approach to speed orders, as described in Chinowsky et al. (2019). This risk-based approach allows train operators to target speed orders to specific lines based on the temperature and the traffic expected on that line during extreme heat events. In contrast, a blanket speed order is less targeted and applies to all rail lines in a region, resulting in more significant delays. Our analysis for this proactive scenario estimates the costs of purchasing, installing, and maintaining these sensors and the associated software systems. In addition, we estimate the hours of delay per grid cell using the same approach as applied for the status quo scenario.

Results

Overall, the Canadian rail network will experience effects from projected climate change due to increases in temperature. As the temperature increases over historic levels, the potential for rails to fail due to buckling increases. To offset this possibility, slowdown orders must be put in place across an entire section of the network to reduce the pressure on weaker rails. Table 3-21 presents the annual rail repair and investment costs under RCP 4.5 and RCP 8.5 for both the status quo and proactive adaptation scenarios.[24] As the results in the table show, estimated climate change costs related to the rail network are significantly higher under the status quo scenario than under the proactive scenario. For RCP 4.5, costs under the status quo are more than five times greater than the costs of proactive adaptation. For RCP 8.5, the costs under status quo operations are greater than the costs of proactive action by a factor of 25.

As noted above, costs under the status quo scenario are the repair costs associated with buckling events, while costs under the proactive scenario are the costs of obtaining and using track temperature sensors to prevent buckling events in a more targeted manner. Based on the results in Table 3-21 alone, the cost of

[24] As noted above, the monetized value of time delays are presented in the section below on delay costs.

investing in sensors under the proactive scenario yield significantly greater repair cost savings (i.e., costs under the status quo). For each RCP, the results in the table represent annual undiscounted costs averaged across GCMs. On an average annual basis, the costs associated with buckling are fairly flat under RCP 4.5 and the status quo at approximately $6 to $7 million per year. Under RCP 8.5, status quo costs are not only higher but also increase by more than a factor of three between eras, from $18.2 million during the 2050s era to $60.8 million under the 2080s era. The sensor-based proactive adaptation strategy, under which sensors can pinpoint more precisely where speed reductions need to be put in place, significantly reduces costs under both RCP 4.5 and RCP 8.5. Under both RCPs, we estimate that this strategy reduces costs by more than 80 percent during both eras.

For context on the results shown in Table 3-21, the combined operating expenses of Canadian Pacific and Canadian National, the country's two biggest rail operators, were approximately $14 billion in 2019.[25] The costs shown in Table 3-21 are less than 0.5 percent of this value. As highlighted in Section 3.5, however, the delay cost impacts associated with rail are much more significant than the operating cost impacts shown in Table 3-21.

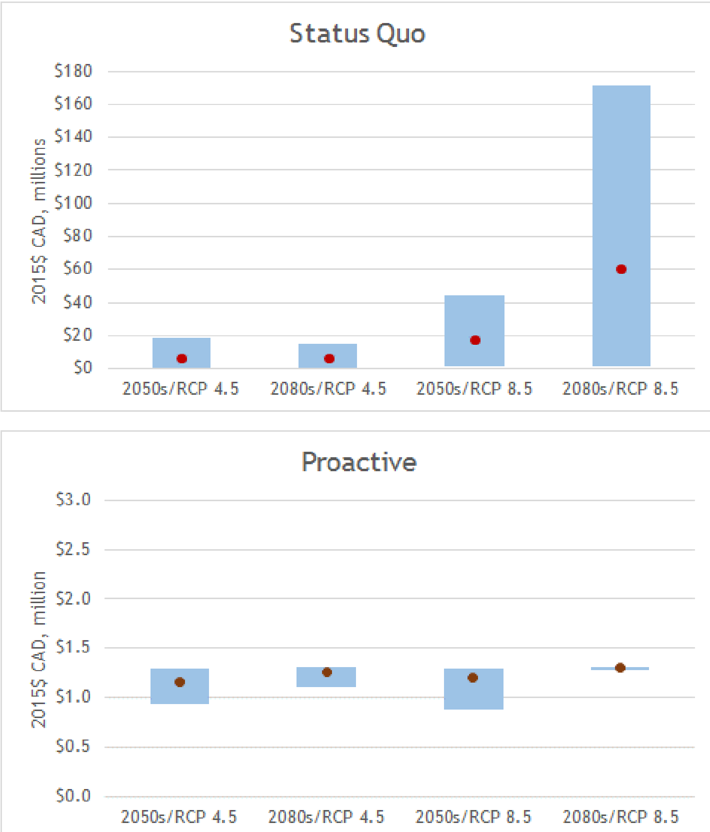
TABLE 3-21. AVERAGE ANNUAL RAIL SYSTEM UNDISCOUNTED COSTS BY ERA (MILLIONS OF $2015 CAD)

RCP	SCENARIO	2040-2069	2070-2099
RCP 4.5	Status Quo	$6.7	$6.3
	Proactive	$1.2	$1.3
RCP 8.5	Status Quo	$18.2	$60.8
	Proactive	$1.2	$1.3

To provide insight into the uncertainty around each of the values shown in Table 3-21, Figure 3-18 shows the range of undiscounted average annual values across GCMs for each combination of RCP and scenario. The average values across GCMs are shown with the red dots in the figure. As indicated in the figure, the ranges around the average values are much wider in both proportional and absolute terms under the status quo scenario than under the proactive scenario. This reflects the greater uncertainty in repair costs under the status quo than in the costs of applying sensors under the proactive scenario.

[25] The $14 billion reflects $4.7 billion in operating expenses for Canadian Pacific and $9.3 billion in operating expenses for Canadian National. Both values are from the companies' respective annual reports for 2019.

FIGURE 3-18. RANGE OF AVERAGE ANNUAL RAIL SYSTEM UNDISCOUNTED COSTS BY ERA



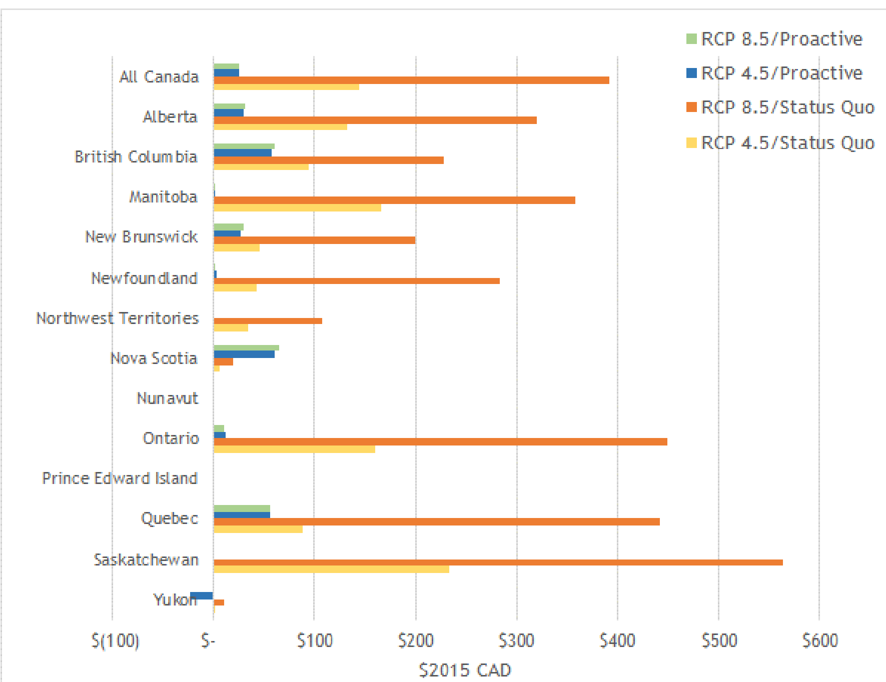
Expanding upon the national results shown above, Table 3-22 presents the estimated costs to the rail system by province/territory and era. Overall, costs under the status quo are greatest for Ontario. This result is consistent with the size of Ontario's rail network relative to other provinces and territories. Under the proactive scenario, the distribution of costs across provinces and territories differs somewhat from the status quo, but costs are still concentrated in the provinces with the most extensive rail networks. Table 3-18 also shows that the proactive approach is effective in reducing the costs of climate change across all of Canada, with such savings approaching a full order of magnitude in most provinces/territories. For example, average annual rail-related costs in Ontario under RCP8.5 decline from $15.4 million under the status quo in the 2080s to $0.2 million when proactive action is taken.

TABLE 3-22. AVERAGE ANNUAL UNDISCOUNTED RAIL SYSTEM COSTS BY PROVINCE AND ERA ($2015 CAD, MILLIONS)

Province/Territory	Status Quo				Proactive			
	2040-2069		2070-2099		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Alberta	$0.9	$2.1	$0.9	$8.5	$0.2	$0.2	$0.2	$0.2
British Columbia	$0.7	$1.6	$0.6	$7.0	$0.4	$0.4	$0.5	$0.5
Manitoba	$0.80015	$1.7	$0.6	$5.6	$0.0	$0.0	$0.0	$0.0
New Brunswick	$0.1	$0.2	$0.0	$0.8	$0.0	$0.0	$0.0	$0.0
Newfoundland and Labrador	$0.0	$0.1	$0.0	$0.3	$0.0	$0.0	$0.0	$0.0
Northwest Territories	$0.0	$0.0	$0.0	$0.1	$0.0	$0.0	$0.0	$0.0
Nova Scotia	$0.0	$0.0	$0.0	$0.0	$0.0399	$0.0423	$0.0467	$0.0485
Nunavut	$0.0	$0.0	$0.0	$0.0	$0.0000	$0.0000	$0.0000	$0.0000
Ontario	$1.8	$5.0	$1.9	$15.4	$0.1	$0.1	$0.2	$0.2
Prince Edward Island	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Quebec	$0.5	$2.7	$0.50	$9.8	$0.3	$0.4	$0.4	$0.4
Saskatchewan	$1.9	$4.6	$1.8	$13.3	($0.0)	$0.0	$0.0	$0.0
Yukon	$0.0	$0.0	$0.0	$0.0	($0.0)	$0.0	$0.0	$0.0
TOTAL	**$6.7**	**$18.2**	**$6.3**	**$60.8**	**$1.2**	**$1.2**	**$1.3**	**$1.3**

For additional perspective on these estimates at both the provincial and national level, Figure 3-19 presents the undiscounted costs per rail km by province/territory for the first era (2040-2069) for each combination of RCP and scenario (status quo versus proactive). As the figure indicates, the costs per km of rail vary across Canada and, under the status quo, are highest in Saskatchewan. In addition, per-km rail costs are significantly lower in most areas when proactive action is taken to adapt the operation of the rail network to a changing climate. The one exception is Nova Scotia, where rail repair costs per km under the status quo are projected to be quite low relative to the rest of Canada.

FIGURE 3-19. AVERAGE UNDISCOUNTED COSTS PER RAIL KM FOR 2040-2069 ($2015 CAD)



Overall, the main takeaways from this analysis are:

- The costs of the status quo far outweigh costs under the proactive adaptation scenario, even without considering the monetized impact of time delays, which are addressed in the delay cost section below. This strongly suggests that the proactive approach to adaptation considered here—the use of track temperature sensors as part of a risk-based approach for managing speed orders—represents a more cost-effective approach for managing climate change risk than the status quo repair-based approach.
- The repair and investment costs presented here are fairly small compared costs for the other categories of infrastructure presented in this report. However, as described below, the delay cost impacts associated with heat stress on the rail network are much more significant than rail-related repair and investment costs.
- Climate change costs for rail are largely concentrated in those provinces with the most extensive rail networks,

Limitations and Caveats

The major caveats and limitations to this approach are noted below.

- We note that one potentially important limitation of our approach for the proactive scenario is that some transit agencies may already have rail sensors capable of monitoring rail temperatures that would enable changes in the issuance of speed orders. Anecdotally, we understand that some rail operators such as Metrolinx in the Toronto area may have begun limited use such sensors, though we are uncertain about the degree to which sensors have been installed by other rail operators.[26] Similarly, it is unclear whether any rail operators already possess the software necessary to use sensors in a manner that would allow them to reduce the frequency of speed orders. Due to these uncertainties, our analysis assumes that all rail operators would need to purchase both sensors and the associated software systems under the proactive scenarios. To the degree that such systems are fully or partially in place already, we may overestimate the costs under the reactive scenario as well as the costs of proactive adaptation incremental to current practice.
- In addition to the sensor-based approach that we examine here, rail operators could potentially implement other technologies or approaches to adapt proactively. Potential options include longitudinal stress monitoring or a combination of neutral ambient temperature and rail temperature difference thresholds. The degree to which the cost of these approaches would differ from the sensor-based approach examined in this analysis is uncertain but we expect that they would be roughly equivalent.
- Relevant to both the proactive and reactive scenarios, another limitation of our approach is that it does not account for the extent to which climate change may reduce cold-related speed orders during the winter months. Under extreme cold conditions, switches on the rail system occasionally freeze up and cease to function properly, necessitating the issuance of speed orders.

[26] Personal communication with Quentin Chiotti, Senior Advisor Sustainability & SME Climate Resiliency, Metrolinx; June 10, 2020.

In addition, as documented in Zhang et al. (2018), extreme cold can cause rail breaks by reducing the tensile strength of steel rails. Increased temperatures could lead to reduced frequency of these events, resulting in a cost savings. To our knowledge, no studies in the literature have quantified the relationship between temperature and the frequency of cold-related speed orders.

3.3 NORTHERN CANADA

Our analysis of climate change costs in Northern Canada focus on damages to roads, runways, and buildings and the corresponding adaptation costs where applicable. To assess these effects, we integrate the methods applied in Melvin et al. (2017) with those applied by IEc in our analysis of winter road impacts for Canada's NRTEE (Industrial Economics 2010). Consistent with our analysis of climate change costs for transportation infrastructure (see above), we will perform this analysis using IPSS.

Table 3-23 identifies the specific types of infrastructure that will be captured in our analysis of Northern Canada, the climate stressors and related damage sources affecting each infrastructure type, and the responses available under either a status quo scenario or proactive adaptation scenario.

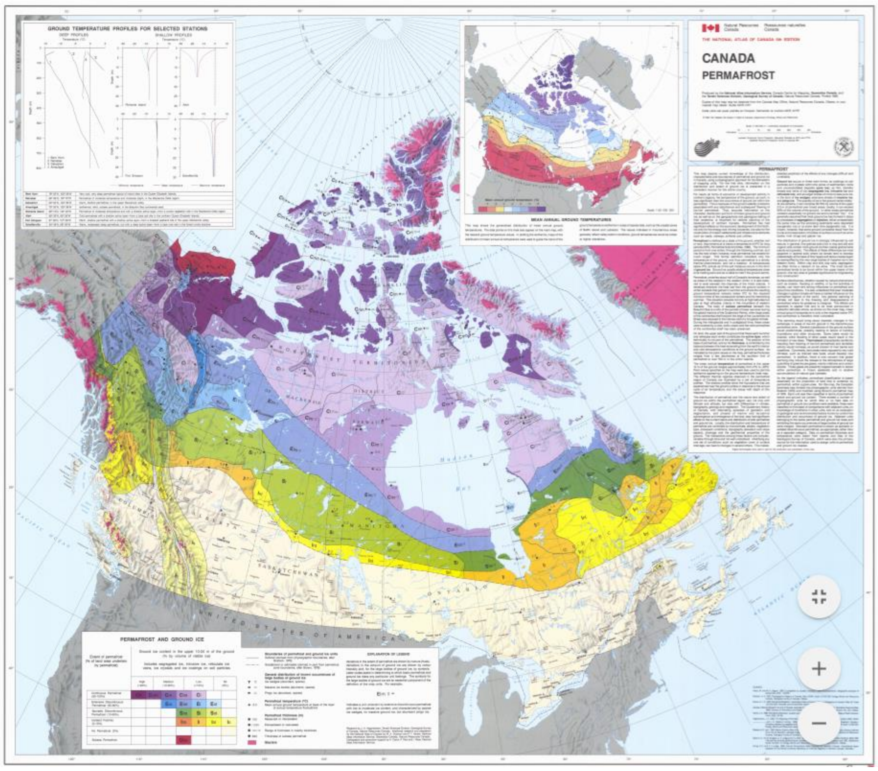
TABLE 3-23. SUMMARY OF CLIMATE CHANGE DAMAGES AND SCENARIO ASSUMPTIONS FOR NORTHERN CANADA

INFRASTRUCTURE TYPE	STRESSOR	DAMAGE SOURCE(S)	RESPONSES
Roads (excluding winter roads)	Permafrost thaw	Cracking, subsidence	Base layer modification, air-cooled embankments, thermosyphon installation
Airport Runways	Temperature	Surface degradation & increased roughness due to thermal cracking & rutting.	Increased repair costs due to climate-related damage.
	Permafrost thaw	Cracking, subsidence	Base layer modification, air-cooled embankments, thermosyphon installation
Winter roads	Temperature	Melting ice	Construct all-weather road
Buildings	Permafrost thaw	Cracking, subsidence	Additional maintenance, thermosyphon installation, Rebuilding of the structure

3.3.1 PERMAFROST THAW

Permafrost thaw represents an important climate stressor for Northern Canada that will impose costs on multiple types of infrastructure, including roads, buildings, and runways (see Melvin et al. 2017, Hjort et al. 2018). This analysis is a high-level assessment of the potential costs of permafrost thaw on these three infrastructure categories and covers Northern Canada, including the three territories and the northern tiers of the majority of the provinces. The official permafrost map of Canada is presented in Figure 3-20 below. Absent an existing model for Canada capable of projecting permafrost thaw (discussed further below), we first develop a reduced-form permafrost damage index, and then project this index for each decade at a 1/12° spatial resolution through the end of the 21st century, under the 14 GCM/RCP projections. Shifts in the index over time then drive infrastructure impacts and responses under three adaptation scenarios.

FIGURE 3-20. CURRENT PERMAFROST CONDITIONS ACROSS CANADA



Source: Heginbottom et al. (1995). Downloaded from:
http://ftp.geogratis.gc.ca/pub/nrcan_rncan/raster/atlas_5_ed/eng/environment/land/mcr4177.pdf

Methods

The objective of this analysis is to provide an estimate of infrastructure damage from permafrost thaw in Northern Canada. The analysis follows four steps, which are described briefly here. More detail follows.

1. **Build infrastructure inventory.** Develop an inventory including roads, buildings, and runways.
2. **Develop and project permafrost damage index** that scales based on excess ground ice content (GIC) in the uppermost 5 m of the permafrost and changes in ground surface temperature. Spatial GIC data were resolved to an appropriate spatial resolution, and ground surface temperature projections were developed based on projected changes in thawing and freezing degree days under each GCM and RCP.
3. **Structure adaptation scenarios and response costs**. Create a set of three adaptation scenarios that are triggered at specified damage index thresholds, and associated response costs.
4. **Estimate damages to infrastructure inventory**, under the three adaptation scenarios.

Step 1. Build Infrastructure Inventory
Only infrastructure in permafrost zones is considered in this analysis, which has the following effect: (a) the majority of included infrastructure is in Yukon and the Northwest Territories, with much smaller but still substantial amounts in Manitoba and Nunavut; (b) minimal infrastructure in Quebec, Ontario, Saskatchewan, Alberta, British Columbia, and Newfoundland and Labrador is included; and (c) infrastructure on Prince Edward Island, Nova Scotia, and New Brunswick is excluded entirely. Analytically, we only include infrastructure that spatially overlaps with the non-zero GIC levels (see the GIC map below).

The three categories of infrastructure considered in this analysis include:

- **Roads**. The roads inventory is described in depth in the Transportation section above, but in brief, the inventory is from DMTI for the provinces and CanVec (Government of Canada 2020) for territories, and includes (1) paved versus unpaved, (2) road type (e.g., highways, local streets), (3) surface type (e.g., asphalt versus concrete for paved roads and gravel versus dirt for unpaved roads), and (4) number of lanes. Within these datasets, approximately 38,000 lane km of paved roads and 97,000 lane km of unpaved roads are located in permafrost zones (Table 3-24).

TABLE 3-24. LENGTH OF ROAD NETWORK ON PERMAFROST (LANE KM)

Type	Primary	Secondary	Tertiary	Total
Paved	26,706	3,298	7,941	37,946
Gravel	5,150	5,525	86,282	96,957

Source: DMTI and Government of Canada

- **Buildings**. We rely on an open source dataset of roughly 12 million computer generated building footprints across provinces and territories (see Table 3-25), with additional data provided by the Government of Nunavut. This dataset is translated into the amount of building area contained within each of the 1/12° gridcells we analyze. After intersecting building area with non-negligible GIC, total building area included in the study is 42.5 million square meters.

TABLE 3-25. NUMBER OF BUILDINGS ACROSS CANADIAN PROVINCES AND TERRITORIES

Province/Territory	Number of Buildings
Alberta	1,777,439
British Columbia	1,359,628
Manitoba	632,982
New Brunswick	350,989
Newfoundland and Labrador	255,568
Northwest Territories	13,161
Nova Scotia	402,358
Nunavut	11,085
Ontario	3,781,847
Prince Edward Island	76,590
Quebec	2,495,801

Province/Territory	Number of Buildings
Saskatchewan	681,553
Yukon	11,395

Sources: https ://cgs-pals.ca/downloads/gis/ for Nunavut, and https://github.com/Microsoft/CanadianBuildingFootprints for all other provinces and territories.

- **Airports.** 290 airports are included in the analysis. The list of airports in this analysis are below, and all are in either the Northwest Territories or Nunavut. Runway lengths vary from 400 to 3,000 meters and widths vary from 10 to 90 meters, which are drawn from the Canadian Flight Supplement on runway length, material, and operational status. There are private and unmaintained airstrips across Northern Canada, servicing mines, Department of Defense radar sites, and culturally significant sites and hunting grounds. Despite the importance of these air strips, we did not include unmaintained and private airstrips because we were not able to determine if and how long they would be operational.

Step 2. Develop and Calculate Permafrost Damage Index

To analyze costs of permafrost thaw, we must first estimate the degree to which climate change leads to thaw over the time period of our analysis. There are several complexities that will drive costs, including site-specific ice content, drainage and disturbance conditions, delays between atmospheric changes and permafrost thaw, and that bearing capacity falls before complete thaw (Lewkowicz 2020). The preferred approach to address these challenges would be to rely on existing projections or a detailed numerical model similar to that employed by Melvin et al. (2017) in Alaska; however, no such projections or model currently exist for Canada. The Permafrost Partnership Network for Canada (PermafrostNet) – which is a project funded by the Natural Sciences and Engineering Research Council of Canada – is currently developing projected permafrost conditions under a range of climate models, however these projections were not available in the timeline for this study.[27]

Absent either a model or existing projections, we develop a permafrost damage index that relies on two variables: ground ice content (GIC) and modelled ground surface temperature (see Lewkowicz 2020). This draws on principles developed within the temperature at the top of the permafrost (TTOP) methodology employed by Obu et al. (2018), which allows us to relate air temperature to ground surface temperature. Importantly, the aim of this effort is not to develop permafrost projections for site-specific adaptation recommendations, but rather to understand the possible territorial and national-level effects of permafrost thaw.

The damage index was calculated according to the following steps:

Step 2a. Predict mean surface temperature (T_s) for each grid cell for the highway or runway centerline, embankment toe, and building footprint for the baseline period (1986 to 2005) and for each future decade (2020 to 2090 with a one decade lag) under each climate scenario. This requires calculating the freezing and thawing degree days for air temperature (FDD_a and TDD_a; using an approach in Smith and Riseborough 2002) at each grid cell, and then multiplying these by n-factors to develop FDD_s and TDD_s for the ground surface. These are then summed and divided by 365 to generate baseline and projected

[27] Based on written communication with Stephan Gruber of Carleton University, on February 24, 2020.

mean T_s values.[28] Figure 3-21 shows the mean annual baseline TDD_a and FDD_a patterns, and Figure 3-22 shows projected patterns across the 2050s and 2080s eras, the two RCPs, and GCMs with the least and most warming through the 2080s. Note that TDD_a tends to increase most in the southern latitudes, whereas FDD_a tends to decline by far the most in northern regions.

FIGURE 3-21. MEAN ANNUAL TDD_a (LEFT) AND FDD_a (RIGHT) FOR 1986-2005 (°C DAYS)

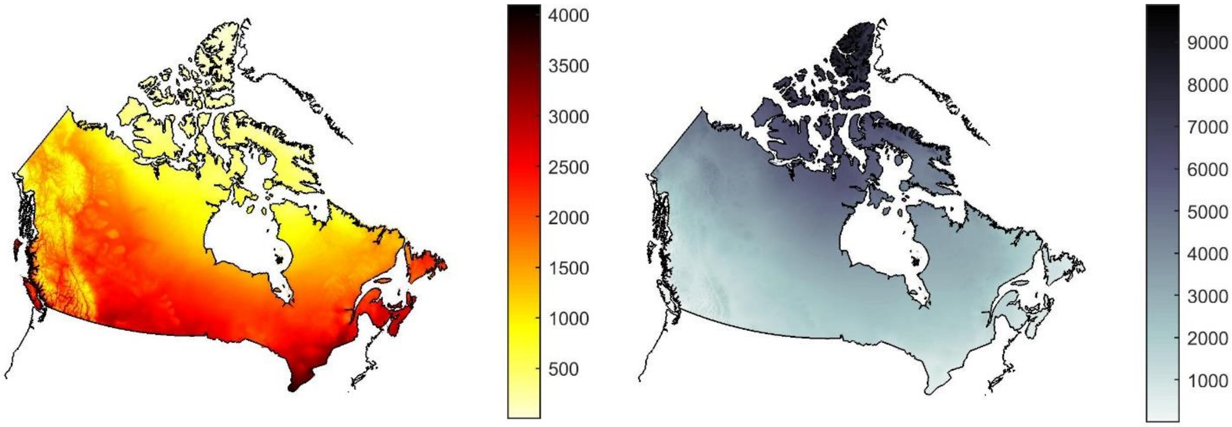
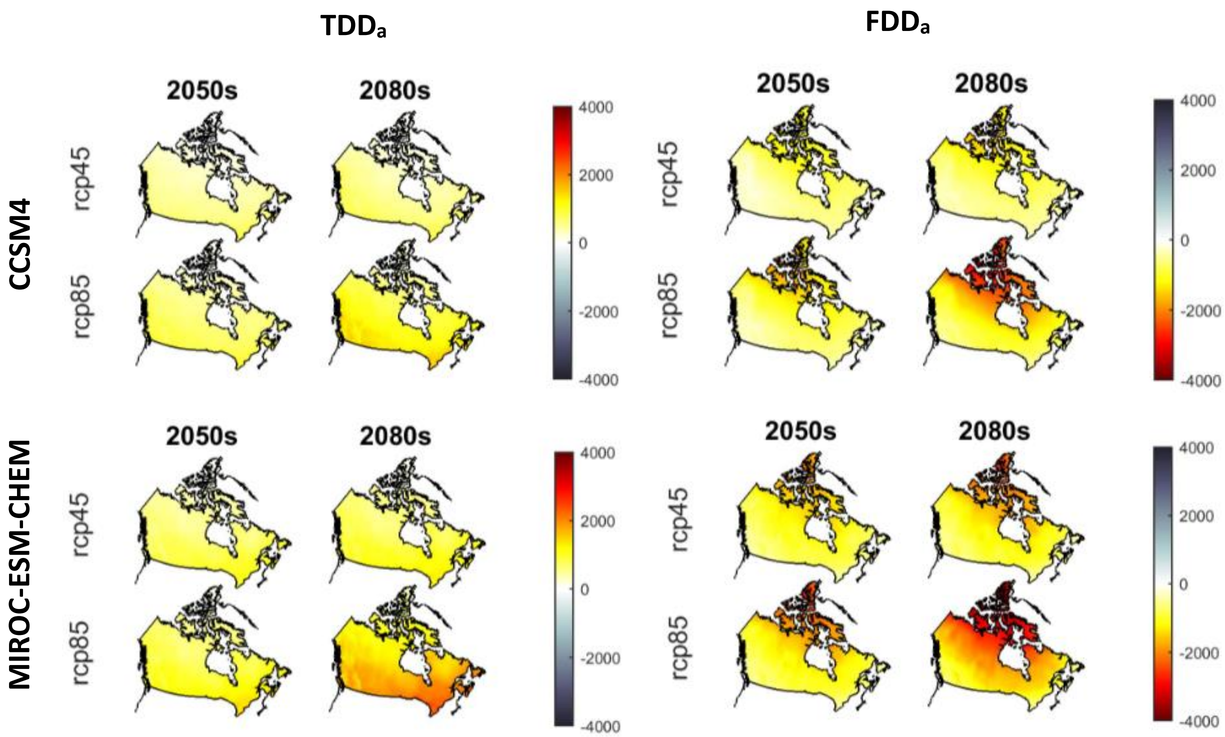


FIGURE 3-22. MEAN PROJECTED CHANGES IN TDD_a AND FDD_a FOR TWO GCMs (°C DAYS)



---

28 Note that for modelling purposes, we calculate FDD_a and TDD_a within calendar years. In reality, the thawing index is for a single summer while the freezing index runs across two years (i.e. from the start of freezing in the fall through to the end of freezing the following spring).

Table 3-26 below presents the n-factors used for roads, runways, and buildings.

TABLE 3-26. FREEZING AND THAWING N-FACTORS FOR HIGHWAY SURFACES

Infrastructure		n_f	n_t
Gravel roads and runways	Centerline	0.7	1.1
	Embankment Toe	0.35	1.05
Paved roads and runways	Centerline	0.8	1.4
	Embankment Toe	0.35	1.05
Beneath Buildings		0.45	0.7

Sources: Written correspondence with Antoni Lewkowicz, who relied on Darrow (2011) for roads/runways, and Oswell and Nixon (2015) for buildings. Values for the embankment toes are the averages measured at two Alaskan sites.

Step 2b. Take the difference between the baseline and projected T_s values for the centerline, embankment toe and building footprint for a given grid cell to predict the thaw intensity values for any given decade from Table 3-27. Note that these values have an 'upside down U' shape, where thaw intensity increases until 0°C, and then fall as warming continues and all excess GIC has thawed. However, there is no way to 'leapfrog' past this point on the curve – if full thawing is projected under climate change in a given grid cell, impacts can be delayed but not avoided. Note that for runways and roads, thaw intensity will differ between the centerline and embankment, such that the damage levels will vary as well.

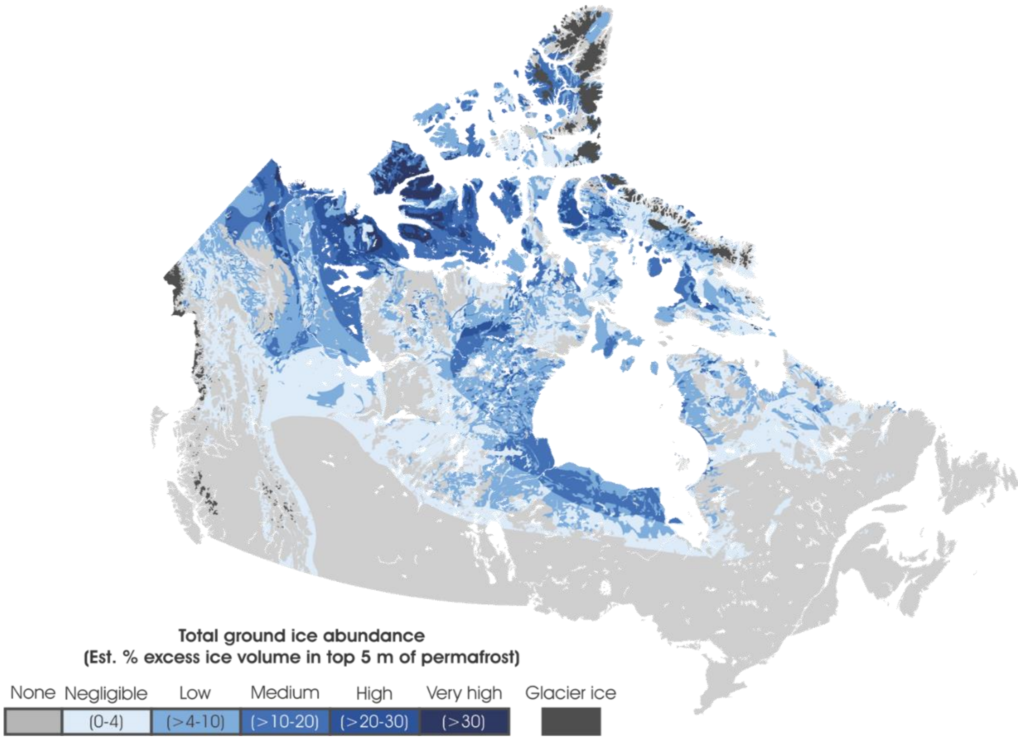
TABLE 3-27. ASSUMED RELATIVE THAW INTENSITY VALUES (0-5) IN RELATION TO BASELINE AND PROJECTED TS (°C)

Baseline T_s	Projected decadal T_s								
	<-2.0	-2.0 to -1.5	-1.5 to -1.0	-1.0 to -0.5	-0.5 to 0.0	0.0 to +0.5	+0.5 to +1.0	+1.0 to +2.0	+2.0 to +3.0	>+3.0
<-2.0	0	1	2	2	3	5	4	3	2	0
-2.0 to -1.5		0	2	2	3	5	4	3	2	0
-1.5 to -1.0			0	2	3	5	4	3	2	0
-1.0 to -0.5				0	3	5	4	3	2	0
-0.5 to 0.0					0	5	4	3	2	0
0.0 to +0.5						0	4	3	2	0
+0.5 to +1.0							0	3	2	0

Note: If T_s values are greater than +1.0°C under baseline climate then it is assumed that any ongoing thaw is due to the disturbance associated with the highway and is unrelated to future climate change. Once T_s values exceed 3°C permafrost is assumed to have thawed out or if still present at depth, to be thawing so slowly and with a low enough excess ice content that it does not to affect infrastructure.
Source: Lewkowicz 2020.

***Step 2c*.** Extract the excess ice content for each grid cell from O'Neill et al. (2012). We rely on the latest GIC information across Canada from O'Neill et al. (2020; see Figure 3-23). We apply the center point of each range in the damage index calculation, e.g., negligible is 2, low is 7, and so on.

FIGURE 3-23. EXCESS GROUND ICE CONTENT IN TOP 5M



Source: O'Neill et al. 2020 (or in press)

Step 2d. Calculate the damage index as thaw intensity from Step 2b multiplied by GIC from Step 2c. These are calculated for each climate scenario, decade, and across the centerline, embankment toe and building footprint. The index varies in space and time between 0 and greater than 150 because the highest category of excess ice content in the ground ice map is greater than 30 percent.

Step 3. Structure Adaptation Scenarios and Response Costs

The damage index is then linked to specific adaptation responses, which are linked to costs. Reactive and proactive measures are detailed in Table 3-28. Reactive and proactive options differ where the text in the table is red – for instance, instead of foundation repair in response to moderate damages, a proactive response would install thermosyphons. We apply the threshold approach from Melvin et al. (2017) to identify where critical foundation damage is likely to occur. For buildings located in areas where the critical threshold is met, we estimate climate change costs under both the status quo and proactive scenarios as the cost of rebuilding the entire building, using cost data from RSMeans (2016; https://rsmeansonline.com/). We assume the same costs for the status quo and proactive scenarios because the only foreseeable response is rebuilding (either in response to damage from thawed permafrost or in advance of expected permafrost thaw).[29] For roads and runways, we identify where thaw is likely to result in asset failure using the same approach specified in Melvin et al. (2017). Similar to buildings, costs for roads and runways will be the same under the status quo and proactive adaptation scenarios, based on the cost of reinforcement of the road/runway base layer, reconstructing with Air Cooled Embankments (ACE) and installation of thermosyphons to maintain lower soil temperatures.[30]

TABLE 3-28. REACTIVE ADAPTATIONS AT VARIOUS DAMAGE INDEX LEVELS

Damage Category	Buildings	Paved Roads/Runways	Gravel Roads/Runways
Reactive Adaptations			
Low (>0-20)	Nothing	Cracking repair cost	Regravel/grade
Moderate (>20-50)	Foundation repair	Rehabilitate	Rehabilitate
High (>50-100)	Rebuild	Reconstruct	Reconstruct
Extreme (>100-150)	Relocate	Relocate	Relocate
Proactive Adaptations			
Low (>0-20)	Nothing	Cracking repair cost	Regravel/grade
Moderate (>20-50)	**Thermosyphon**	**Base upgrade**	**Base upgrade**
High (>50-100)	**Thermosyphon**	**Reconstruct w/ ACE**	**Reconstruct w/ ACE**
Extreme (>100-150)	Relocate	Relocate	Relocate

Note that ACE (Calmels et al., 2016), and thermosyphon installation (O'Neill and Burn, 2017), are linked to T_s and damage index values. Under these two proactive adaptation strategies T_s is adjusted to account for the reduction in temperature. The max T_s reduction is set to 1°C. For gravel roads it is assumed that only primary and secondary gravel roads utilize ACE. It is unrealistic to assume the 65,000 km of gravel tertiary roads will be reconstructed with ACE.

Two versions of the proactive method were analyzed. The first implements ACE or thermosyphons in the decade where the damage index is high for roads and moderate or high for buildings. The second 'early action' alternative looks forward and implements ACE or thermosyphons in 2020 if there is a damage index of high for roads and moderate or high for buildings in any decade included in the analysis. Under both methods the thermosyphons and ACE are only installed once, so a possible reinstall at the end of the life is not included in the costs.

Cost sources vary by adaptation strategy and include RSMeans, engineering studies and cost guides. All reactive and proactive road costs and airport costs except for ACE are consistent with the larger roads

29 In areas with low ice content in the soil, we will explore the feasibility of modeling foundation repair instead of building replacement.

30 We may also explore the feasibility of assessing status quo costs for roads that involve road base reinforcement only, without thermosyphons. This would require assessment of how the upgrade of the road base alone (without thermosyphons) affects the frequency of road base reconstruction.

analysis and were derived from RS Means. Table 3-29 provides costs and source information for four of the key adaptation options.

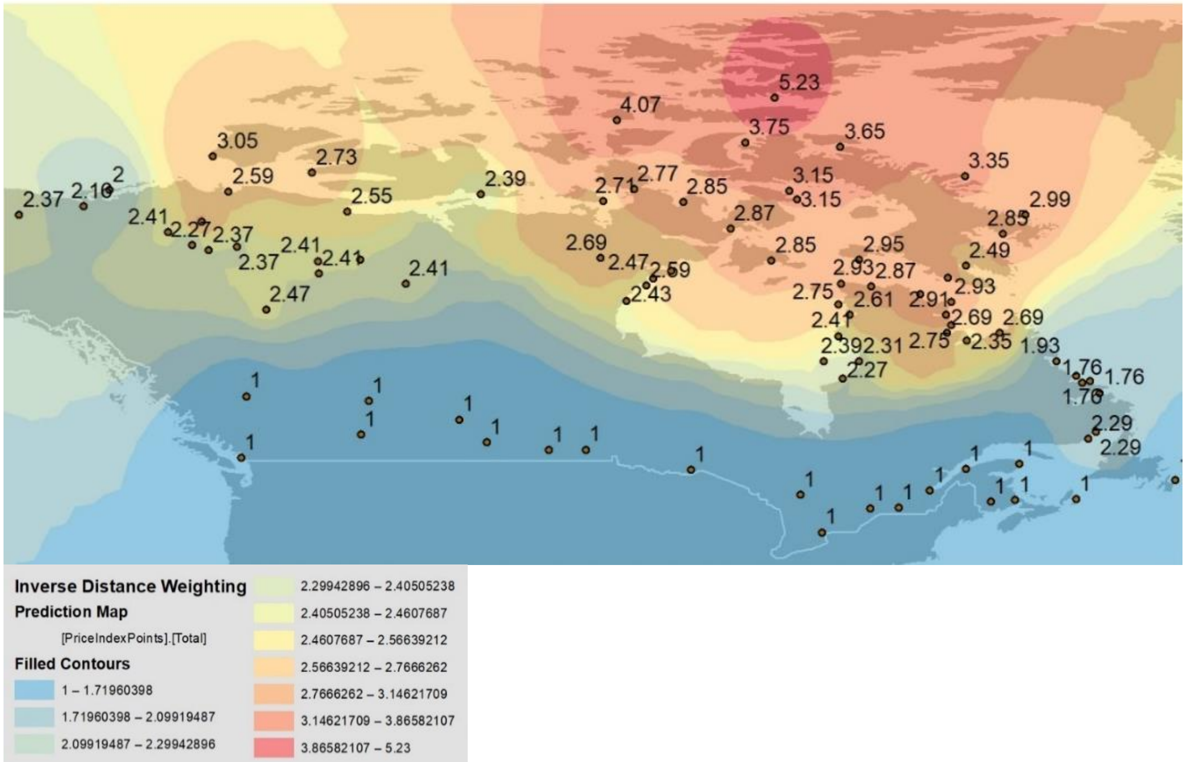
TABLE 3-29. ADAPTATION UNIT COSTS

Adaptation	Cost	Notes
Air cooled embankments[1]	$1.47 million per lane-km	i.e., $2.94 million per km for a 2-lane road
Thermosyphon[2]	$2,800 per thermosyphon	Number of thermosyphons will range by building size and shape. Typical home assumed to have 9 syphons and commercial building with footprint area of 750 square meters assumed to have 18. This is an average cost of $166 per square meter of building footprint.
Foundation repair[3]	$78 per square meter	Cost guide for typical foundation repair. This includes mud jacking the building due to settlement and repair of cracks associated with settlement.
Rebuild and relocate buildings[4]	$2,300 per square meter	Average cost of wood framed residential home, industrial facility, school, medical facility, and civic building. So little is known about the stock breakdown, so a simple average was taken.

Sources:
1. http://cem.uaf.edu/media/290338/ACE-Final-Report.pdf
2. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=DE0889C7E1CAB30E261608ACD607BDE8?doi=10.1.1.492.9448&rep=rep1&type=pdf
3. https://www.inchcalculator.com/foundation-repair-cost-guide/
4. https://creston.ca/DocumentCenter/View/1957/Altus-2018-Construction-Cost-Guide-web-1

Unit costs for construction vary widely across Northern Canada, depending on available delivery options (i.e., road, rail, sealift, air). In order to appropriately capture the costs of permafrost thaw, it is important to capture these variations. CCI provided unit cost multipliers for 63 communities across Northern Canada, where the base multiplier of 1 would be a city, town, or community with ready access to a major highway network. Figure 3-24 presents the locations and magnitudes of these cost multipliers. In order to apply these multipliers to all infrastructure in permafrost zones, we interpolated between the points using an inverse distance weighting algorithm. The values of 1 in southern Canada are major cities, added to the 63 community values in order to allow for smooth interpolation.

FIGURE 3-24. COST MULTIPLIER SURFACE



Source: Written communication with CCI and Antoni Lewkowicz; IEc calculations

Step 4. Estimate Damages to Infrastructure Inventory

We then calculated the damage index (Step 2) for the infrastructure inventory (Step 1), and applied resulting costs based on resulting damage category (Step 3). Damages are calculated across space, infrastructure type, climate scenario, and decade.

Results

The following section presents the results of the analysis by infrastructure type, and over time and space. Unlike other infrastructure categories, the permafrost analysis shows significant adaptation investments between 2020 and 2040 that influence investment decisions in following periods. As a result, we add the 2020 to 2040 period to the other two eras reported elsewhere (2050s and 2080s), and label it “2030” in the graphics.

Also note that the ‘early action’ proactive adaptation option—in which ACE or thermosyphons are installed in 2020 if there is a damage index of high for roads and moderate or high for buildings in any future decade—provided minimal additional benefit relative to the standard proactive approach. It is unrealistic to assume that a large-scale investment would occur immediately without an anticipated large-scale return, so we do not present this alternative proactive approach in the results below.

Infrastructure Impacts Over Time and across GCMs

Figure 3-25 shows the pattern of average annual effects each decade from the 2020s through 2090s. In this figure and those that follow, baseline costs are subtracted from the future costs to isolate the impact of climate change. Average costs range from approximately $130 million to $260 million annually across RCPs, decades, and adaptation strategies. We observe that the peak costs under both adaptation strategies occur in the 2060s for RCP 8.5, whereas under RCP 4.5 the costs are more constant over time, with a peak in 2090. This is because warming occurs more rapidly under RCP 8.5, triggering larger adaptation investments earlier, whereas under RCP 4.5 these occur later in the century. Under the proactive strategy, RCP 4.5 costs are universally lower over time, whereas under RCP 8.5, early savings from proactive investment delay the need for reconstruction until later in the century, causing costs in the later decades to exceed reactive levels.

FIGURE 3-25. AVERAGE TOTAL ANNUAL COSTS BY DECADE, RCP, AND ADAPTATION STRATEGY, AVERAGED ACROSS GCMs

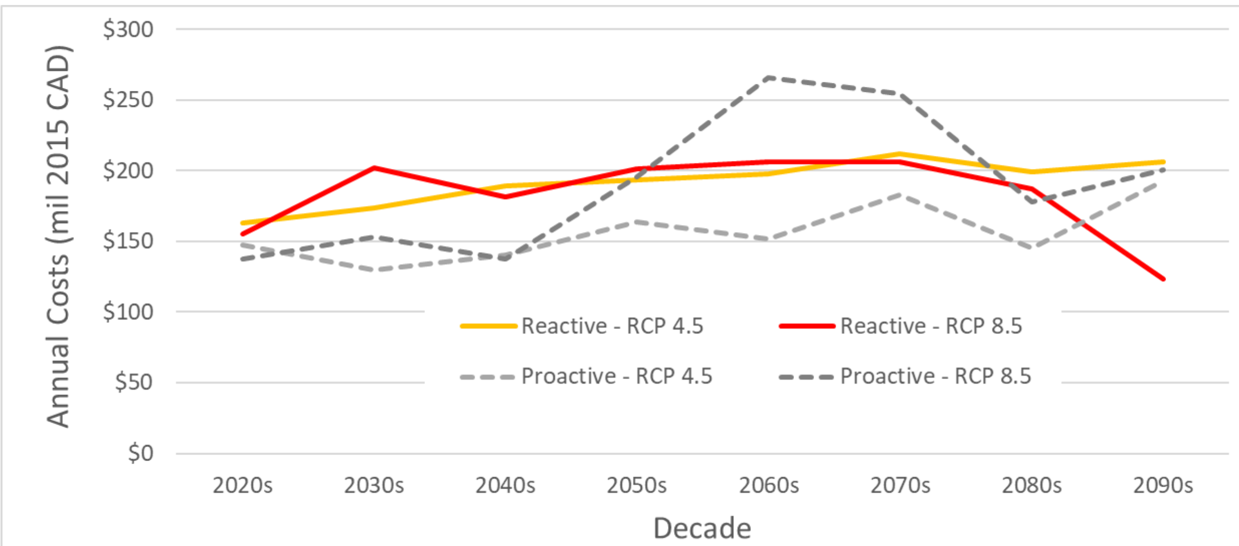
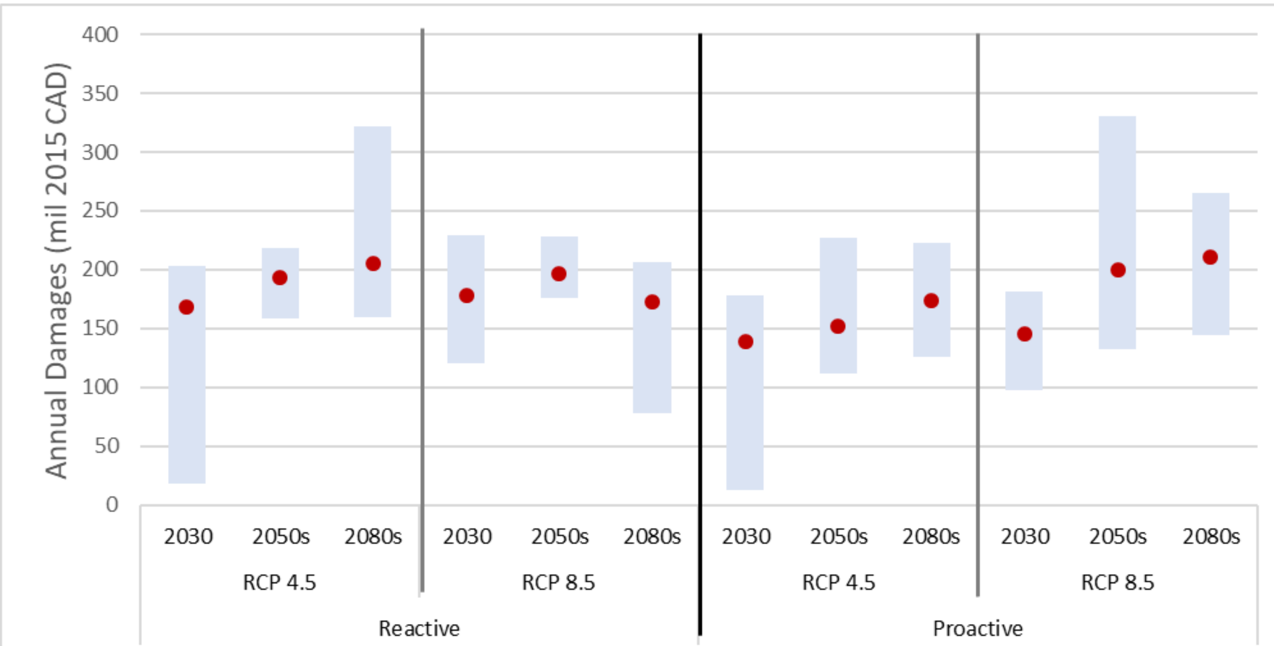


Figure 3-26 (and the accompanying table) shows the distribution of average annual nationwide permafrost thaw impacts across GCMs with a table that follows with averages across the GCMs and adaptation cost savings that result from adopting the proactive scenario. Although proactive costs are generally lower than reactive costs, the highest single GCM cost occurs under the proactive scenario in the 2050s at approximately $330 million per year. This GCM, GFDL-CM3, has temperature spikes in the middle century that triggers large investments in thermosiphons and ACE, which drive up the average costs this period. Another notable observation is the low-end costs that occur under the 2020 to 2039 period in RCP 4.5, for both adaptation strategies. These are from the MRI-CGCM3 GCM, and are approximately 10 times lower than the next lowest GCM (i.e., $18 and $12 million versus $180 and $140 million under reactive and proactive). Compared to other GCMs, the RCP 4.5 run of MRI-CGCM3 warms more slowly and has no significant temperature spikes in the territories with greatest impacts (Yukon and Northwest Territories), and thus does not trigger significant adaptation investment until later in the century.

When moving from a reactive to proactive adaptation strategy, adaptation costs fall approximately 15 to 20 percent for RCP 4.5 across the three eras. For RCP 8.5, costs fall approximately 18 percent in the 2020 to 2039 period, remain roughly constant in the mid-century, and increase roughly 22 percent in the late century. This pattern reflects the large initial savings and then net costs described in the figure above. Overall, the benefits of adopting a proactive strategy to permafrost thaw are not as profound as in other categories described in this report. This is because proactive adaptation (e.g., thermosiphons, ACE) only delay, rather than prevent, the loss of bearing capacity and subsidence that occurs with sufficient warming. Once certain warming thresholds have occurred, reconstruction and/or relocation will be required.

FIGURE 3-26. TOTAL NATIONAL ANNUAL COSTS OVER TIME (MILLIONS OF 2015 CAD)



RCP	Reactive 2030	Reactive 2050s	Reactive 2080s	Proactive 2030	Proactive 2050s	Proactive 2080s	Savings from Proactive 2030	Savings from Proactive 2050s	Savings from Proactive 2080s
RCP 4.5	168.3	193.4	205.8	138.6	151.8	173.9	29.7	41.6	31.9
RCP 8.5	178.6	196.2	172.4	145.2	199.7	211.1	33.4	-3.4	-38.8

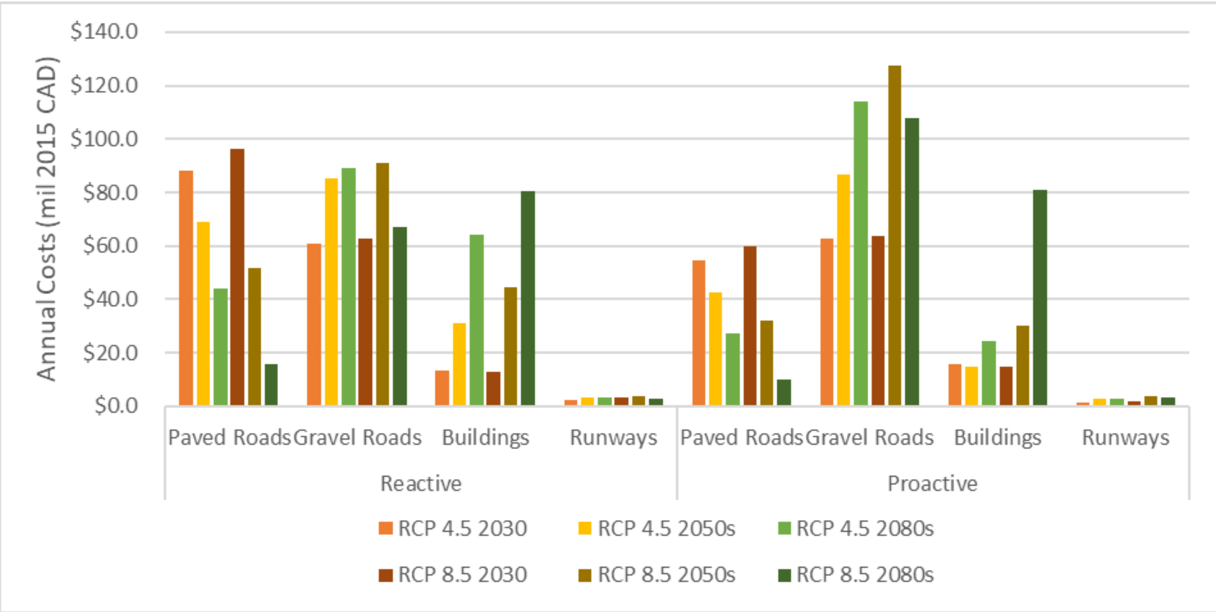
Note: In the figure, the red dot in each bar is the average across the seven GCMs, and the surrounding box shows the range. Values in the table immediately above are average costs across the GCMs.

Impacts by Infrastructure Type

Figure 3-27 (and the accompanying table) shows the total average annual costs broken down by the four infrastructure types, using the mean of the seven GCMs. In the mid-century, reactive and proactive gravel road costs account for between 45 and 66 percent of total costs, with the remainder weighted toward paved roads under RCP4.5 and split between buildings and paved roads under RCP8.5. This is only a snapshot of costs, however; the temporal patterns in this figure reflect the location of infrastructure across Northern Canada. Paved roads are concentrated in the southern regions, where permafrost thaw and thus peak damages occur by the early century. Gravel roads and airports are spread out more uniformly across the region, such that thaw peaks in the late century under RCP4.5 and mid-century under RCP8.5. Because a large share of the buildings on permafrost are located in the far north, impacts are concentrated in the late century.

We also find that proactive costs for gravel roads are higher than reactive costs across all three time periods, for two reasons. First, in our model, ACE can be built into primary gravel roads as a proactive adaptation option, and the cost of ACE are higher than relocation or reconstruction costs. If relocation costs are considerably more expensive than we estimate, it may make economic sense to construct ACE on critical gravel roads to extend their life. Second, reactive costs per kilometer for gravel roads are lower than for paved roads, so the shift to proactive ACE investments for gravel roads is more costly.

FIGURE 3-27. TOTAL NATIONAL ANNUAL COSTS OF CLIMATE CHANGE TO EACH INFRASTRUCTURE TYPE SHOWN, BY ADAPTATION AND RCP, USING THE GCM MEAN FOR THE RCPs



RCP	Infrastructure	Reactive			Proactive		
		2030	2050s	2080s	2030	2050s	2080s
RCP 4.5	Paved Roads	$88.2	$69.0	$43.8	$54.8	$42.6	$27.2
	Gravel Roads	$60.9	$85.3	$89.0	$62.5	$86.5	$113.9
	Buildings	$13.4	$30.9	$64.1	$15.6	$14.7	$24.4
	Runways	$2.4	$3.5	$3.5	$1.4	$2.7	$2.9
RCP 8.5	Paved Roads	$96.3	$51.6	$15.8	$60.0	$31.9	$9.8
	Gravel Roads	$62.8	$90.9	$67.1	$63.7	$127.6	$107.8
	Buildings	$12.7	$44.5	$80.6	$14.9	$30.0	$81.0
	Runways	$3.2	$3.8	$3.0	$1.9	$3.7	$3.2

Geographic Variability in Costs

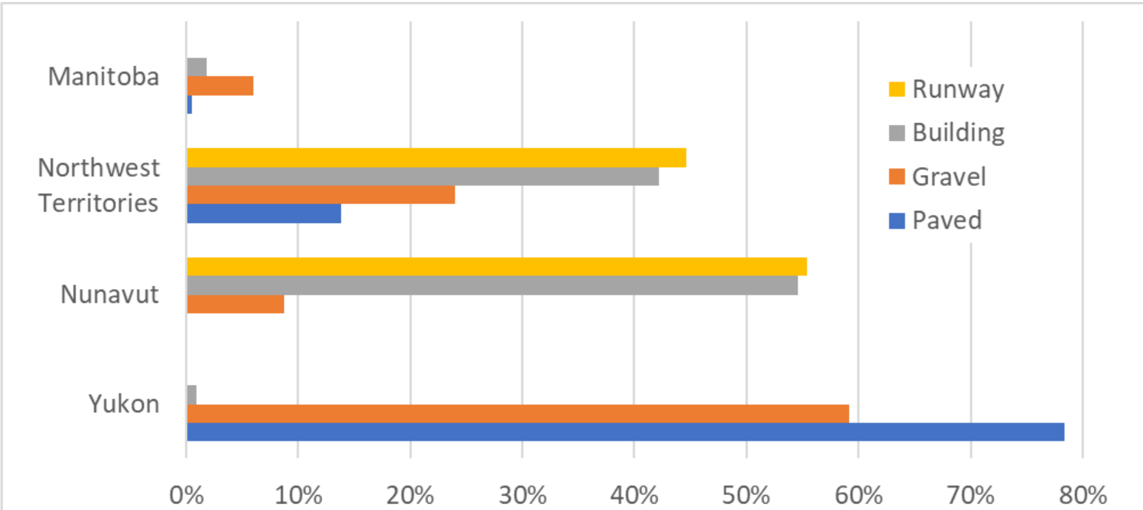
Table 3-30 shows the annual costs under the reactive scenario (the spatial pattern of proactive costs is very similar) for the three eras and two RCPs by province or territory, averaged across the GCMs. Yukon and Northwest Territories have the largest share of infrastructure in permafrost zones and thus incur the largest impacts by a wide margin. Over time, the impacts shift northward, as seen in costs to Nunavut, which show a large spike due to building and runway impacts in the 2080s.

TABLE 3-30. PROVINCE AND TERRITORY ANNUAL COSTS FOR THE REACTIVE SCENARIO, GCM MEAN (MILLIONS 2015 CAD)

Province/Territory	2020-2039		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Alberta	$0.9	$1.2	$0.6	$0.5	$0.4	$0.1
British Columbia	$9.6	$10.4	$6.4	$3.8	$3.8	$1.5
Manitoba	$26.6	$29.2	$21.2	$20.1	$16.6	$6.4
New Brunswick	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Newfoundland and Labrador	$0.1	$0.1	$0.1	$0.1	$0.1	$0.0
Northwest Territories	$50.7	$54.3	$57.2	$69.5	$73.2	$53.8
Nova Scotia	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Nunavut	$0.1	$0.0	$6.5	$6.2	$22.1	$54.2
Ontario	$1.7	$1.9	$1.4	$1.2	$0.9	$0.3
Prince Edward Island	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Quebec	$2.8	$3.6	$3.6	$3.8	$3.3	$2.1
Saskatchewan	$1.3	$1.4	$1.0	$0.7	$0.6	$0.2
Yukon	$74.5	$76.5	$95.4	$90.4	$85.0	$53.8
TOTAL	**$168.3**	**$178.6**	**$193.4**	**$196.2**	**$205.8**	**$172.4**

Figure 3-28 breaks down the results in the rightmost column of Table 3-30, showing the share of costs to each infrastructure type by the four provinces and territories with the majority of vulnerable infrastructure. Yukon bears 80 percent of the paved road costs that period, and 60 percent of the gravel road costs, with the Northwest Territories bearing 25 percent. On the other hand, Nunavut incurs over half of the costs in the building and runway categories, also shared with the Northwest Territories.

FIGURE 3-28. BREAKDOWN OF COSTS FOR EACH INFRASTRUCTURE TYPE ACROSS PRIMARY PROVINCES AND TERRITORIES, FOR THE 2080S AND RCP 8.5, REACTIVE ADAPTATION



Main takeaways

The main takeaways from this analysis are:

- Average costs of permafrost thaw across eras and GCMs range from approximately $130 million to $260 million annually, depending on the RCP, era, or adaptation strategy considered. The high-end cost for an individual GCM is $330 million. Paved and gravel roads account for between 49 and 91 percent of this cost, depending on RCP, adaptation strategy, and era. Buildings impacts range between 7 and 48 percent of the total, and runways account for 2 percent or less. Over time, impacts shift northward as temperature rises, as seen in costs to Nunavut, which shows a large spike in the 2080s under RCP 8.5, due primarily to building impacts.
- Due to more rapid warming under RCP 8.5 that trigger larger adaptation actions earlier, peak costs occur in the 2060s, whereas under RCP 4.5 the costs increase steadily over time. RCP 4.5 costs are universally lower over time under a proactive strategy, whereas in RCP 8.5, savings from proactive investment delay reconstruction until later in the century, causing costs in the later decades to exceed reactive levels.
- Overall, the benefits of adopting a proactive strategy to permafrost thaw are not as profound as in other categories described in this report. This is because proactive adaptation (e.g., thermosiphons, ACE) only delay, rather than prevent, the loss of bearing capacity and subsidence that occurs with sufficient warming. Once certain warming thresholds have been breached, more significant and costly actions (e.g., reconstruction and/or relocation) will be required.

Limitations and Caveats

The aim of this effort is not to develop permafrost projections for site-specific adaptation recommendations, but rather to understand the possible territorial and national-level effects of permafrost thaw. The major caveats and limitations to this approach are noted below.

- The permafrost damage index developed in this work is a highly stylized representation of the likely effects of permafrost on infrastructure, for several reasons:

- The thaw index, which is based solely on climate data and GIC, is a rough substitute for the much more detailed outputs from a numerically-based process model, such as that used by Melvin et al. (2017). However, no such model is available for Canada. Further, the index does not consider the myriad site-specific factors that drive permafrost impacts, such as soil drainage conditions, soil type and topography,
- The values for the thaw component of the index are from professional judgment based on generalized behavior of thawing soils, rather than empirically derived estimates. Similarly, the damage index thresholds that define various levels of infrastructure damage and action are defined based on professional judgment and could be enhanced through empirical study.
- The 10-year lag in thaw timing is an approximation and could be improved through further study.

- The analysis assumes that all infrastructure located in grid cells that contain excess GIC is susceptible to permafrost thaw impacts, and that the level of susceptibility scales directly with the share of ice content. It is unclear what effect this assumption will have on the analysis.
- The unit cost data that drive the analysis are not location-specific, and as a result may over or underestimate the total costs estimated in this study.

3.3.2 WINTER ROADS

Rising temperatures associated with climate change are likely to adversely affect winter roads across much of Northern Canada. Because the integrity of winter roads is dependent on persistent sub-freezing temperatures, a warming climate may render winter roads unusable for at least a portion of the winter.

Methods

This analysis examines climate change costs for winter roads based upon the magnitude of this usability effect. This impact is unlikely to be uniform across the entire winter, as temperatures for much (though a shorter portion) of the winter will remain sufficiently low for winter roads to remain passable. That is, climate change will shorten but not necessarily eliminate the winter road season. This effect will vary geographically based on regionally-specific changes in temperature. The associated costs will also vary by location, based on what a given winter road is used for and the feasibility of individual adaptive responses at each location. For example, where winter roads serve industrial sites, adaptation might involve more intensive transportation of supplies during the shortened winter road season. Alternatively, if an industrial site is near an airfield or the terrain near the site is amenable to construction of an airfield, air transport of supplies may represent a viable adaptive response. In other cases, replacing winter roads with conventional roads may be the only viable option.

To assess the extent to which climate change affects the usability of winter roads, we assume that a winter road is impassable during a given month if the monthly average temperature exceeds -5 degrees C. This reflects the threshold recommended by the Treasury Board of Canada (undated) for assessing the stability of winter roads. To implement this assumption in our analysis, we estimate climate change costs as the cost of replacing winter roads with two-lane paved roads in areas where climate change is projected to lead to a four-month reduction in the winter road season for three years in a five-year span. Based on cost data from RSMeans, the assumed cost of constructing a paved road to replace a winter road is $653,000 (CAD) per lane-km. The km of paved roads constructed is assumed to be the same as the length of winter road replaced. We apply this approach under both the status quo scenario and the proactive adaptation scenario to the winter road network summarized in Table 3-31. While Table 3-31 presents the best data available on the length of winter roads in Canada, winter road length nationwide can vary over time given that many winter roads are built and maintained by mining companies whose need for winter roads varies with the intensity of their mining operations. In addition, because the permafrost modeling described elsewhere in this chapter is not integrated into the winter road analysis, we do not assess any additional costs that might arise from permafrost thaw when a winter road is converted to a paved road.

TABLE 3-31. CANADIAN WINTER ROAD NETWORK BY PROVINCE/TERRITORY

PROVINCE/TERRITORY	KM OF WINTER ROAD
Alberta	396
British Columbia	0
Manitoba	2,405
New Brunswick	0
Newfoundland and Labrador	0
Northwest Territories	2,084
Nova Scotia	0
Nunavut	117
Ontario	3,238
Prince Edward Island	0
Quebec	15
Saskatchewan	223
Yukon	<10

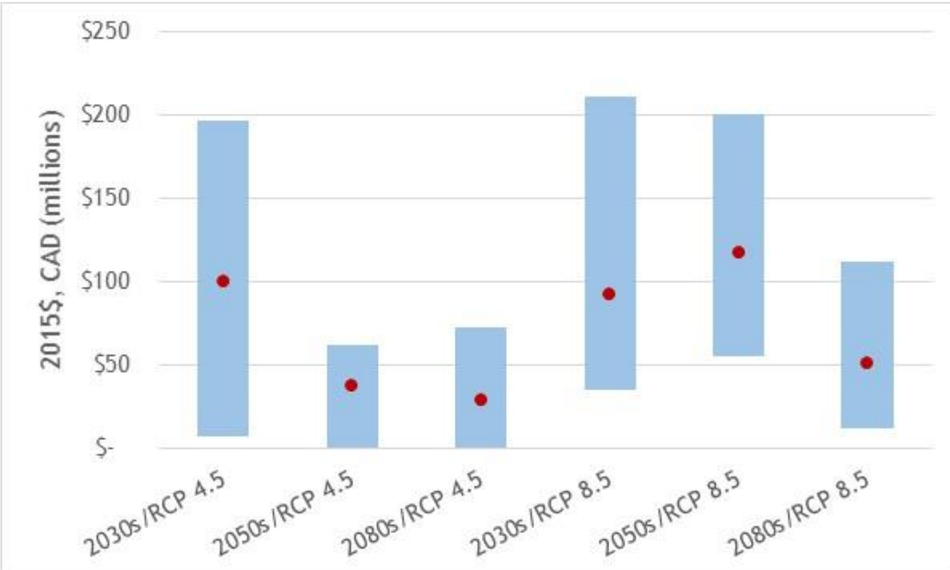
Results

Similar to the permafrost analysis, the winter road analysis shows significant investments in adaptation between 2020 and 2039. Because the assumed adaptation (i.e., construction of a paved road to replace a winter road) represents a one-time investment that affects costs for later periods, we include the 2020 to 2039 period with the other two eras reported elsewhere (2050s and 2080s). Also, as noted above the winter road costs presented here do not reflect the degree to which permafrost thaw may affect the costs of building and maintaining paved roads that might replace winter roads.

Figure 3-29 presents the estimated climate change costs for winter roads by RCP and era. The range of costs across GCMs is represented by the blue bars shown in the graph; the red dots represent average costs across GCMs. As the figure shows, costs are similar between RCP 4.5 and RCP 8.5 in the first era but then are 80 to 210 percent higher for RCP 8.5 than RCP 4.5 in the second and third eras. In addition, for RCP 4.5, costs in the first era are much higher than costs during subsequent eras. This reflects the one-time nature of the adaptive response in our analysis. Based on the projected changes in temperature under RCP 4.5, an adaptive response will be necessary for many winter roads during the first era. Assuming that paved roads are constructed as the adaptive response, adaptation costs for these winter roads are front-loaded into the first era. Once a paved road is constructed to replace a winter road, costs for that road are limited to regular maintenance. Alternative adaptive responses (e.g., increased reliance on air or marine transport) might be more uniform over time. This decline in average annual costs lags somewhat for RCP 8.5, with costs declining between the second and third eras rather than between the first and second eras.

This reflects more growth in the geographic area affected by the shortened winter road season during the second era under RCP 8.5 than under RCP 4.5.

FIGURE 3-29. RANGE OF MEAN ANNUAL CLIMATE CHANGE COSTS FOR WINTER ROADS BY RCP AND ERA (MILLIONS OF $2015 CAD)



RCP	2020 to 2039	2040 to 2069	2070 to 2099
RCP 4.5 Average	$99.7	$37.8	$28.7
RCP 8.5 Average	$92.5	$117.5	$51.2

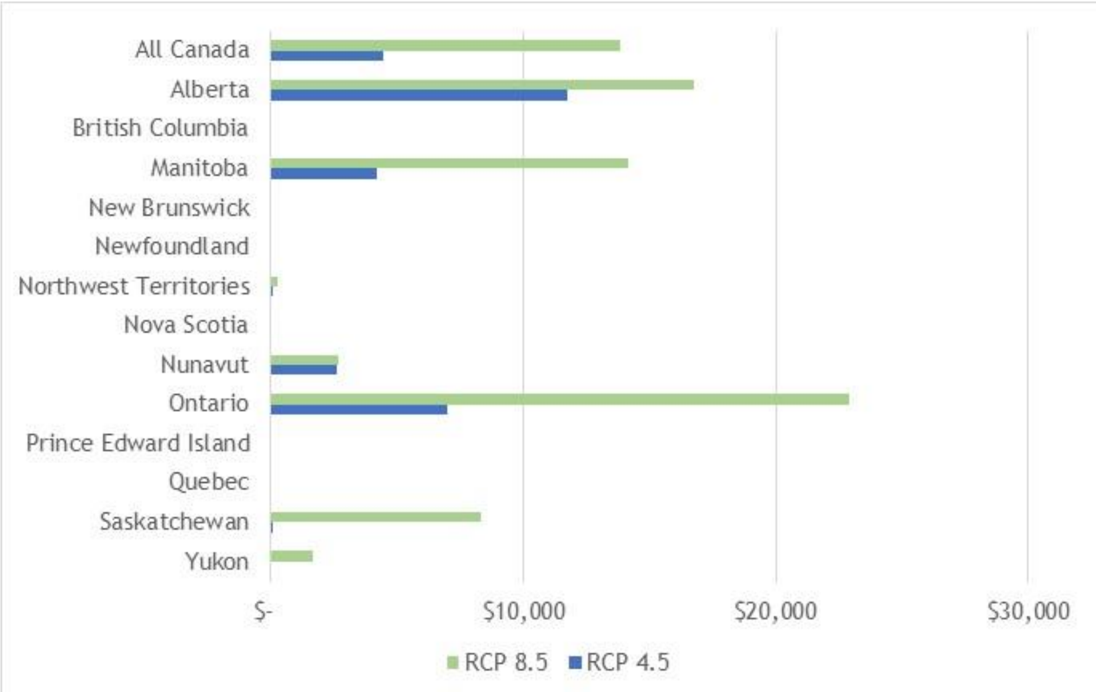
Table 3-32 shows the distribution of winter road costs across provinces and territories for each era and RCP. As shown in the table, costs are highest for Ontario followed by Manitoba, which together account for approximately two-thirds of Canada's winter road network. Notably, costs for the Northwest Territories, which have a winter road network comparable in size to Manitoba, are just a small fraction of costs for Manitoba. This reflects the geographic advantage of the Northwest Territories relative to other areas in terms of winter road integrity. Despite projected increases in temperature, much of the Northwest Territories are located far enough north such that absolute temperatures with climate change do not render many of the region's winter roads unusable for four months of the year (for three years within a five-year span). The shortened duration of the winter road season in the far north, however, could have other economic implications such as increased costs associated with goods that have a relatively short shelf life.

TABLE 3-32. WINTER ROAD COSTS BY PROVINCE (MILLIONS OF $2015 CAD)

Province/Territory	2020-2039		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Alberta	$8.2	$10.9	$4.7	$6.6	$2.7	$2.5
British Columbia	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Manitoba	$23.3	$26.6	$10.1	$34.0	$9.6	$17.3
New Brunswick	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Newfoundland and Labrador	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Northwest Territories	$0.0	$0.0	$0.1	$0.5	$0.8	$12.1
Nova Scotia	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Nunavut	$0.6	$0.5	$0.3	$0.3	$0.0	$0.1
Ontario	$67.6	$54.4	$22.5	$74.1	$15.0	$15.6
Prince Edward Island	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Quebec	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Saskatchewan	$0.0	$0.0	$0.0	$1.9	$0.6	$3.6
Yukon	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
TOTAL	**$99.7**	**$92.5**	**$37.8**	**$117.5**	**$28.7**	**$51.2**

On a per-km basis, winter road costs are highest for Alberta under RCP 4.5 and Ontario under RCP 8.5, as shown in Figure 3-30 below, followed by Manitoba and Saskatchewan. Costs per km for the territories are significantly lower. As described above, although climate change will lead to increased temperatures in the territories, the resulting temperatures in these areas will still be sufficiently low to maintain the integrity of winter roads during the winter. Costs per km for the maritime provinces are zero because our inventory data suggest that no winter roads are located in this region.

FIGURE 3-30. WINTER ROAD COSTS PER KM BY PROVINCE/TERRITORY (STATUS QUO SCENARIO, 2040-2069)



As described above, our analysis of winter road costs is based on winter road replacement in areas where the winter road season shortens in duration by at least four months. However, the threshold at which aggressive adaptive action such as this is taken could vary. To test the sensitivity of our results to this threshold, we conducted an analysis in which winter roads are replaced with paved roads if the winter road season shortens by only half a month (for three years out of five, as in the primary analysis). This analysis found that costs during the first era more than triple for RCP 4.5 relative to our primary estimate and more than quadruple for RCP 8.5 (see Table 3-33). In contrast, costs for the third era are significantly lower than under the primary analysis, due to the more significant investment in replacements for winter roads in the first and (to a lesser extend) second eras.

TABLE 3-33. ALTERNATIVE ESTIMATES OF WINTER ROADS COSTS, BASED ON LOWER THRESHOLD FOR WINTER ROAD REPLACEMENT

RCP	2020 to 2039	2040 to 2069	2070 to 2099
RCP 4.5 Average	$369.4	$85.4	$18.6
RCP 8.5 Average	$401.6	$93.1	$4.1

Overall, the main takeaways from our analysis of costs related to winter roads are as follows:

- Winter road costs are projected to be heavily concentrated in Ontario and Manitoba. Although the Northwest Territories have an extensive winter road network, the projected winter temperatures with climate change in the Northwest Territories will be low enough to maintain the integrity of most winter roads there.

- Adaptation strategies based on the replacement of winter roads with other infrastructure (e.g., paved roads) will be front-loaded in the first era of the analysis under RCP 4.5 and the first two eras under RCP 8.5. Based on the threshold established for this analysis (i.e., a four-month reduction in the winter road season), many of the winter roads projected to be unusable reach this condition within the first or second era (depending on the RCP).
- Based on the sensitivity analysis presented above, the choice of threshold for investing in winter road replacement (e.g., four-month shortening of the winter road season versus half-month shortening) may significantly affect the estimated costs of climate change for winter roads. The threshold will likely be unique regionally as communities determine how long they can use substitute transportation methods or stockpile goods before freeze-up.

Limitations and Caveats

Our analysis of climate change costs for winter roads represents the best feasible assessment of these costs, but we note the following uncertainties/caveats:

- The threshold at which adaptation will occur for winter roads is highly uncertain. As the winter road season shortens, the threshold for implementing adaptation strategies that involve substitute forms of transportation (e.g., constructing and using a paved road to replace a winter road or switching to air transport) will likely vary from road to road, even within the same region. When such decisions are driven by economic considerations only, the decision to transition to a substitute form of transportation will likely depend on the size of the communities and industries served by a given winter road. For example, for winter roads that support a significant number of communities or industries, a modest shortening of the winter road season may trigger a transition to alternative forms of transportation. A more significant shortening of the winter road season may be necessary to economically justify such an investment for winter roads serving smaller populations/industries. As an alternative to this economics-focused approach to decision-making, policymakers may also opt to devote resources to winter road alternatives for equity reasons. For example, to the degree that even a small reduction in the winter road season exacerbates existing disadvantages for a specific community, policymakers may decide to devote resources to alternative forms of transportation to serve that community. As these examples illustrate, investment decisions regarding winter road replacement are complex and difficult to represent in the context of the analysis presented here.
- The choice of adaptation strategy is also likely to vary across winter roads, based on which strategies are feasible for a given road and the activities that a given winter road supports. As a simplifying assumption, our analysis assesses adaptation costs based on the replacement of a winter road with a paved road. In practice, however, the adaptation strategies adopted will vary. It is uncertain whether our modeling of paved road construction as the sole adaptation strategy systematically underestimates or overestimates climate change costs for winter roads.
- The analysis presented here examines only the cost of developing an alternative to winter roads once a certain threshold is met in terms of the shortening of the winter road season. Before that

threshold is reached, however, communities and businesses reliant on winter roads may realize various negative impacts that we have not quantified or monetized. For example, Northern communities may have more limited access to various goods that are transported via winter roads, and businesses that are reliant on winter roads for supplies may produce less than they would if the winter road season were to remain unchanged.

3.4 ELECTRICITY AND ENERGY

This analysis estimates damages to elements of Canada's electrical grid infrastructure and the effects on hydropower generation under the selected climate change scenarios, using process-based approaches. The grid infrastructure analysis is conducted at the census division resolution, whereas the hydropower analysis is evaluated at the catchment scale.

3.4.1 ELECTRICAL GRID

A warming and more variable climate will directly affect electrical grid infrastructure, resulting in increased replacement, repair, and operations and maintenance costs. These costs can be considerable – in the U.S., Fant et al. (2020) find 2018 to 2099 impacts of approximately 300 billion USD, using stressor-response functions that model the impact of various climate drivers on power poles, transmission & distribution lines, transformers, and substations.

Methods

This analysis focuses on the subset of infrastructure-climate stressor combinations that (a) can be characterized with reasonable certainty and (b) are likely to have significant costs. Meeting the first criterion requires sufficiently detailed infrastructure inventory information, usable projections of the climate stressor, and a stressor-response function that relates how the stressor affects the infrastructure. We rely on the stressor response functions developed by Fant et al. (2020) for the U.S. The infrastructure-stressor damage categories considered in that study are presented in Table 3-34, where green highlighting indicates the relationships included in the U.S. analysis, and the physical impact assessed is denoted as either repair/replacement (R), lifespan reduction (L), and/or capacity change (C). Note that Fant et al. find that floods, high winds, and ice storms are stressors that are too uncertain to estimate. We reach the same conclusion and exclude these stressors due to uncertainty; see the text box below on challenges with wind and ice storms. The analysis is conducted for each Census Division, climate scenario, and year, although the results are summarized into two eras: "2050" (2041-2070) and "2080" (2071-2100). [31]

[31] Census Divisions were used here because that is best scale at which we can estimate electric transmission and distribution infrastructure

TABLE 3-34. GRID STRESSOR RESPONSE RELATIONSHIPS CONSIDERED IN FANT ET AL. (2020)

Infrastructure	Air Temp-erature	Rain	Light-ning	Veg. Mana-gement	Wild-fires	SLR & Storm Surge	Floods	High Winds	Ice Storms
Transmission Lines	C (#1)	i	R* (#2)	i	R (#3)	i	i	i	i
Distribution Lines	C (#4)	i	R* (#5)	R (#6)	u	u	u	u	u
Transmission Towers	i	i	i	i	i	i	i	i	i
Wood Poles	L (#7)		u	R (#6)	u	u	u	u	u
Substations / Large Transformers	L, C (#8)	i	i	I	u	R (#9)	u	u	u
Distribution Transformers	L,C (#10)	i	u	R (#6)	u	u	u	u	u

Key Repair/Replacement/Interruption (R), Lifespan Reduction (L), Capacity Change (C), insignificant costs (i), significant uncertainty in costs (u).
Green indicates relationship is included in the analysis, white and grey indicate relationship is not included, and grey further indicates significant uncertainty in the underlying climate stressor.
Numbers in brackets correspond to the numbering of the summary list following the table.
* These stressor-responses not associated with infrastructure damages, just interruption costs, as discussed in Section 4.

There are also several categories analyzed by Fant et al. that we will not be considering. These include the lightning and wildfire because the projections of these variables are not available for Canada, to our knowledge. In addition, sea level rise and storm surge were not considered here because these effects were minor compared to the overall costs and that is likely to be the case in Canada as well, and would require a highly resolved inundation model of coastal Canada.

A Note on Wind and Ice Storms

Both high winds and ice storms cause a significant amount of damage to distribution infrastructure, and as a result can cause power outages ranging from local to regional scales. Using the Interruption Cost Estimator (ICE), Larsen et al. (2016) found that additional power interruptions from wind, ice storms, and other drivers under climate change could cost the U.S. economy over 1 trillion USD by the middle of the 21st century. Within Canada, IBC (2015) used a statistical approach to evaluate the change in the frequency and severity of ice and wind storms, and the resulting business interruption costs for specific case studies.

However, as discussed by Fant et al. (2020, supplemental material) the climatological drivers causing wind and ice storm events are too complex to produce reasonable projections of either their frequency or severity at a national scale. For wind events, IPCC (2013) indicates low confidence in the projection of near-surface wind speed changes from GCM outputs. The GCMs provide wind speed at 10-meter elevation, which is a derived variable based on conditions in the atmospheric layer closest to the surface, and does not take into account topography or the other local factors that drive these events. At a larger scale, hurricanes and convective storms, which are often the cause of distribution infrastructure failure, are not represented in GCMs and need to be approximated using separate modeling techniques that post-process GCM outputs (e.g., Emanuel et al. 2013). The IPCC (2013) also reports low confidence in projecting the rate of change in the vertical structure of the atmosphere, which is the underlying driver of ice storm events. While Regional Climate Models (RCMs) have been shown to simulate past ice storm events over Canada reasonably well (Bresson et al. 2017), there is less assurance that GCMs (and therefore the statistically downscaled GCMs employed in this study) can represent changes in vertical temperature profiles (Klima and Morgan 2015).

For these reasons, we do not evaluate the impacts of wind and ice storm events on infrastructure, or the resulting power interruptions that occur. Research is ongoing that may open avenues to the analysis of wind and ice storm events. Cheng et al. (2011, 2014) apply complex downscaling techniques to provide estimates of changes in wind speed gusts and freezing rain event occurrence for a set of meteorological stations across Canada, but these are for a small subset of GCMs within the CMIP3 rather than CMIP5 ensemble, and are for specific locations rather than at a nationally gridded scale. Future refinements in GCMs, possibly within the CMIP6 ensemble, may allow for more confident downscaling of these events.

The electrical grid analysis considers the remaining categories of effect, which are described in Table 3-35 and cover the bulk of damages in Fant et al. (2020). In the Fant et al. study, the highest impacts were to substation transformers and vegetation management, followed by impacts to wood pole decay and distribution transformers.

Three adaptation scenarios are considered, each of which represents a specific response by decision-makers to the impacts of a changing climate. For the No Adaptation strategy, utilities make no adjustments to infrastructure design, treating climate as if it has remained stationary. When infrastructure needs to be replaced, i.e., end of a life cycle, it is replaced with the same design/model.

For the Reactive and Proactive Adaptation strategies, utilities respond by "designing" infrastructure to either recent climate (reactive) or an expected future (proactive) climate based on climate projections. This is done by upgrading infrastructure until it meets the baseline performance or service level. For example, for wood pole lifespan reductions, upgrades are made until the historic aggregate baseline lifespan is achieved. Reactive and Proactive Adaptation are distinguished by designing to different climates, either reactive to the past climate or proactive to a projected future climate.

Proactive Adaptation designs to the future lifespan using an "expected" climate. Perfect foresight is not used, as it would be unrealistic. Instead, it is designed using the mean over all the climate projections to provide a projected change from current climate. In this way, Proactive Adaptation is forward-looking but does not design perfectly. Depending on the actual future climate that occurs, the infrastructure could be overdesigned and in others it could be under-designed, both causing undesirable outcomes. For this reason, and only in rare cases, the proactive approach can be more costly overall because the uncertainties in the projection related to the lifespan of the infrastructure are such that a reactive approach is more cost-effective. This approach does not take into account potential improvements in climate model projections over the next century.

TABLE 3-35. SUMMARY OF CLIMATE CHANGE DAMAGES AND ADAPTATION ASSUMPTIONS FOR ELECTRICITY AND ENERGY

EFFECT	DESCRIPTION	NO CONSIDERATION OF CLIMATE CHANGE ("NO ADAPTATION")	STATUS QUO ("REACTIVE SCENARIO")	DESIGN USING PROJECTED CLIMATE ("PROACTIVE SCENARIO")
Reduced Transformer (both substation and distribution) Lifespan	Changes in air temperature cause changes in lifespan of large power transformers	Build replacement transformers with the existing design (historical climate)	Build replacement transformers adapted to recent climate	Build replacement transformers adapted to projected climate
Reduced Transmission Line Capacity	High temperatures on transmission lines cause a reduction in ampacity	Build additional transmission lines using existing design	Ampacity upgrade of existing lines using recent climate	Ampacity upgrade of existing lines using projected climate
Wood Pole Decay	Changes in precipitation and temperature alter the rate of decay at the base of the wood poles	Increased wood pole replacement interval	Steel reinforcement as needed based on recent climate	Steel reinforcement as needed based on projected climate
Change in Vegetation Management	Changes in climate result in altered vegetation growth, which requires changes in vegetation management	Increased O&M options	Increased O&M options (no adaptation option available)	Increased O&M options (no adaptation option available)

Further details on the methods for the five categories are provided below, with more extensive explanations available in Fant et al. (2020).

Substations and distribution transformers. Transformers are structures that convert voltage. We consider two types of transformers: large power transformers within substations (substation transformers); and standalone transformers, either on the ground in a covered metal box or fixed on power poles (distribution transformers). As in the Fant et al. work, transformers are modelled as being primarily impacted by changing ambient air temperature, which affects transformer lifespan and capacity.[32] Air temperature impacts transformer peak load capacity such that higher temperatures decrease capacity. Ambient air temperature also impacts transformer lifespan, by developing “hot spots” within the cooling system that can damage the insulating paper that prevent short circuits. We apply a function developed by Lundgaard et al. (2004) and Stahlhut et al. (2008) to estimate reduced transformer lifespan. Both the reduction in capacity and lifespan results in more transformers needed or more frequent replacement. These impacts are valued in the no adaptation scenario by multiplying substation and distribution transformer unit costs by the increased number of transformers needed over time. Under the reactive and proactive scenarios, unit costs are higher for transformers with higher temperature thresholds, but replacement frequency is lower.

Change in summertime capacity of the high-voltage transmission system. Rising ambient air temperature increases the resistance of conductors and thereby decreases the carrying capacity of cables. These decreases in capacity may create a bottleneck in the grid if extremely hot days become more common. Bartos et al. (2016) developed a method for evaluating these impacts, which are applied here with only minor modifications as described in Fant et al. (2020). The Bartos research found that by mid-century, U.S. transmission capacity will decline by 1.9 to 5.8 percent. If planners ignore these capacity losses, lines may need to be shut off on hot days, potentially causing major outages. However, typically these lines are monitored closely since outages on the transmission system are generally very rare. In order to maintain system capacity, we assume that either additional lines will be constructed at estimated per mile costs (no adaptation), or existing lines will have ampacity upgrades during routine replacement of cables (reactive/proactive), at a higher cost per mile.

Wood pole decay. The primary mechanism by which air temperature and precipitation impact wood poles is through degradation from fungal attack at the base. Following Fant et al., we estimate timber pole degradation using a general form of the relationship between climate and pole decay rate (caused by fungal attack) developed by Wang and Wang (2012). Decay reduces the diameter of the pole, which then reduces the pole strength to the point of requiring a replacement. Similar to transformers, reduced wood pole lifespan means more frequent replacement. This is valued based on estimated unit costs for wood pole replacement under the reactive scenario and based on steel reinforcement under a reactive/proactive case.

Vegetation management. In Fant et al. (2020), the impact of increased vegetation on the electricity transmission and distribution system is quantified in a simple way. With increased vegetation, the authors assume vegetation management costs will also increase and that this relationship is linear, while recognizing that in areas of the U.S. with more tree cover, vegetation management costs are higher than in regions that are drier (e.g., Arizona). Costs are based on costs per line km from Hydro-Québec, which are $5,545 / km. Accounting for tree density, these are roughly 4 percent higher than costs used in Fant et al. (2020) for the U.S. One of the key variables for this analysis is tree growth rates, which we do not have available for Canada. Instead, a model is developed using the vegetation growth projections from for the U.S (CITE)., which is applied to the southern part of Canada only, excluding the northern Territories. Growth is approximated with a multivariate linear regression, where changes in precipitation and CO_2 concentrations are both significant and beneficial predictors for vegetation biomass with a n R-squared of

[32] Complete transformer failure due to high temperatures or lightning strikes is rare and poorly characterized historically, and are thus excluded from this analysis.

0.67. It is important to note that while the model explains 67 percent of the variance, it does not accurately capture the increase in growth over time and as a result is likely an underestimate of increased costs. Increased vegetation management costs under climate change are based on estimated costs per mile per tree density. It is assumed that utility companies will increase vegetation management expenses to keep vegetation away from lines and other infrastructure instead of neglecting the increased growth, which would be much more costly, likely causing outages or requiring repair/replacement. Adaptation is not considered for vegetation management, i.e., all adaptation scenarios are the same.

Inventory of of Electrical grid Infrastructure

Transmission infrastructure is available from the DMTI dataset and includes the locations of all substations and transmission lines. Information on the distribution infrastructure (wood poles, distribution transformers, and power lines) is not available for Canada. As a result, estimates of the locations of these infrastructure were estimated using an ordinary least squares multivariate linear regression using data from the U.S., which is primarily based the 2017 UDI Directory of Electric Power Producers and Distributors from S&P Global Platts (S&P Global 2018).

The most important variables for predicting distribution infrastructure in the U.S. are demand and population density. Province and territory electricity demand was sourced from CCI calculations, which disaggregate demand into 31 sectors, which can be reduced into 7 major sectors. National demand for these sectors is shown in Table 3-36, where the two largest consumers are households and manufacturing. Total national demand in 2015 is 555 tera-watt hours (TWh).

TABLE 3-36. PROVINCE AND TERRITORY DEMAND (TWH) IN 2015 BY MAJOR SECTOR

PROVINCE / TERRITORY	HOUSEHOLDS	MANUFACT-URING	RESOURCES	SERVICES	TRANSPOR-TATION
Alberta	8.0	19.6	33.8	14.1	1.9
British Columbia	18.6	18.8	7.1	16.4	3.2
Manitoba	8.3	2.8	6.5	5.1	2.0
New Brunswick	6.0	4.1	0.6	2.7	0.2
Newfoundland and Labrador	4.5	0.6	0.4	2.6	0.0
Nova Scotia	4.7	1.5	0.8	3.8	0.2
Ontario	47.9	43.7	5.5	47.5	0.4
Prince Edward Island	0.2	0.2	0.2	0.9	0.0
Quebec	70.1	68.9	17.0	24.3	4.3
Saskatchewan	3.6	1.9	9.5	3.6	3.4
Territories	0.3	0.0	0.0	0.4	0.0
TOTAL	**172.4**	**162.0**	**81.4**	**121.4**	**15.5**

Note: construction and utilities are not included in the table, which nationally are 0.5 TWh and 1.6 TWh, respectively.

Electricity demand was disaggregated to each Census Division using both population (for household demand) and employment counts (for all non-household demand) by labor sector, which were mapped to the 31 energy sectors.

The inventory of wood power poles, distribution transformers, and distribution lines was developed with a two-step approach. First, the model was trained using demand and population density by U.S. State, where we have the most confidence in the inventory database. Both demand and population density were found to be significant and beneficial predictors of wood power poles and distribution transformers while only demand was used for distribution transformers. R-squared values for the models are 0.87 for distribution transformers, 0.84 for power poles, and 0.82 for power lines. Province / Territory inventories were estimated using these three models, and then disaggregated to Census Divisions using demand. The resulting inventory by province / territory is shown in Table 3-37.

TABLE 3-37. PROVINCE AND TERRITORY INFRASTRUCTURE INVENTORY

PROVINCE / TERRITORY	SUBSTATION TRANSFORM-ERS	TRANSMISS-ION LINES (km x10^3)	DISTRIBUTION TRANSFORM-ERS (x10^3)	DISTRIBUTION LINES (km x10^3)	POWER POLES (x10^3)
Alberta	542	11.3	676	253	6,418
British Columbia	210	13.1	586	135	5,486
Manitoba	356	9.9	309	68	2,604
New Brunswick	138	5.5	224	48	1,721
Newfoundland and Labrador	80	5.9	187	39	1,338
Nova Scotia	246	5.1	209	44	1,562
Ontario	3,238	23.0	1,102	260	10,850
Prince Edward Island	10	0.3	146	29	909
Quebec	404	27.6	1,377	327	13,708
Saskatchewan	280	9.2	276	60	2,260
Territories	18	1.4	141	28	858
TOTAL	**5,522**	**112**	**5,230**	**1,289**	**47,713**

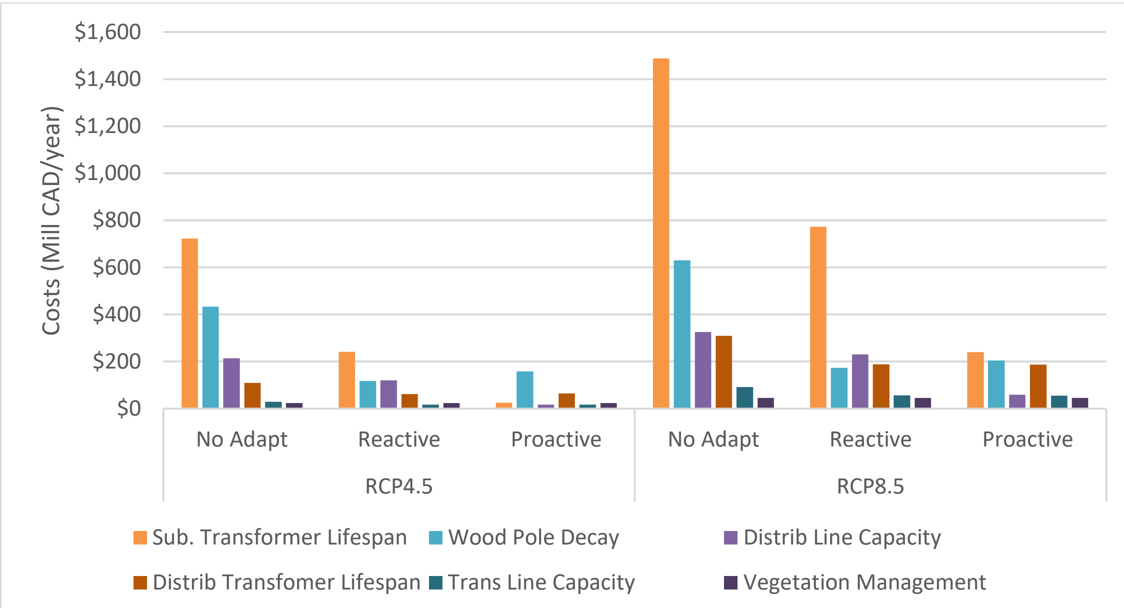
Results

The following section presents the results of the analysis by stressor-response, and over time and space.

Impacts by Stressor-Response

Figure 3-31 shows the total average annual costs for 2071-2100, which include costs of adaptation as well as damages, across the six impact types, by RCP, using the mean of the seven GCMs. Baseline costs are subtracted from the future costs to isolate the impact of climate change, which is the case for all costs shown in this report. Total costs range from $0.30 to $1.5 billion / year for RCP4.5 and $0.79 to $2.9 billion / year for RCP8.5 with the higher costs for No Adaptation and the lowest for proactive adaptation. For reference, the sum of replacement costs and vegetation management for the baseline is about $24 Billion CAD / year so the additional costs of $2.9 billion for RCP 8.5, No Adaptation is roughly a 12 percent increase in annual expenditures. Annual impacts under the more extreme RCP8.5 scenario are roughly double the lower emissions RCP4.5 scenario due to the much higher end-of-century temperature projections. Moving from a strategy of No Adaptation to a Reactive strategy is about half the expected costs of climate change experienced in 2090 for RCP 8.5 but is a about a third for RCP 4.5. This is likely because temperatures accelerate faster for RCP8.5 in the later half of the century, making a reactive strategy less effective in reducing costs. A proactive strategy reduces costs even further to about half those for the reactive adaptation scenario for both RCPs.

FIGURE 3-31. TOTAL NATIONAL ANNUAL COSTS OF CLIMATE CHANGE OF EACH IMPACT SHOWN FOR EACH ADAPTATION SCENARIO AND RCP, USING THE GCM MEAN FOR THE RCPs, 2080s



Impact Type	RCP4.5			RCP8.5		
	No Adapt	Reactive	Proactive	No Adapt	Reactive	Proactive
Sub. Transformer Lifespan	$723	$241	$25	$1,488	$772	$240
Wood Pole Decay	$433	$117	$158	$630	$174	$204
Distrib. Line Capacity	$214	$121	$18	$325	$230	$59
Distrib. Transformer Lifespan	$110	$62	$64	$310	$189	$186
Trans Line Capacity	$30	$17	$17	$92	$56	$55
Vegetation Management	$24	$24	$24	$45	$45	$45
TOTAL	**$1,534**	**$582**	**$307**	**$2,891**	**$1,467**	**$790**

The most costly impact categories are substation transformer lifespan reduction and wood pole decay, contributing to about 75 to 56 percent of the total, depending on the RCP and adaptation scenario. In most cases the proactive strategy is cost-effective. However, that is not true for all impact categories. Similar to the U.S. study, wood pole decay is less costly with a reactive strategy over a proactive strategy. The fungal growth that causes decay in wood structures thrives in moist soils and is therefore dependent on changes in precipitation. Since there is more variance across GCMs on changes in precipitation compared to temperature, the adaptation strategy based on the median projection is more likely to over or under design. Transmission line capacity and vegetation management represent the two lowest cost categories. Vegetation management was the second highest cost in the U.S. study but that is not the case for Canada due in part to shorter growing seasons in Canada. Also, these costs may be an underestimate, as mentioned in the previous section, due to the underrepresented trend over time from the statistical model of vegetation growth.

Table 3-38 shows the national average annual costs per unit of infrastructure for transformers, cables, and wood poles. In all cases, the scenario without adaptation is the most expensive. Savings with proactive adaptation for transformers is significant—almost 10 times cheaper than reactive and over 20 times cheaper than without adaptation. For cables, the proactive and reactive scenarios are similar, indicating that a forward-looking adaptation strategy may not be worth the extra effort to anticipate climate change impacts given the state of climate change uncertainty now. For wood poles, the proactive scenario is less effective than a reactive approach because changes in precipitation vary and are difficult to project, as already discussed.

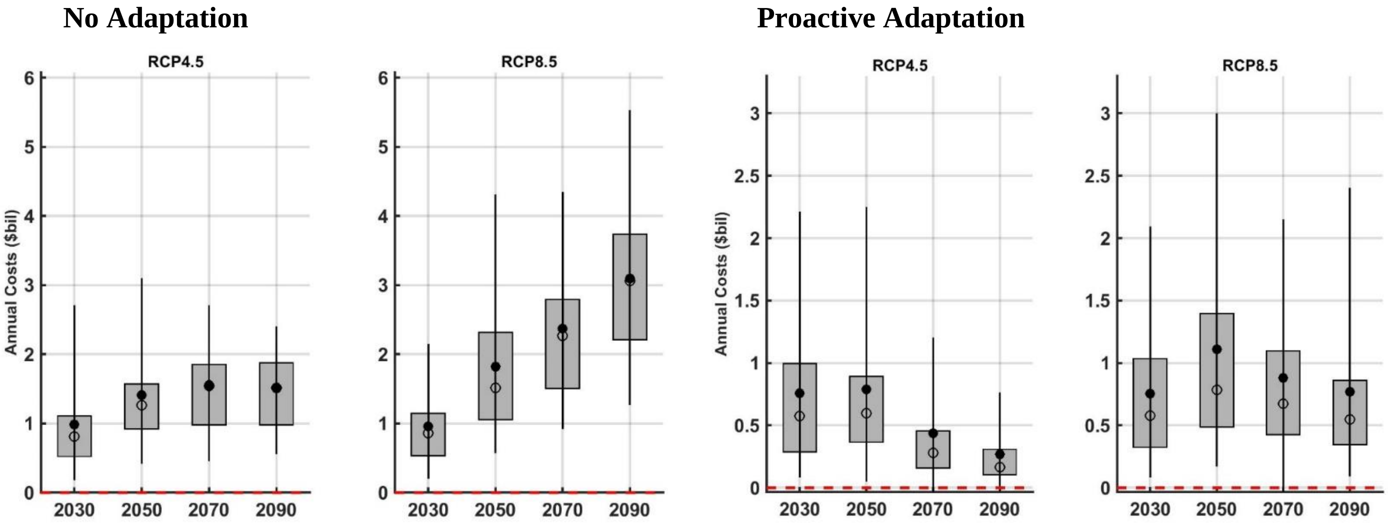
TABLE 3-38. ANNUAL COSTS PER UNIT OF INFRASTRUCTURE (2015 CAD)

RCP	Adaptation Scenario	Transformers (CAD/trans.)	Cables (mil. CAD/km)	Wood Poles (CAD/pole)
RCP4.5	No Adaptation	$2,686	$1.16	$272
	Reactive	$1,038	$0.73	$74
	Proactive	$123	$0.75	$99
RCP8.5	No Adaptation	$5,194	$3.19	$396
	Reactive	$2,872	$2.07	$109
	Proactive	$856	$2.05	$128

Infrastrucuture Impacts Over Time

The rate of evolution of impacts over time can inform strategies to deal these additional costs. Figure 3-32 shows the evolution of national annual costs over the century. Each boxplot contains 100 points made up of the five GCMs and 20 years within each era. The whiskers represent the 5th to 95th percentiles of these data, the boxes capture the 25th to 75th percentiles, and the filled and open circles are the mean and median across the data, respectively. With No Adaptation, RCP 4.5 shows an increase early in the century then costs flatten off the later half while RCP 8.5 shows a steady increase throughout the century. Variance across GCMs and years is particularly larger for RCP 8.5 than RCP 4.5. With proactive adaptation, a very different story emerges. Early spending on adaptation significantly reduces costs in the later half of the century, especially for RCP 4.5 where costs in 2090 are nearly half the costs in 2030.

FIGURE 3-32. TOTAL NATIONAL ANNUAL COSTS OVER TIME WITH 20-YEAR ERAS ACROSS THE CENTURY FOR THE NO ADAPTATION SCENARIO (LEFT) AND THE PROACTIVE SCENARIO (RIGHT).



Geographic Variability in Costs

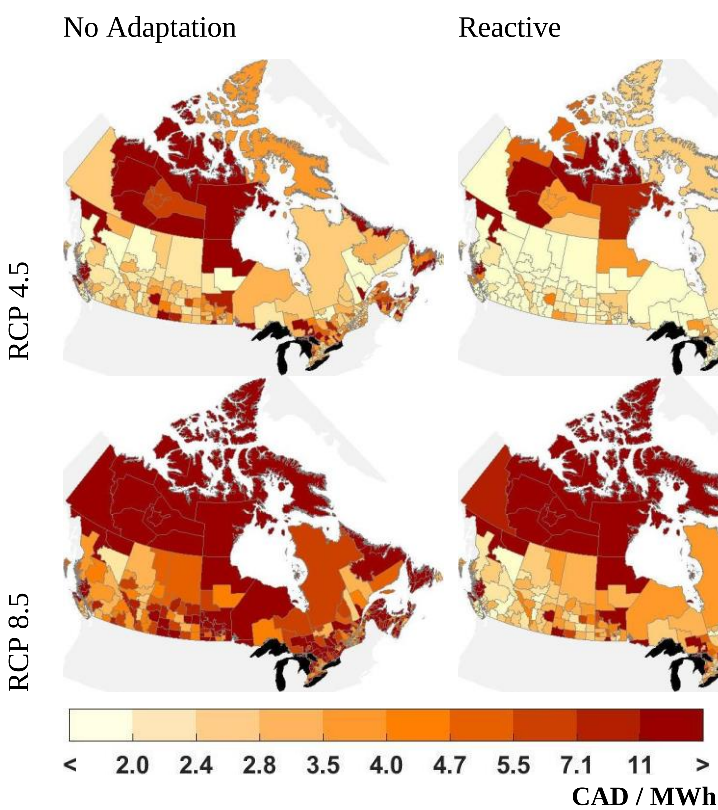
Table 3-39 shows the annual damages for the two eras by province or territory, average across the GCMs. Both Ontario and Quebec show the highest damages, composing over half the total for all scenarios. These differences between provinces and territories are largely driven by the inventory of grid infrastructure.

TABLE 3-39. PROVINCE AND TERRITORY ANNUAL DAMAGES FOR THE REACTIVE SCENARIO, GCM MEAN (MILLIONS 2015 CAD)

	2041-2070		2071-2100	
Province / Territory	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alberta	173	224	81	169
British Columbia	86	118	51	120
Manitoba	79	111	39	90
New Brunswick	62	78	22	56
Newfoundland and Labrador	34	41	11	27
Nova Scotia	46	59	17	42
Ontario	371	476	180	446
Prince Edward Island	28	32	7	21
Quebec	363	493	140	408
Saskatchewan	63	89	31	74
Territories	6	12	3	16

Figure 3-33 shows maps of the census division costs per MWh of electricity demand. It is unclear how much of these costs might be absorbed by the utility versus passed along to ratepayers, but these values show relative costs to electricity sales for an easier comparison across regions. National costs per sales (or demand) range from \$0.60/MWh for RCP4.5 - Proactive to \$5.30/MWh for RCP8.5 - No Adaptation. Impacts vary across census divisions from about \$0.30/MWh to \$24/MWh. The highest costs per demand tend to be in areas with very low demand density, and due in part to the lower population densities, infrastructure is comparatively higher per demand in order to connect the grid to the users.

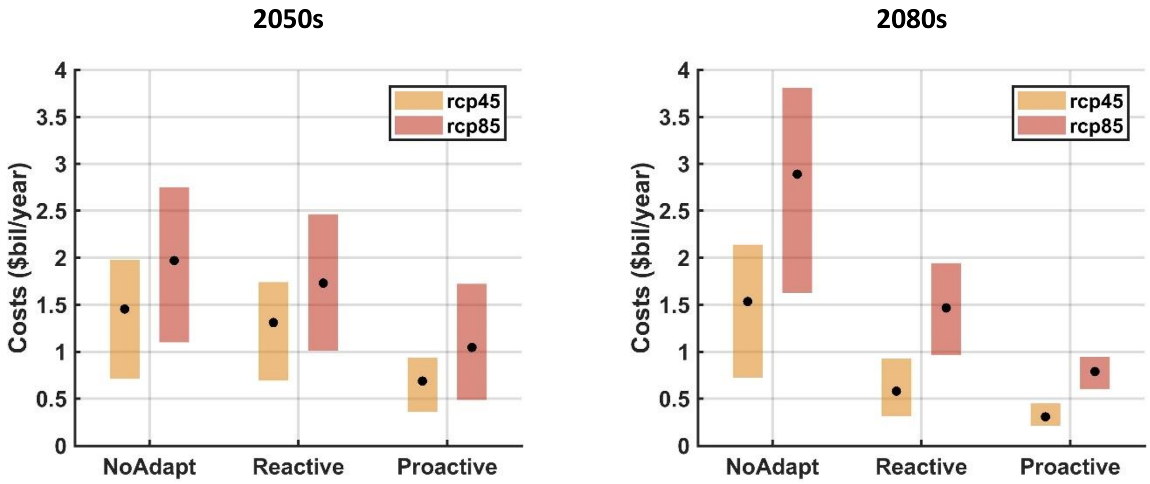
FIGURE 3-33. COSTS PER MWH DEMAND BY CENSUS DIVISION FOR 2071-2100



Annual Costs of Climate Change Impacts

Figure 3-34 shows the national annual costs for both eras, where the dots show the GCM mean and the boxes show the range of values across GCMs. In the 2050s era, the range across GCM estimates is considerably higher than differences between adaptation scenarios. By the 2080s, the benefits of using a proactive or even reactive adaptation strategy are quite evident. Even the range across GCMs, i.e., uncertainty, is considerably reduced.

FIGURE 3-34. NATIONAL ANNUAL COSTS FOR BOTH ERAS, BOXES SHOW THE RANGE OF GCM OUTPUTS AND DOTS SHOW THE MEAN



These results explore the costs of climate on the electrical grid in Canada. The approach was built around a series of stressor-response functions that relate the physical effects of climate change on the various components of the transmission and distribution network. The parsimonious approach used here provides a national estimate of costs of climate change to transmission and distribution infrastructure focusing on those that are likely to have substantial costs and tractable given the information available and scale. The hope is that these estimates can inform policy and to identify regions or sectors where resources should be used for targeted impacts and adaptation analysis.

The main takeaways from this analysis are:

- A proactive approach, using climate projections to inform the infrastructure design is cost-effective in most cases and can significantly reduce future spending in this sector.
- The majority of the costs are from impacts on substation transformers and wood structures. Substation transformers are the most expensive per unit in the electrical grid but there are fewer to supervise, which may necessitate earlier adaptation measures and real-time monitoring. Wood poles are relatively inexpensive per pole but there are many, which may result in less attention and monitoring.
- The range of estimates across the climate projections used in this analysis are substantial. In the U.S. study, the range of costs across the GCMs was on par with the range across adaptation scenarios and RCPs. While the U.S. study only used five GCMs compared to the seven used here, along with various other differences in the way the projections were downscaled, the range across GCM costs are about 3 times larger than for the U.S. in relative terms. Making decisions for the electrical grid under these uncertainties may be challenging going forward.

Limitations and Caveats

The major caveats and limitations to this approach are noted below.

- As mentioned, this work focuses on a subset of six stressor-response infrastructure interactions and as such capture only a portion of the range of climate change impacts to the grid.
- While the stressor-response functions are primarily based on physical processes and relationships rooted in engineering principles, they are designed to require a limited set of input. Specific caveats to each of these are listed in Fant et al. (2020).
- This analysis focuses on long-term infrastructure deterioration or performance reduction and does not include consideration of the costs of power interruptions, which have been shown to be substantial (Larsen 2016; Larsen et al. 2018). This omission of any customer costs associated with power interruptions is a critical area of future study and research in this area needed both in terms of characterizing the causes of interruptions and in developing a better understanding of how extreme weather events that cause interruptions will change in the future.
- The current state of the infrastructure (e.g., age, deterioration, etc.) is not considered due to lack of information. If the infrastructure is already in need of replacement and repair, costs may be higher in the near-term. On the other hand, infrastructure components are assumed to be designed to historical climate where vulnerabilities that result in impacts occur as the climate changes outside the range of observed climate. If design of these components has already incorporated long-term trends in climate, costs may decrease. Also, advances in technology may help to reduce adaptation costs and future impacts.

3.4.2 HYDROPOWER GENERATION CAPACITY

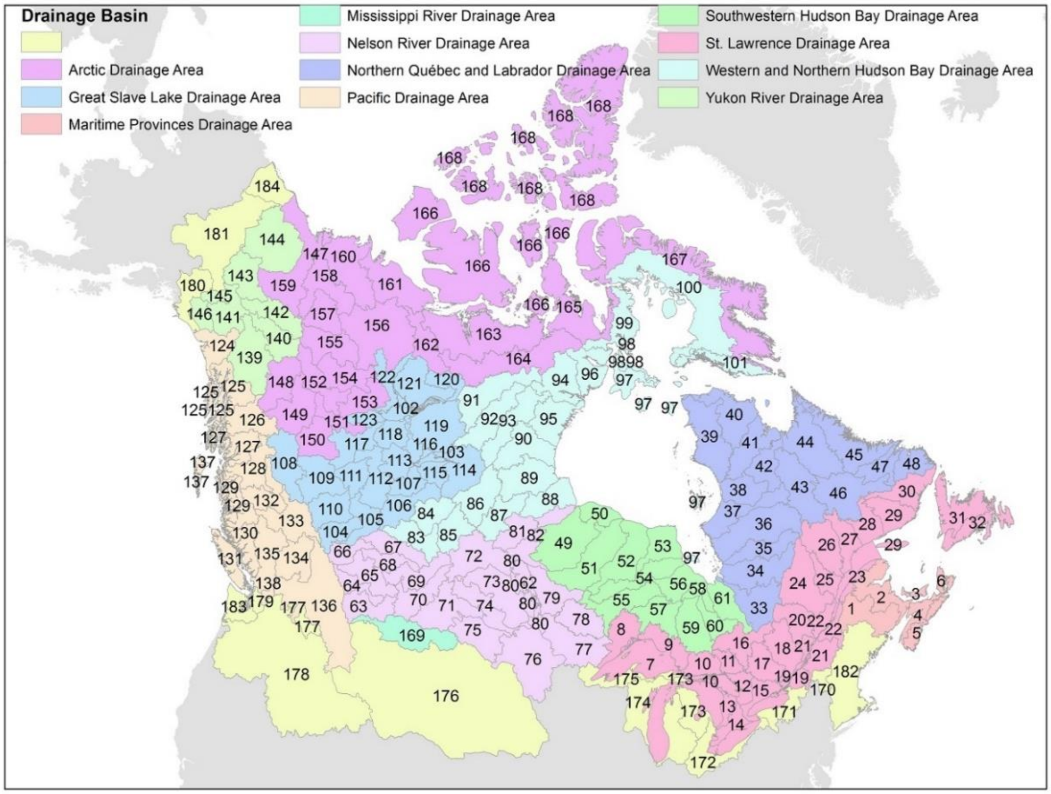
Canada has over 81 Gigawatts of installed hydropower capacity and generates over 380 Terawatt-hours of hydropower annually on average, making it the third largest producer in the world in 2018.[33] Shifting precipitation, snowmelt, and evaporation patterns will affect the magnitude, timing, and variability of hydropower generation, potentially posing challenges for energy planners and utilities seeking to achieve a stable and reliable energy supply.

Although conducting a comprehensive and detailed analysis of the effect of climate change on Canadian hydropower generation would be an enormously complex endeavor, this study seeks to provide an initial assessment of those effects, following an approach similar to Boehlert et al. (2016), who analyzed the impacts of climate change on U.S. hydropower generation through 2100. That study used a water systems model with over 2000 river basins and a moderately detailed accounting of the U.S. hydropower system. Although this level of modeling effort was not feasible here, we apply a water balancing approach to 184 basins across Canada that evaluates how projected runoff would be converted to hydropower generation by tracking reservoir volumes, elevations, and turbine releases in 67 of the basins that contain hydropower facilities (see Figure 3-35). While simplified, this approach offers more detailed insights than stylized approaches that have been taken in some other previous studies. Hamududu and Killingtvelt (2012) conduct a global assessment of hydropower generation and use changes in mean annual runoff under climate change as an indicator of changes in generation. Shu et al. (2018) report a statistical approach that relates projected changes in precipitation and temperature to changes in

[33] https://www.hydropower.org/country-profiles/canada

hydropower generation. Because these approaches assume that annual river flow is the primary driver of generation, they will have inaccuracies given the role of seasonal dynamics and reservoir management.

FIGURE 3-35. RIVER BASINS ANALYZED



Source: IEc analysis

Methods

The objective of this analysis is to provide an estimate of the effects of climate change on hydropower generation across Canada. The analysis follows four steps, which are described briefly here. More detail follows.

1. **Develop input dataset** on location, installed capacity, reservoir storage, and other information for hydropower generation facilities across Canada. Capacity factors for each facility are estimated using generation data at the province/territory level.
2. **Estimate simulated flows and net evaporation in each basin**. A central input to the water balance models is projections of river runoff under climate change. We use a calibrated monthly rainfall-runoff model to translate climate data into runoff projections for the baseline and each of the 14 climate change scenarios. These are then translated from runoff into flows (i.e., the water available at a hydropower facility), by summing all upstream runoff for each basin.
3. **Build water balance models.** Using information from Steps 1 and 2, we next develop water balance models that track monthly hydropower facility water levels, releases, spill, and reservoir volumes based on inflows and evaporation. Hydropower generation is calculated from releases

through turbines and reservoir elevation, and these are bias corrected to the approximate generation levels for each basin.[34]

4. **Estimate change in generation and revenues.** The changes in generation are then calculated for each basin and facility, and these are aggregated to the province level to estimate total changes in energy production. We then apply an average price per megawatt-hour (MWh) to estimate economic implications.

Step 1. Develop Input Dataset

The aim of this step was to develop a dataset with key information on hydropower facilities that covers approximately 90 percent of the installed capacity across the country, as well as ensuring that the majority of capacity within each of the provinces and territories is included. We relied primarily on three sources for this:

- For each of over 500 hydropower facilities across Canada, data on **installed capacity** (i.e., megawatts [MW]) and **location** (latitude and longitude) are available through DMTI.
- Data on **reservoir volume** and **height** are available from the Canadian Dams Association large dams dataset (CDA 2019). In many cases, the facility names in the CDA dataset did not match DMTI names; in many cases we were able to make the match, but in others no match could be established. For larger facilities that were critical to the analysis and were missing data, we researched information on reservoir heights and volumes from a range of sources.
- Information on **hydropower generation** was available at the province/territory level from Statistics Canada (2020), but we were unable to locate a centralized source of generation data at the facility level. We also relied on facility level data for some of the larger facilities, and for the main river basins within Quebec.

We also calculated two additional variables derived from those above. First, we calculated **maximum turbine capacity** (in m3/s) using information on installed capacity and height, assuming a turbine efficiency of 90 percent.[35] This variable is critical for ensuring that increased flows under climate change only increase hydropower generation if they do not exceed turbine capacity. Second, to approximate **capacity factors** of the facilities (i.e., the ratio of actual hydropower generation to theoretical generation based on installed capacity), we aggregated installed capacity (from DMTI) to the province/territory scale and then compared the observed mean annual hydropower generation (from Statistics Canada 2020) at that resolution to theoretical generation. We then assigned each facility the capacity factor from its province/territory.

Lastly, we mapped the facilities into each of their respective basins, then created a lumped facility in each basin by summing most variables across facilities (volume, installed capacity, maximum turbine

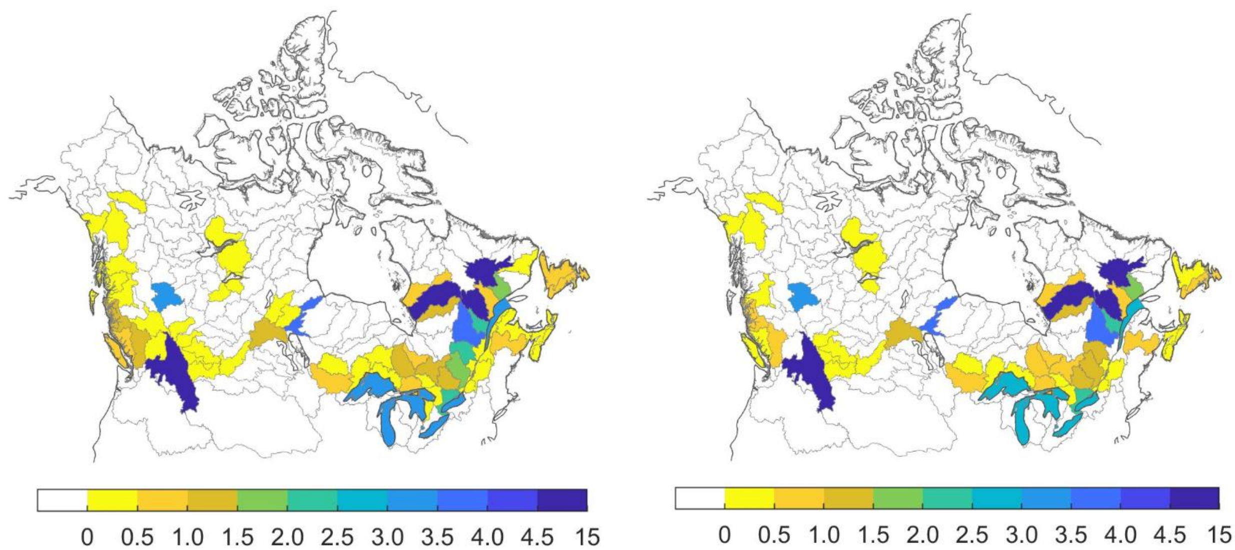
[34] Although other water demands don't typically compete with hydro generation needs in Canada, the model could be made more representative with information on upstream water demands, environmental flow considerations, and so on. Given the limited scope of this aspect of the work and the fact that demands are less likely to change considerably under climate change, our focus is on runoff impacts only.

[35] The equation to calculate maximum turbine capacity is (installed capacity) / (9.81 * 1000 * 0.9 * height) where installed capacity is in MW, and height is in meters.

capacity), and then using the installed capacity and maximum turbine capacity to estimate representative height, which we take to be maximum head for hydropower generation. This also allows us to produce an estimated level of mean annual hydropower generation for each of the basins. In the absence of more detailed information on the location of facilities within the river network of each catchment, our approach assumes that the lumped facility is at the catchment outlet, which means that more runoff is available for generation in our model than would be actually available. Given that this upward bias is present in both the baseline and projections, the relative effects of climate change reported here are unlikely to be significantly affected.

This dataset provided the inputs needed for the water balance modeling in Step 3. In total, this process developed facility information for 89 percent of the installed capacity of facilities in the DMTI database, distributed across Canada as shown in Figure 3-36. The figure on the left includes all DMTI facilities, whereas on the right only those facilities with data available for the necessary characteristics are included.

FIGURE 3-36. INSTALLED CAPACITY ACROSS THE 184 BASINS INCLUDING ALL FACILITIES (LEFT) AND THOSE INCLUDED IN THIS ANALYSIS (RIGHT)



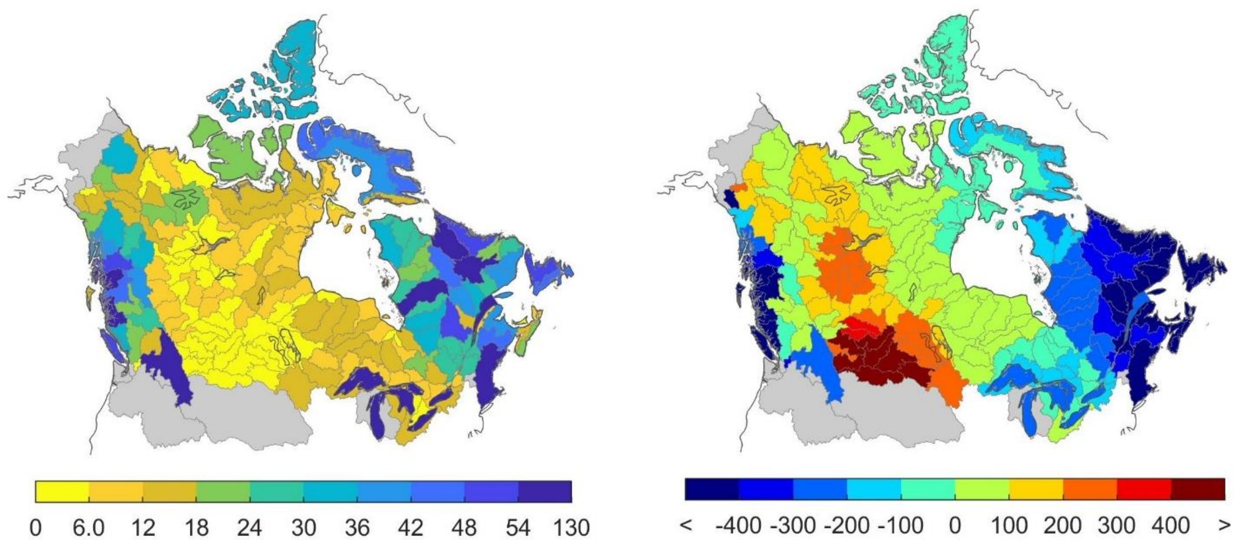
Step 2. Estimate Simulated Flows and Net Evaporation in each Basin

To generate river runoff projections at the 184 basins, we use model calibration parameters from our 2010 NRTEE study (Industrial Economics, 2010) to simulate runoff for the baseline and projected climate data used throughout this analysis. The 2010 work calibrated modeled runoff outputs (developed using a different climate baseline) to 'observed' runoff data produced by the Global Runoff Data Center (GRDC), which is a gridded global data product for 12 months at the 0.5° spatial resolution. Although it was beyond the scope of this current activity, recalibrating the model using (a) the climate baseline used in this study and (b) an improved and Canada-specific runoff dataset would improve the accuracy of these results. Further, a more refined observed runoff dataset than GRDC would have improved the temporal and spatial accuracy of the calibration, however, to our knowledge no such Canada-wide naturalized runoff dataset exists.

Input data to the projections includes monthly precipitation and potential evapotranspiration (PET; calculated using the modified Hargreaves approach) for the 1986 to 2005 baseline and 2011 to 2100 projection period, and the calibration parameters from the 2010 work, for each of the 184 basins. The projections cover all 14 climate scenarios. For inputs to the reservoir balance equation, we also estimate net evaporation (i.e., PET – precipitation) for each month in each basin.

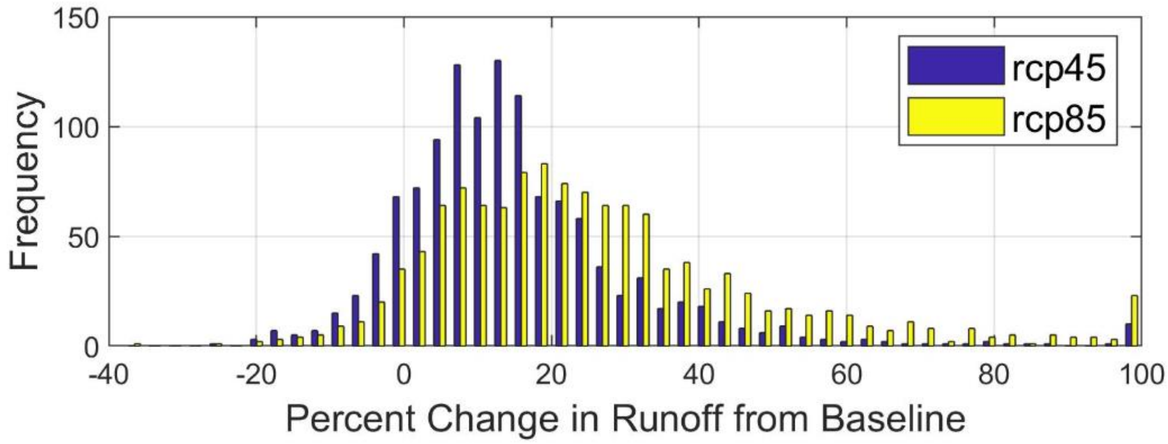
Overall, the simulated baseline (between 1970 and 2010) estimates an average Canada-wide runoff of 3,240 km^3 annually, which compares favorably with estimates presented by Natural Resources Canada (NRC 2020) of 3,600 km^3 per year, and from the AquaStat (FAO 2019) estimate of 2,800 km^3. Figure 3-37 shows baseline annual runoff and net evaporation. Basins wholly in the U.S. (shaded in gray) are not included in runoff or net evaporation calculations.

FIGURE 3-37. MEAN ANNUAL 1986-2005 RUNOFF (LEFT; KM^3) AND NET EVAPORATION (RIGHT; MM)



Projected changes in runoff to the 2080s across GCMs and the 184 basins (i.e., 1288 possibilities for each RCP) are presented in Figure 3-38. The projected changes generally show increasing runoff, ranging from decreases of 40 percent to a maximum of a 540 percent increase (all values above 100 are captured in the 100 bar). This pattern of increasing runoff is more exaggerated under RCP 8.5.

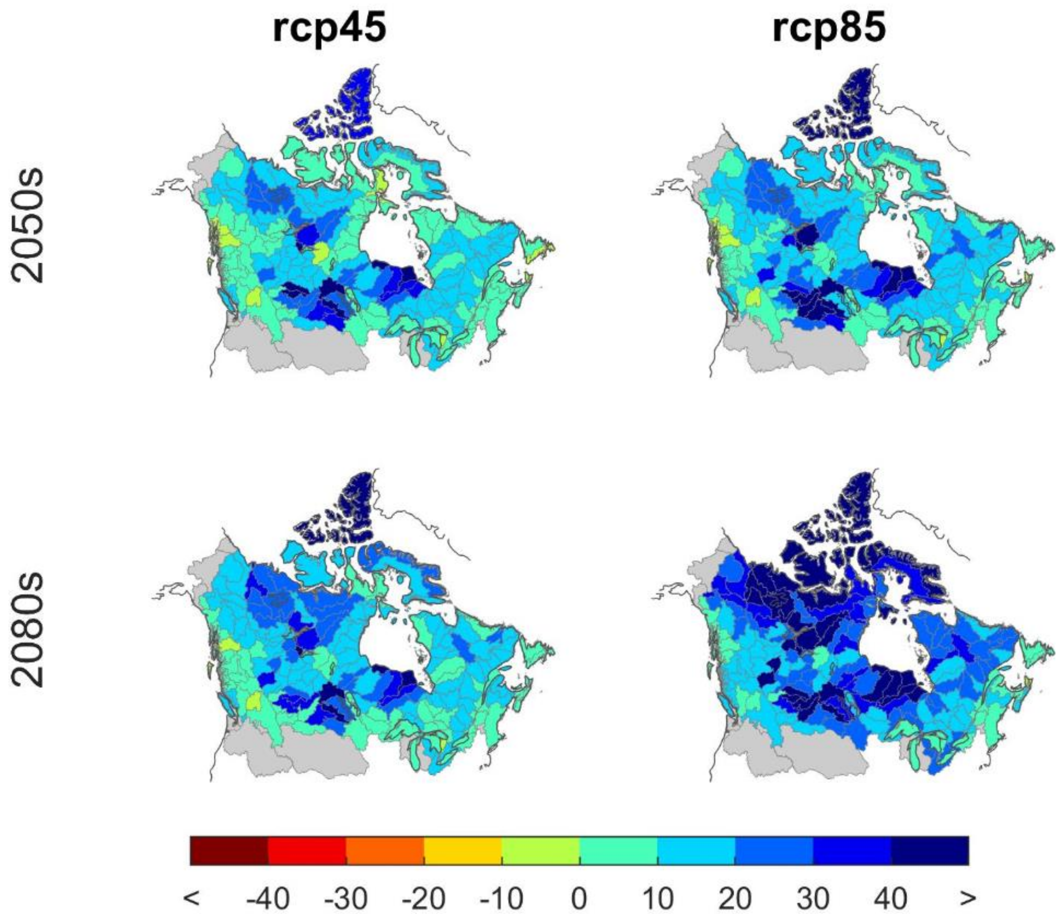
FIGURE 3-38. HISTOGRAM OF CHANGE IN RUNOFF FROM BASELINE TO THE 2080S, ACROSS BASINS AND GCMS



Note that the bar at +100 percent includes all occurrences greater than 100 percent, ranging up to an absolute maximum of a 540 percent increase.

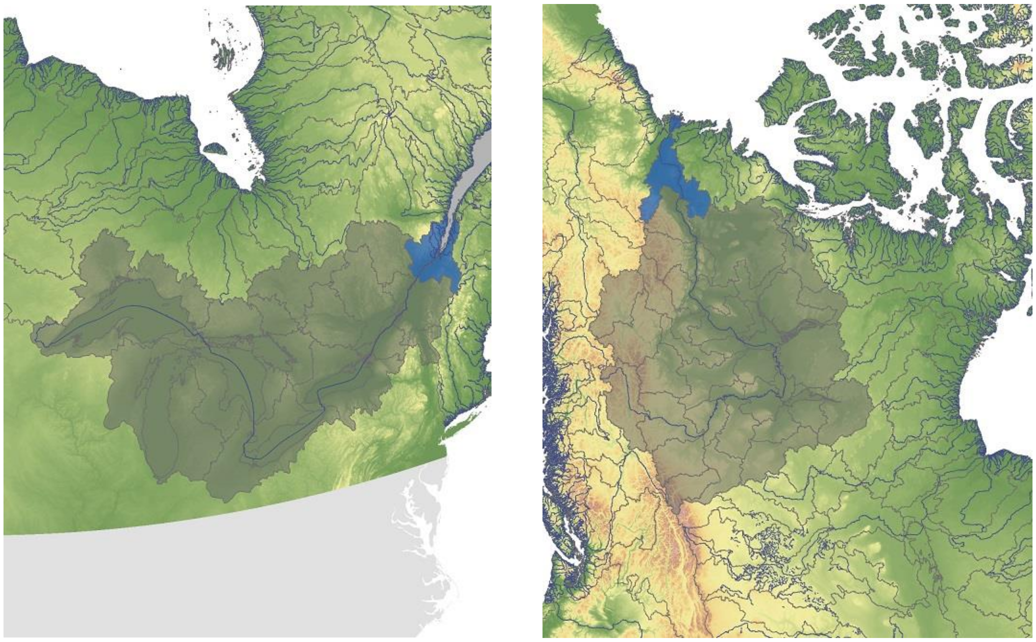
Figure 3-39 looks at changes in runoff spatially for each RCP, averaged across the GCMs. Averaging across GCMs mutes the patterns seen in the above histogram somewhat, including almost entirely removing any reductions in runoff. Generally, inland areas are anticipated to have the largest increase in runoff, whereas the projected increases in coastal areas will be more muted. The range of projected changes is comparable to findings of Guay et al. (2015), who show modeled increases in runoff for Quebec ranging between 2 to 14 percent through 2050.

FIGURE 3-39. PROJECTED PERCENTAGE CHANGE IN MEAN ANNUAL RUNOFF ACROSS GCMs UNDER TWO RCPs AND TIME PERIODS



As a last step, runoff was converted into flows by assessing the upstream-downstream relationships between each basin using topological information in the HydroAtlas (WWF 2020), and summing runoff in all upstream basins. Figure 3-40 provides two examples of the basins upstream whose runoff is summed to produce flow in the outlet basin, in blue.

FIGURE 3-40. ILLUSTRATIONS OF THE UPSTREAM BASINS FROM TWO OUTLETS



Step 3. Build Water Balance Models

The facility characteristics from Step 1 were combined with the flow and net evaporation projections in Step 2 to populate water balance models for each basin. The basic water balance formulation is:

$$Storage_t = Storage_{t-1} + Inflow_t - Evap_t - Release_t - Spill_t$$

Or storage this month is equal to storage last month plus inflow, less net evaporation, releases through the turbines, and spill (t denotes each month over the time series). As noted above, this formulation does not consider upstream demands or consumptive use, environmental flow requirements, or seepage from the reservoir into groundwater. The usable storage in this formulation is assumed to be 75 percent of total storage from the database in Step 1, where the remaining 25 percent is dead storage not accessible for hydropower generation. This assumption is adopted from Boehlert et al. (2016), who apply these ratios for basins in the U.S. where information on dead storage is not available. The upper bound on release is the maximum turbine capacity defined above, and decisions around how to allocate between release, spill, and holding water back in storage are driven by a simplified rule curve. This rule curve is designed to accommodate the spring freshet, where more freeboard is maintained in the reservoir from December through May, and the reservoir can remain nearly full from June to November. When storage exceeds rule curve levels each month, water is first released through the turbines up to max capacity, then any excess is spilled. Any months where storage is below the rule curve levels, no water is released. Reservoir elevation (for head) and area (for evaporation) are calculated each month based on representative volume elevation curves.

We input monthly baseline and projected runoff and evaporation into the above formulation to estimate head and turbine releases under the baseline and all climate scenarios. We use these outputs, combined with turbine efficiency, to calculate average power output each month for all climate scenarios (in MW).

This is then translated to energy generation (in GWh) by multiplying by number of hours per month and the capacity factors for each of the basins estimated in Step 1. In order to ensure that the total generation being modeled is consistent with historically observed levels, a "bias correction multiplier" is then developed for each basin that divides the basin-level generation values from Step 1 by the modeled baseline levels. The more this value deviates from 1, the more biased the modeled estimate is.[36] This set of basin multipliers is then applied to hydropower generation in each scenario.

Step 4. Estimate Change in Generation

Lastly, we compare generation levels across GCMs and RCPs to baseline levels. The hydropower generation outputs are aggregated to the province/territory and national levels.

Results

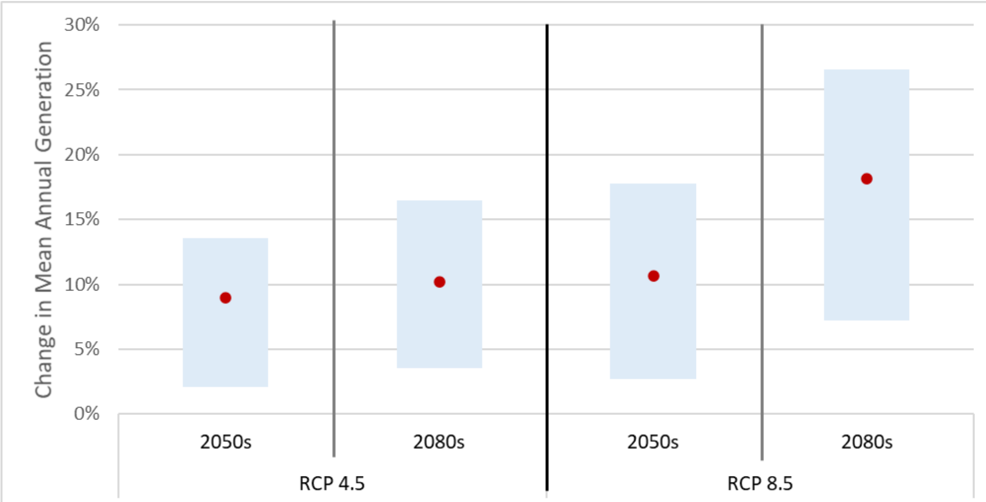
The following section presents the results of the analysis over space and time. Unlike other analyses, this study does not monetize the effects because of uncertainties in both modeling generation and how those would ultimately be monetized.

Infrastrucuture Impacts Over Time and across GCMs

Figure 3-41 shows the overall effects of climate change on hydropower generation at the national scale, in terms of percent change relative to the 1986 to 2005 baseline. From this perspective, even the GCMs that show the smallest generation levels still show increases nationally. Average increases across GCMs are roughly 10 percent for the 2050s and 2080s under RCP 4.5 and the 2050s under RCP 8.5. Given the much larger projected increases in temperature into the late century under RCP 8.5, those effects are nearly twice as high at an 18 percent average increase. Under RCP 8.5 in the 2080s, the minimum projected increase is 7 percent relative to the baseline period.

[36] Generally, the most biased basins appear to be those that have cascades of hydropower facilities. For this type of configuration, a more appropriate way to develop a lumped basin-level facility would be to sum reservoir heights and average maximum turbine capacity, rather than the approach we have taken which does the opposite. It was not possible, within the scope of this analysis, to research the configuration of hydropower facilities in each basin so this is an outcome of our study design.

FIGURE 3-41. CHANGE IN MEAN ANNUAL GENERATION OVER TWO RCPs AND PERIODS



Note: the red dot in each bar is the average across the seven GCMs, and the surrounding box shows the range.

Geographic Variability in Costs

Effects at the provinces at territory level are similar, with the majority experiencing increases that scale with time and emissions intensity. The low-end estimates of future generation levels do show decreases relative to the baseline in a few provinces, including Manitoba for all era-RCP combinations, on Ontario, Alberta, and British Columbia for a subset of era-RCPs (Table 3-40). GCMs showing the largest increases in the 2080s under RCP 8.5 suggest a roughly 30 percent increase in generation relative to baseline levels.

TABLE 3-40. PERCENT CHANGE IN MEAN ANNUAL HYDROPOWER GENERATION FOR PROVINCES AND TERRITORIES, FOR THE MINIMUM, MEAN, AND MAXIMUM ACROSS GCMS

	RCP 4.5						RCP 8.5					
	2050s			2080s			2050s			2080s		
Province/Territory	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Alberta	-1%	9%	23%	0%	9%	22%	2%	10%	21%	1%	14%	33%
British Columbia	-1%	5%	14%	3%	8%	17%	2%	7%	16%	6%	14%	32%
Manitoba	-7%	9%	19%	-5%	8%	17%	-4%	10%	21%	-2%	16%	25%
New Brunswick	8%	16%	20%	12%	17%	26%	8%	15%	23%	13%	23%	33%
Newfoundland and Labrador	7%	14%	21%	10%	16%	21%	9%	17%	26%	15%	25%	35%
Nova Scotia	1%	5%	8%	6%	7%	9%	3%	6%	10%	3%	8%	12%
Northwest Territories	7%	11%	14%	4%	12%	18%	6%	12%	17%	11%	18%	22%
Nunavut												
Ontario	-2%	7%	14%	-1%	7%	18%	-1%	7%	16%	3%	15%	25%
Prince Edward Island												
Quebec	4%	9%	13%	3%	10%	16%	2%	11%	18%	6%	19%	28%
Saskatchewan	0%	11%	24%	2%	10%	18%	0%	12%	20%	5%	16%	28%
Yukon	0%	4%	6%	0%	6%	10%	1%	5%	8%	4%	11%	17%

Main takeaways

The main takeaways from this analysis are:

- Average effects of changes in hydropower generation across eras and GCMs range from approximately 2 percent to 26 percent increases in generation annually, depending on the RCP and era. Average increases across GCMs are roughly 10 percent for the 2050s and 2080s under RCP 4.5 and the 2050s under RCP 8.5. Under RCP 8.5, those effects are nearly twice as high at an 18 percent increase.

- Effects at the provincial and territorial level are similar, with the majority experiencing increases that scale with time and emissions intensity. The low-end generation levels do show the potential for decreases relative to the baseline in a few provinces, including Manitoba for all era-RCP combinations, on Ontario, Alberta, and British Columbia for a subset of era-RCPs.

- The above results do not address projected changes in firm power, which is a potentially critical effect of climate change, particularly given increases in summer electricity demand for cooling under a warmer climate. Boehlert et al. (2016) found that although overall hydropower generation in the U.S. generally increased under climate change (primarily due to rising generation in the Pacific Northwest), reliability of monthly flows decreased because of falling summer rainfall and earlier snowmelt.

Limitations and Caveats

The purpose of this analysis is not to develop facility-level hydropower projections or site-specific adaptation recommendations, but rather to understand the possible regional and national-level effects of climate change on hydropower generation. The major caveats and limitations to this approach are noted below.

- Calibrating the rainfall runoff model using (a) the climate baseline used in this study and (b) an improved and Canada-specific runoff dataset would improve the accuracy of these results, and allow for a more defensible estimation of effects on firm power. How this would affect the magnitude of relative changes in generation under climate change, however, is unclear.
- The model of the Canadian hydropower system developed in this work is a highly stylized representation of the actual system, for several reasons:
    - Although information on installed capacity for each facility was available, often other characteristics such as maximum turbine flow, height, and usable reservoir volume were not. These needed to be reconstructed using available data.
    - One of the sources of data used to tune facility characteristics and system-wide production is energy generation at the province/territory level. Ideally, a dataset with more generation data at the facility level would have been available to allow for facility-specific calibration.
    - Individual facilities within each basin are lumped into a single facility for modeling purposes, with an average height and a sum across maximum turbine flows. As documented by Wiberg and Strzepek (2005), how facility characteristics are combined depends on the configuration of the system, i.e., if the system is a cascade, summing heads is more sensible, whereas if the reservoirs are on separate tributaries within a basin, summing across maximum turbine capacities is the better choice. However, in the

absence of information about the configuration of facilities in each basin, it was not possible to reflect these characteristics in the lumping approach.

  - The management of each basin-level lumped facility is treated as independent, with flow from all upstream basins available for hydropower generation. In reality, these systems are interdependent and operated as a system. Further, absent detailed information on how each facility is managed, we use a stylized monthly rule curve that is identical (in percentage of volume terms) across basins that may not accurately reflect how releases occur each month.
  - Inter-basin transfers, water demands, and environmental flows are not considered. Although generally water is plentiful in Canada and unlikely to have a major effect on the availability of hydropower flows, in specific instances any of these three omissions could have a significant effect.

- The generally positive effects of climate change on hydropower generation in this study are driven by projected increases in precipitation and thus runoff, but may be overstated because of some of the simplifying assumptions about operational constraints described above. Under these omitted constraints (e.g., minimum required reservoir levels through the summer for recreation, releases for salmon, or maximum system energy demand that constrains generation) often more water would not allow production of more hydropower.

3.5 DELAY COSTS

For many of the sectors described above, the costs of climate change include not only the direct cost of repairing, preventing, or minimizing the physical damage caused by climate change but also the indirect costs borne by both households and businesses. These indirect costs represent an interruption in the normal course of business for households and firms and are an important element of the societal losses associated with climate change.

Although these effects are relevant to several of the sectors included in this report, the available data and methods support the analysis of these effects for roads and rail only, in the form of delay costs. Below we describe our approach for estimating these delay costs and the results of our analysis.

Methods

Roads

Our analysis of delay costs for the roads sector captures climate-related increases in the costs of motorist delay related to road damage. The analysis is based upon the methods applied in Neumann et al. (2019), which estimates these effects for the United States. To estimate delays, Neumann et al. (2019) relied upon the relationship between present serviceability rating (PSR) and free-flow speed developed by Wang et al. (2013), using research by Al-Omari and Darter (1994) to convert IRI to PSR. To quantify the cost of delay from the change in free-flow speed, Neumann et al. relied on the following equation:

(4) $$\text{Total Cost of Delay} = \left(\frac{L}{V - \Delta V} - \frac{L}{V}\right) * ADT * 365 * C_D$$

Where:
L = length of road (miles)
V= Posted speed limit (mph)
ΔV=Change in free-flow speed (mph)
ADT=Average daily traffic (vehicles per day)
C_D=Unit cost of delay (USD/hour)

To quantify the unit cost of delay for passenger vehicle travel, Neumann et al. (2019) relied on the value of travel time savings (VTTS) estimates from the U.S. Department of Transportation's 2016 guidance for intercity surface transportation models. For the average occupancy of passenger vehicles, Neumann et al. relied on data from the 2017 National Household Travel Survey (FHWA 2017). To quantify the unit cost of delay for freight vehicle travel, Neumann et al. rely on data from the National Cooperative Highway Research Program (NCHRP) that are used as inputs to their Truck Freight Reliability Valuation Model (NCHRP 2016).

The methods used in the Neumann et al. (2019) study are applicable to the Canadian context, but to our knowledge the data necessary to directly apply this approach to Canada are not readily available. For example, we were unable to identify the detailed traffic data necessary to use the Neumann et al. (2019) approach. In the absence of these data, we applied the ratio of delay costs to adaptation costs from Neumann et al. (2019) to the direct adaptation costs that we estimate for Canada. Because the types of adaptation costs included in this study and in Neumann et al. (2019) are the same, this provides a reasonable approximation of delay costs in the Canadian context. These ratios are summarized in Table 3-41. As shown in the table, these ratios vary by RCP, stressor (temperature versus precipitation), and scenario (status quo versus proactive). Sections 3.2.1 and 3.2.2 above describe the types of damages to roads and rail, respectively, that can result in delay costs.

TABLE 3-41. RATIO OF DELAY COSTS TO ADAPTATION COSTS

	PROACTIVE/ PRECIPITATION	STATUS QUO/ PRECIPITATION	PROACTIVE/ TEMPERATURE	STATUS QUO/ TEMPERATURE
Baseline	1.096	1.068	1.034	1.410
RCP 4.5	1.095	1.050	1.074	1.224
RCP 8.5	1.093	1.054	1.080	1.165
Source: Derived from Neumann et al. (2019).				

Rail

Similar to roads, we also examined how climate change may result in delay costs for rail. At the grid cell level, our analysis of delay minutes per year under the status quo scenario follows the approach in Chinowsky et al. (2019). Under this approach, we estimate delay based on the reduction in speed per delay incident, the total length of rail per grid cell, the total hours of speed reduction orders per grid cell, the number of hours that the railroad typically operates, the average number of trains per day, and the mix of passenger and freight traffic.[37] To estimate total delay time based on this information, we follow a two-step process:

- ***Step 1: Estimate train delay minutes per grid cell per incident per train.*** To match the spatial specificity of the climate data, we estimate the per incident delay separately for each grid cell, based on the following equation:

$$(5) \quad TDM_g = \left(\frac{L_g}{S_r} - \frac{L_g}{S_o}\right) \times 60 \times \frac{H_d}{H_o}$$

  Where

  TDM_g = Train delay minutes per grid

  S_r = Reduced speed

  S_o = Base speed

  L_g = Total Length of rail traveled per grid

  H_d = Hours of speed order

  H_o = Hours of railroad operation

- ***Step 2: Estimate annual train delay minutes per grid cell.*** Building upon the delay per grid cell per incident (TDM_g) calculated in Step 1, we estimate the annual minutes of delay per grid cell per year as follows:

$$(6) \quad DM_g = TDM_g \times T_d \times I_d$$

  Where

  DM_g = Delay minutes per grid cell per year

  T_d = Average number of trains per day

  I_d = Number of incident days[38]

As noted above, our analysis of the proactive adaptation scenario assumes that train operators install track temperature sensor technology that allow them to implement a risk-based approach to speed orders that allows train operators to target speed orders to specific lines based on the temperature and the traffic

---

[37] We estimate train traffic based on Transportation Canada's grade crossings inventory, which includes data on the average number of trains that pass through each crossing daily. This is consistent with the approach applied in Chinowsky et al. (2019). To parse train traffic for a given area between freight and passenger service, we rely on the freight versus passenger rail designation for individual rail lines as specified in Natural Resources Canada's National Railway Network data and the national distribution between freight and passenger train traffic published by the Railway Association of Canada.

[38] Section 3.2.2 above presents a detailed description of how we estimate the expected number of rail buckling events.

expected on that line during extreme heat events. We estimate the hours of delay per grid cell using the same approach as applied for the status quo scenario.

To value changes in delay time, we apply separate approaches for passenger travel versus freight. The available rail traffic data was not broken down into freight vs passenger traffic. To estimate the ratio of passenger to freight traffic in the grid, we relied upon data from the NRCan rail stock on "User Type". "User Type" was broken down into three categories: freight, passenger and both. We assumed that rail with freight user type is assumed to have all freight traffic and that rail with passenger user type is assumed to have all passenger traffic. Rail with both freight and passenger user type was assumed to be 75 percent freight and 25 percent passenger.[39] Using these assumptions, the final rail traffic breakdown is 86 percent freight and 14 percent passenger. By comparison, freight and passenger train-miles from the Railway Association of Canada's Rail Trends 2019 report indicate that 90 percent of train traffic is freight and 10 percent is passenger. Based on this Rail Trends source, we assume 161 passengers per passenger train.

To value passenger travel, we calculate the value of delay based on the average hourly value of an individual's time. For leisure travelers, we specify this time loss based on an average, post-tax market income of $27.45 per hour (in year 2015 CAD).[40] The corresponding value for work travel is $34.38 ($2015 CAD), which reflects total pre-tax compensation per hour.[41] Assuming that the distribution between leisure and passenger train travel in Canada is similar to the corresponding distribution in the U.S., we assume that 6 percent of rail passenger trips in Canada are business trips and the remaining 94 percent are leisure trips (Talebian and Zou, 2015). To estimate the value of freight delays, we rely on the additional costs incurred by freight operators based on the approach specified in Chinowsky et al. (2019).

Results

Table 3-42 presents the estimated value of delay costs by scenario (status quo versus proactive), era, and RCP. As indicated by the results, projected delay costs are much higher under the status quo than under the proactive scenario. The difference between the two scenarios is most significant under RCP 8.5 during the second era, with status quo delay costs nearly an order of magnitude higher than proactive effects. The results in Table 3-42 also show that delay costs for roads are generally larger than the corresponding effects related to rail, though not in all cases. For RCP 8.5 during the second era, delay costs related to rail are more significant than road-related delay costs, under both the status quo and proactive scenarios.

[39] These values were assumed to yield an aggregate freight-passenger distribution reasonably consistent with that reported by the Railway Association of Canada, as summarized below.

[40] This value is based on average post-tax market income of $57,100 in 2018, as reported in Statistics Canada's *The Daily* on February 24, 2020. We adjusted this value for inflation and converted it to an hourly value by assuming 2080 labor hours per year.

[41] This value from 2018 is adjusted for inflation and derived from Statistics Canada, Labour productivity and related measures by business sector industry and by non-commercial activity consistent with industry accounts, Table 36-10-0480-01.

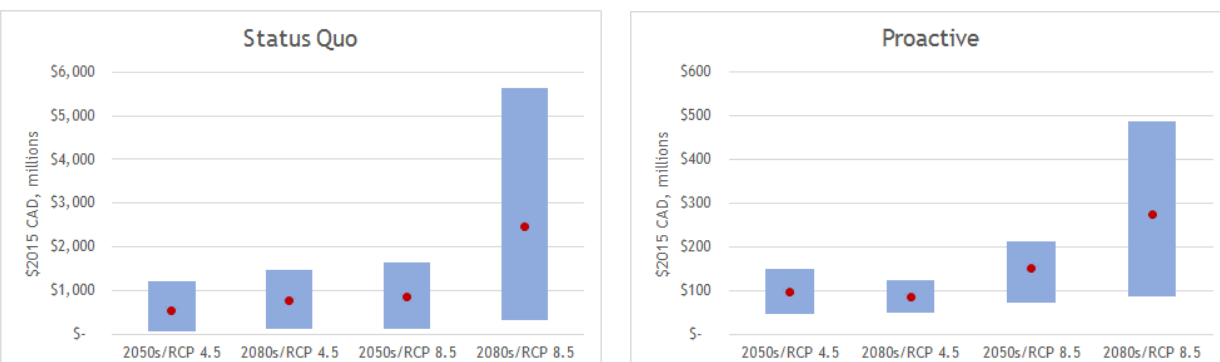
TABLE 3-42. DELAY COSTS BY SCENARIO, ERA, AND RCP ($2015 CAD, MILLIONS)

SECTOR	STATUS QUO				PROACTIVE			
	2040-2069		2070-2099		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Roads	$386.4	$455.6	$610.3	$1,143.0	$72.1	$84.5	$58.5	$86.1
Rail	$159.1	$397.9	$157.9	$1,334.8	$26.1	$68.0	$27.5	$188.6
Era Total	**$545.4**	**$853.5**	**$768.1**	**$2,477.8**	**$98.2**	**$152.5**	**$86.0**	**$274.7**

The magnitude of the delay costs shown in Table 3-42 relative to the climate change costs presented earlier in this report differs significantly for roads versus rail. The delay costs for roads represent between 14 and 20 percent of the road-related climate change costs presented in section 3.2.1 above, with the exception of one combination of scenario, era, and RCP. Delay costs related to rail, however, are more than an order of magnitude higher than the climate change costs for rail presented in section 3.2.2. This finding suggests that focusing on the reduction of time losses is the most cost-effective adaptation strategy for the rail sector.

For insights on the climate model uncertainty reflected in the estimates above, Figure 3-42 presents the range of delay costs across the seven GCMs applied in this analysis, by scenario, era, and RCP. These ranges are represented by the blue bars in the figure; the red dots represent the average values as presented above. For each scenario (status quo and proactive), the range of estimates around the average is fairly similar between eras and RCPs, with the exception of RCP 8.5 during the second era. This reflects a wider range of results across GCMs rather than a single outlier.

FIGURE 3-42. RANGE OF DELAY COSTS BASED ON MULTIPLE GCMS



Note: Due to differences in the magnitude of costs between the status quo and proactive scenarios, the two graphs above use different ranges on their vertical axes.

Table 3-43 presents the estimated delay costs by province/territory. Overall, delay costs are most significant for Ontario. Quebec, Alberta, and British Columbia make up the second tier, with similar delay costs across all three provinces. The high delay costs for Ontario reflect the combination of its extensive road network and the high volume of rail traffic in Ontario.

TABLE 3-43. DELAY COSTS BY PROVINCE/TERRITORY

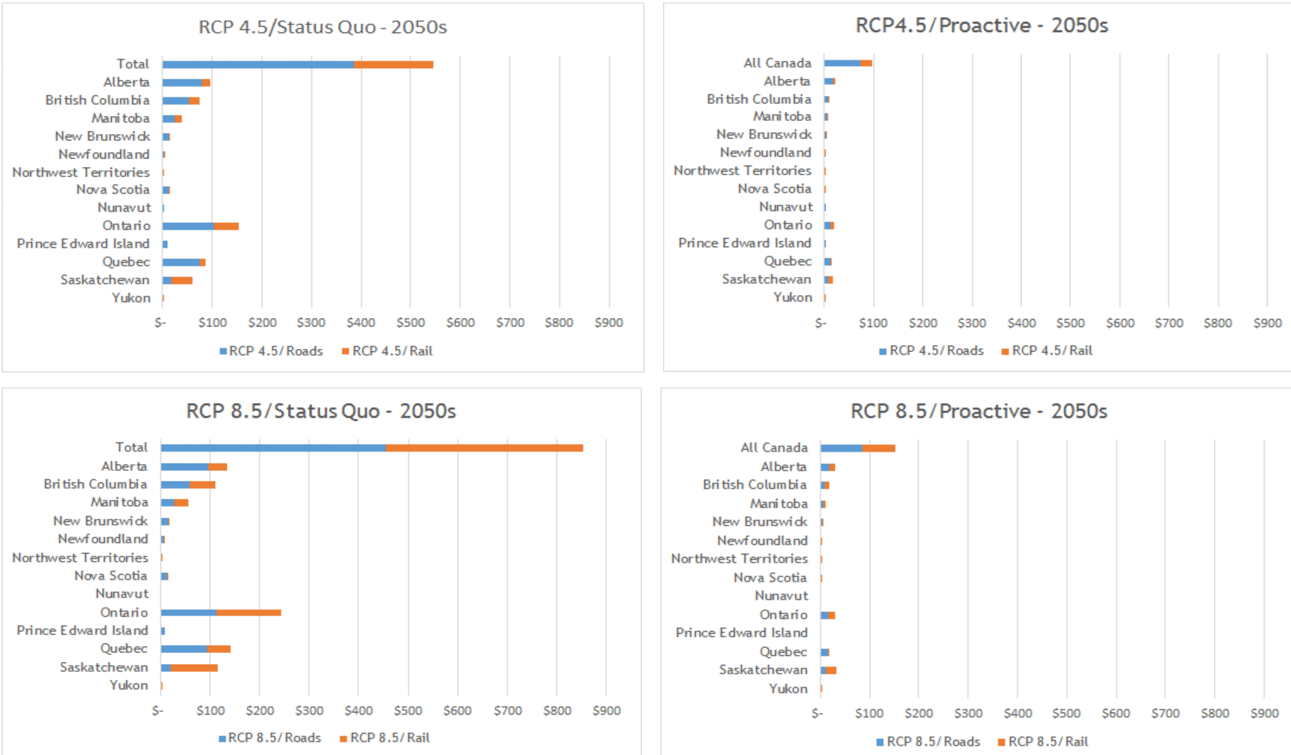
Province/Territory	Status Quo				Proactive			
	2040-2069		2070-2099		2040-2069		2070-2099	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Alberta	$96.4	$135.4	$146.7	$383.0	$22.1	$30.6	$12.0	$46.4
British Columbia	$75.1	$111.7	$102.0	$370.2	$10.5	$18.1	$9.7	$47.1
Manitoba	$37.9	$56.9	$51.1	$173.2	$7.3	$12.3	$7.1	$23.2
New Brunswick	$13.4	$18.9	$18.7	$52.5	$2.9	$4.4	$3.2	$5.3
Newfoundland and Labrador	$4.0	$6.9	$6.1	$20.0	$1.1	$1.6	$1.1	$2.3
Northwest Territories	$0.4	$0.8	$0.8	$2.8	$0.6	$0.9	$0.8	$1.5
Nova Scotia	$11.3	$13.5	$15.5	$33.9	$1.2	$2.3	$1.3	$2.3
Nunavut	$0.0	$0.0	$0.0	$0.1	$0.0	$0.1	$0.1	$0.1
Ontario	$152.8	$242.9	$217.0	$678.9	$19.2	$29.5	$19.8	$64.6
Prince Edward Island	$9.3	$8.7	$11.9	$17.2	$0.3	$0.3	$0.3	$0.4
Quebec	$85.3	$141.3	$131.1	$418.4	$14.4	$19.3	$14.7	$30.9
Saskatchewan	$59.4	$115.8	$66.7	$325.0	$18.2	$32.2	$15.3	$49.0
Yukon	$0.2	$0.6	$0.5	$2.6	$0.4	$0.8	$0.6	$1.6
TOTAL	**$545.4**	**$853.5**	**$768.1**	**$2,477.8**	**$98.2**	**$152.5**	**$86.0**	**$274.7**

To further illustrate delay costs by province/territory, Figure 3-43 shows the distribution between road- and rail-related delay costs for each province and territory by scenario and RCP for the 2040-2069 era. As indicated in the figure, the proportional split between road- and rail-related delay costs varies significantly by province/territory. For example, delay costs related to speed orders for the rail network account for most of the delay costs projected for Saskatchewan but a much smaller fraction of delay costs in Alberta. In addition, rail makes up a much larger fraction of delay costs in most provinces under RCP 8.5 than RCP 4.5.

The main takeaways from our analysis of delay costs are:

- Delay costs are significant relative to the sector-specific costs presented for roads and rail in previous sections. This is particularly true for rail, as delay costs are more than an order of magnitude higher than the rail-related adaptation costs presented earlier in this report. This suggests that strategies focused on reducing delay costs are an important element of cost-effective adaptation.
- Proactive adaptation can significantly reduce the extent to which climate change leads to delay costs, for both roads and rail.

FIGURE 3-43. DELAY COSTS COSTS BY PROVINCE AND SECTOR FOR THE FIRST ERA



Limitations and Caveats

The delay costs associated with climate change are complex and subject to multiple uncertainties. We therefore note the following limitations and caveats for our analysis:

- Although delay costs related to road and rail damage represent important indirect costs of climate change, other sectors may also experience indirect climate change costs. For example, focusing on the electric power sector, to the degree that climate change increases the frequency and/or duration of power outages, households and businesses will both experience losses. Inland flooding may also hamper business activity in affected areas, for short periods of time or for more extended periods in more extreme cases.
- Our assessment of delay costs related to roads is based upon the relationship between delay costs and adaptation costs for roads, as derived from a study focused on the U.S. To the extent that the relationships derived from this study are not representative of the relationship between road-related delay costs and adaptation costs in Canada, we may underestimate or overestimate delay costs associated with Canada's road network.

Having presented detailed methods and results for each of the categories individually in Chapter 3, this chapter summarizes the category results, then provides a set of recommendations for future work.

4.1 SUMMARY OF FINDINGS

Table 4-1 summarizes the costs of climate change by the eight infrastructure categories presented in this report, and delay costs resulting from road and rail impacts. Under the reactive strategy, inland flooding has the highest annual mid-range estimates of costs at between $5 billion and $8 billion per year, which is 15 to 135 percent larger than the next highest category, depending on RCP and era.[42] Road-related costs are next, then resulting delay cost effects in the 2080s, then impacts to the electrical grid, which collectively range between $600 million and $7 billion per year. The next tier includes impacts to coastal properties, driven by permafrost thaw, and to winter roads in the 2050s under RCP8.5 range between $120 million and $450 million. Effects on winter roads in the 2080s and 2050s under RCP4.5, and to rail are generally lower, ranging from $7 million to $60 million.

Adopting a proactive strategy generally has dramatic benefits, driving reactive costs down 76 to 98 percent for roads, rail, and delay costs; 45 to 77 percent for coastal properties; and 38 to 47 percent for the electrical grid. Cost reductions for permafrost thaw and inland flooding impacts are more modest. In the case of permafrost thaw, this is because of the challenge of adapting to this climate hazard – generally costs can be delayed but not avoided, which is why a proactive strategy increases costs in the 2050s and 2080s under RCP 8.5. For flooding, the proactive costs consider only a single adaptation response – abandoning or relocating the most vulnerable properties to flood-free areas –so these adaptation savings are best seen as a partial estimate.

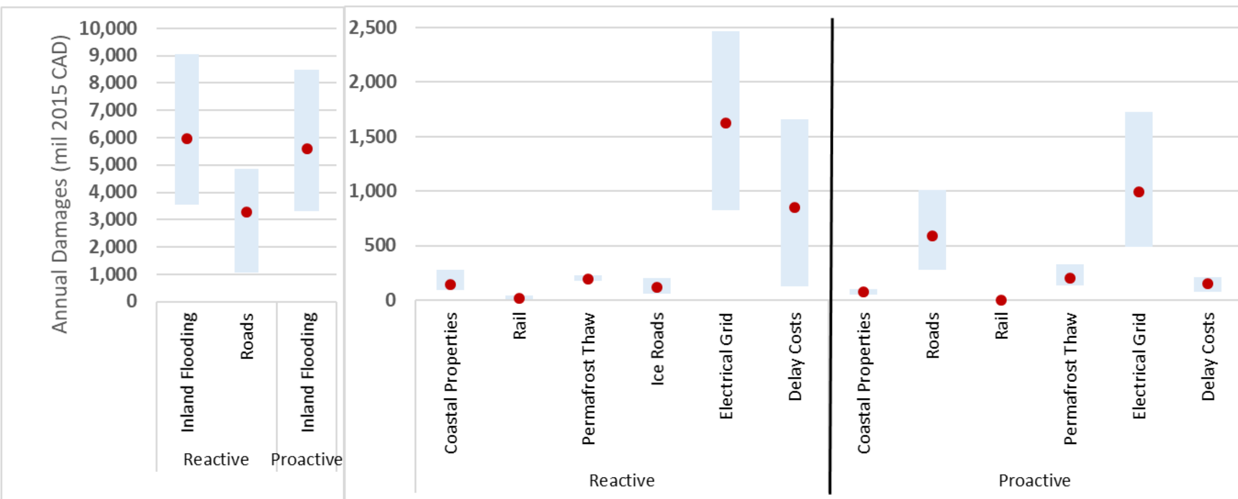
TABLE 4-1. SUMMARY OF ANNUAL NATIONAL COSTS AND ADAPTATION SAVINGS ($MIL 2015 CAD)

	Reactive				Proactive				Proactive Reduction in Costs			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Category	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s
Coastal Properties	$131	$240	$146	$453	$71	$90	$78	$104	-45%	-62%	-47%	-77%
Inland Flooding	$5,269	$5,011	$5,961	$8,289	$4,922	$4,684	$5,579	$7,751	-7%	-7%	-6%	-6%
Roads	$2,242	$3,117	$3,270	$7,229	$532	$295	$591	$118	-76%	-91%	-82%	-98%
Rail	$6.7	$6.7	$18	$61	$1.2	$1.3	$1.2	$1.3	-83%	-81%	-93%	-98%
Permafrost Thaw	$193	$206	$196	$172	$152	$174	$200	$211	-22%	-16%	2%	23%
Winter roads	$38	$29	$117	$51	-	-	-	-	-	-	-	-
Electrical Grid	$1,223	$582	$1,621	$1,467	$663	$307	$997	$790	-46%	-47%	-38%	-46%
Delay Costs	$545	$768	$853	$2,478	$98	$86	$152	$275	-82%	-89%	-82%	-89%

[42] Note that mid-range estimates are an average across GCMs. The range of GCM specific results for each impact category is reported in the relevant sector chapters of this report.

Figure 4-1 presents the variability in total costs across GCMs under the RCP 8.5 scenario, in the 2050s. The reactive costs are split onto two vertical axes to accommodate the large difference in costs between the flooding and reactive roads impacts, and all remaining categories of reactive and proactive costs. Generally, costs vary much more significantly across GCMs for the flooding, roads, the electrical grid, and delay cost categories than the others. This is because impacts in these four categories are driven partly by precipitation projections, which vary much more across GCMs than temperature projections.

FIGURE 4-1. VARIATION IN AVERAGE ANNUAL COSTS ACROSS GCMS, RCP 8.5 SCENARIO, 2050s ($MIL 2015 CAD)



Note: The red dot for each category is the average across GCMs; the blue box surrounding the dot shows the range.

The distribution of these costs over Provinces and Territories varies considerably across the infrastructure damage categories. Table 4-2 provides an example of this distribution for RCP 8.5 in the 2080s, where the size of bars within the cells reflects the magnitude of values wthin a given infrastructure category rather than across all categories. Some categories, such as roads, rail, the electrical grid, and delay costs, tend to scale roughly based on population (i.e., Ontario has the highest impacts, and British Columbia, Quebec, and Alberta tend to have large effects). Although there are notable exceptions, such as the low flooding impacts in Quebec and the high rail impacts in Saskatchewan. Other impacts are also driven based on geography, such as coastal property, permafrost, and winter road effects.

In particular, the combined impacts of permafrost thaw and winter road effects are pronounced for the three Territories (about $170 million per year), considering their combined population is roughly 100 times lower than that of Ontario (i.e., 120,000 versus 14.5 million).

TABLE 4-2. AVERAGE ANNUAL COSTS BY PROVINCE/TERRITORY AND INFRASTRUCTURE DAMAGE CATEGORY, RCP 8.5 SCENARIO, 2080s, REACTIVE ADAPTATION ($MIL 2015 CAD)

Province/Territory	Coastal Properties	Inland Flooding	Roads	Rail	Permafrost Thaw	Ice Roads	Electrical Grid	Delay Costs
Alberta	-	$968	$1,580	$8.5	$0.1	$3	$169	$383
British Columbia	$276	$1,209	$916	$7.0	$1.5	$0	$120	$370
Manitoba	-	$592	$582	$5.6	$6.4	$17	$90	$173
New Brunswick	$63	$156	$256	$0.8	$0.0	$0	$56	$53
Newfoundland and Labrador	-	$135	$66	$0.3	$0.0	$0	$27	$20
Northwest Territories	-	$5	$21	$0.1	$54	$12	$5.2	$2.8
Nova Scotia	$59	$209	$155	$0.0	$0.0	$0.0	$42	$34
Nunavut	-	$1.3	$1.4	$0.0	$54	$0.1	$5.2	$0.1
Ontario	-	$4,111	$1,510	$15	$0.3	$16	$446	$679
Prince Edward Island	$16	$7	$104	$0.0	$0.0	$0.0	$21	$17
Quebec	$39	$780	$1,574	$10	$2.1	$0.0	$408	$418
Saskatchewan	-	$103	$447	$13	$0.2	$3.6	$74	$325
Yukon	-	$12	$18	$0	$54	$0.0	$5.2	$2.6
TOTAL	**$453**	**$8,289**	**$7,229**	**$61**	**$172**	**$51**	**$1,467**	**$2,478**

Note: the size of bars within cells reflect the magnitude of values within a single infrastructure impact category (i.e., table column), rather than across all categories.

4.2 RECOMMENDATIONS FOR FUTURE WORK

This study provides a partial estimate of the potential economic impacts of climate change to Canada and the possible benefits of adaptation. Areas of ongoing research, modeling, and data collection will open avenues to consider a wider range of damages, for example: urban-scale flooding owing to local failure of urban drainage systems to handle higher short-term hydrologic loads, including those from hurricane events; impacts on coastal ports and downstream effects on supply chains; fiscal impacts of climate change linked to infrastructure impacts – such as loss of property tax base and business activity in vulnerable coastal areas, or the impacts on productivity from the impact of transportation system delays on supply chains. Below, we provide several recommendations for future work in the specific categories we analyze in this study.

- **A more comprehensive update to a National coastal risk analysis**, incorporating sea-level rise and storm surge threats, could be useful in guiding GHG mitigation, adaptation, and economic development policy.[43]

[43] In particular, the Stanton et al. (2010) work that currently informs Canadian received knowledge on coastal risks in Canada should be updated with more contemporary assessment of the risk of storm surge, made possible by significant enhancements to the understanding of baseline risks (from JBA) and future coastal storm and surge risk modeling. While such a study was not possible as part of the current report, the current report does provide a basis

- **Potentially important omissions in the sectoral scope of the coastal sector analysis** that may be worth considering for enhancement in future work include intensification of wind damage from coastal storms; accelerated loss of coastal wetlands and other natural areas that provide ecosystem service flows such as flood protection and commercial fish nursery grounds; effects of sea-level rise on the extent of high-tide flooding and other high frequency/low consequence coastal events; and the potential for disproportionate impacts of coastal vulnerability and adaptation decision on socially vulnerable populations.[44]
- **Disproportionate impacts of inland and coastal flooding on small and disadvantaged communities** that rely critically on access to coastal or riverine resources, particularly in Northern Canada, should be assessed with specialized methods that consider both the unique nature of the climate stressors (e.g., loss of winter ice pack in the Arctic Ocean and Hudson's Bay) and the relatively larger economic reliance on these resources among these communities.
- **Refining hydrologic and hydraulic modeling.** There appears to be continued effort across Canada, mostly at the urban scale, to further refine the hydrologic and hydraulic modeling basis to assess impacts of inland flooding. We recommend use of the national-scale analyses presented here, which by necessity rely on more simplified hydrologic and hydraulic modeling methods, to guide geographic priorities for refining hydrologic, hydraulic, and infrastructure impact modeling under future climatic conditions.
- **More comprehensive consideration of benefits of climate change in the roads and rail analysis** will be important to develop a more complete view of impacts to those sectors. Currently, we exclude the benefits to rail of fewer extreme cold temperature breaks, and the benefits to asphalt maintenance of higher minimum temperatures.
- **A process-based permafrost modeling approach**, similar to the Melvin et al. (2017) study of Alaska's infrastructure, would allow for a much more refined analysis of permafrost impacts. Although no such model is currently available for Canada, the Permafrost Partnership Network for Canada is currently developing projected permafrost conditions under a range of climate models that could be leveraged once available.
- **Considering the costs of electric power outages** from more frequent damaging weather events such as ice storms, lightning strikes, and wildfires. Although data and modeling needed to conduct such research in Canada is currently limited, a starting point could be adapting the Interruption Cost Estimate (ICE) Calculator from Lawrence Berkeley National Labs (LBNL) to

for prioritizing the geographic scope of future work. We suggest that an updated model be developed and tested for one or more of the potentially more economically vulnerable coastal locations in Canada (e.g., Vancouver, Quebec City), including surrounding areas which might be less likely to exhibit the dense urban development that provides the most cost-effective justifications for adaptation investments, to explore the margins of economically well-justified coastal adaptation.

[44] Adaptation decision in particular may be heavily influenced by economic efficiency and access to capital criteria, leaving a strong potential to exacerbate existing social inequities. All of these areas are the subject of active research at the local scale and/or in other countries, potentially providing an analytic model for enhancements to the national-scale work completed here, and each of these touch on solutions that might involve infrastructure investments, including increasingly well-studies investments in nature-based coastal protections.

the Canada context. This research will be particularly important as electrification initiatives for transport and home heating advance.

- **More detailed analysis of hydropower impacts** that allows for analysis of firm power effects. Boehlert et al. (2016) found that although annual hydropower generation rises in the U.S. under climate change, firm power declines. Most importantly, this assessment will require a more detailed hydrological dataset so that rainfall runoff models can be properly calibrated to low flows.

REFERENCES

Abeysirigunawardena, Dilumie S., Dan J. Smith and Bill Taylor. 2011. Extreme Sea Surge Responses to Climate Variability in Coastal British Columbia, Canada. *Annals of the Association of American Geographers*, September, Vol. 101, No. 5, pp. 992-1010

Al-Omari, Bashar & Darter, Michael. 1994. Relationships between international roughness index and present serviceability rating. Transportation Research Record Journal of the Transportation Research Board. 130-136.

Arnell, N. W., S. Brown, S. N. Gosling, J. Hinkel, C. Osborn, R. J. Nicholls, and P. Zelazowski. 2016. Global-scale climate impact functions: the relationship between climate forcing and impact. Climatic Change 134:475–87.

Bank of Canada. 2020. Annual Exchange Rates. Available at https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/.

Berkshire Regional Planning Commission. 2001. The Massachusetts Unpaved Roads BMB Manual: A Guidebook on How to Improve Water Quality While Addressing Common Problems, prepared for Massachusetts Department of Environmental Protection and U.S. Environmental Protection Agency. Available at https://megamanual.geosyntec.com/npsmanual/Unpaved%20Road.pdf.

Boehlert, B., K. Strzepek, Y. Gebretsadik, R. Swanson, A. McCluskey, J. Neumann, J. McFarland, and J. Martinich. 2016. Climate change impacts and greenhouse gas mitigation effects on US hydropower generation. *Applied Energy.* doi: 10.1016/j.apenergy.2016.09.054.

Bresson, E., R. Laprise, D. Paquin, J. Theriault, and R. de Elia. 2017. Evaluating the Ability of CRCM5 to Simulate Mixed Precipitation. *Atmosphere-Ocean.* doi: 10.1080/07055900.2017.1310084.

Burn, Donald H., Paul H. Whitfield. 2015. Changes in floods and flood regimes in Canada. Canadian Water Resources Journal. https://doi.org/10.1080/07011784.2015.1026844

CDA (Canadian Dams Association). 2019. Dams in Canada. Accessed from https://www.cda.ca/En/Dams_in_Canada/EN/Dams_In_Canada.aspx?hkey=11c76c52-7794-4ddf-b541-584f9ea2dbe9.

Cheng, C., G. Li, and H. Auld. 2011. Possible impacts of climate change on freezing rain using downscaled future climate scenarios: Updated for eastern Canada. *Atmos.–Ocean*, 49, 8–21.

Cheng, C., E. Lopes, C. Fu, and Z. Huang. 2014. Possible Impacts of Climate Change on Wind Gusts under Downscaled Future Climate Conditions: Updated for Canada. *Journal of Climate.* doi: 10.1175/JCLI-D-13-00020.1.

Chinowsky, P. and C. Arndt. 2012. "Climate change and roads: a dynamic stressor-response model". *Rev. Dev. Econ.* 16(3):448–462.

Chinowsky, P., Helman, J., Gulati, S., Neumann, J., & Martinich, J. 2019. Impacts of climate change on operation of the U.S. rail network. *Transport Policy*, 75, 183–191.

Chinowsky, P.S., J.C. Price, and J.E. Neumann. 2013. Assessment of climate change adaptation costs for the U.S. road network. *Global Environmental Change*. 23(4):764-773. doi: http://dx.doi.org/10.1016/j.gloenvcha.2013.03.004.

Cunderlik, Juraj M., Taha B.M.J. Ouarda. 2009. Trends in the timing and magnitude of floods in Canada. Journal of Hydrology https://doi.org/10.1016/j.jhydrol.2009.06.050

Darrow, M.M., 2011. Thermal modeling of roadway embankments over permafrost. *Cold Regions Science and Technology* 65: 474–487. DOI: 10.1016/j.coldregions.2010.11.001

Dave, E. V., Helmer, B., Hanson, C., Munch, J., & Johanneck, L. 2016. Implementation of laboratory testing to predict low temperature cracking performance of asphalt pavements. In *8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials* (pp. 993-1003). Springer, Dordrecht.

Ehmele, Florian, and Michael Kunz. 2018. Flood-related extreme precipitation in southwestern Germany: development of a two-dimensional stochastic precipitation model. Hydrol. Earth Syst. Sci., 23, 1083–1102, 2019. https://doi.org/10.5194/hess-23-1083-2019

Emanuel, K.A. 2013. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences* 110:12219–12224. Available: https://doi.org/10.1073/pnas.1301293110.

Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich. 2020. Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*.

FAO (U.N. Food and Agriculture Organization). 2019 Country Fact Sheet: Canada. Accessed from https://storage.googleapis.com/fao-aquastat.appspot.com/countries_regions/factsheets/summary_statistics/en/CAN-CF.pdf.

Fussel, H. M., F. L. Toth, J. G. van Minnen, and F. Kaspar. 2003. Climate impact response functions as impact tools in the tolerable windows approach. Climatic Change 56:91–117.

Gaur, Ayushi, Abhishek Gaur, and Slobodan P. Simonovic. 2018. Future Changes in Flood Hazards across Canada under a Changing Climate. Water, 10, 1441; doi:10.3390/w10101441

Gordian. 2017. *Heavy Construction Costs with RSMeans Data 2017.*

Government of Canada. 2020. Transport Networks in Canada - CanVec Series - Transport Features. Accessed from https://open.canada.ca/data/en/dataset/2dac78ba-8543-48a6-8f07-faeef56f9895.

Guay, C., M. Minville, and M. Braun. 2015. A global portrait of hydrological changes at the 2050 horizon for the province of Quebec. *Canadian Water Resources Journal*. doi: 10.1080/07011784.2015.1043583.w

Guy Carpenter. 2015. Guy Carpenter launches new G-CAT® Canada flood model. http://www.gccapitalideas.com/2015/04/16/guy-carpenter-launches-new-g-cat%C2%AE-canada-flood-model/. Accessed 12 Oct 2017.

Gruber, S. 2012: Derivation and analysis of a high-resolution estimate of global permafrost zonation, The Cryosphere, 6, 221-233. doi:10.5194/tc-6-221-2012.

Hamududu, B., & Killingtveit, A. 2012. Assessing climate change impacts on global hydropower. *Energies*, 5(2), 305–322.

Heginbottom, J.A., Dubreuil, M.-A., Harker, P., 1995. Permafrost - Canada (National Atlas of Canada MCR 4177, scale 1:7,500,000). Energy, Mines, and Resources Canada.

Hjort, J., O. Karjalainen, J. Aalto, S. Westermann, V. Romanovsky, F. Nelson, B. Etzelmuller, and M. Luoto. 2018. Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications.* doi: 10.1038/s41467-018-07557-4.

IBC [Insurance Bureau of Canada]. 2015. The Economic Impacts of the Weather Effects of Climate Change on Communities. http://assets.ibc.ca/Documents/Studies/IBC-The-Economic-Impacts.pdf

Industrial Economics. 2010. Costing Climate Impacts and Adaptation: A Canadian Study on Public Infrastructure. Report prepared by IEc for National Round Table on the Environment and the Economy (NRTEE). 15 July 2010.

IPCC. 2013. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate change. Cambridge University Press, Cambridge, 1535 pp

JBA Risk Management, 2018, JBA Canada 30m Flood Data Executive Briefing. Available at: https://www.jbarisk.com/media/1532/canada-30m-flood-data-executive-briefing.pdf

Kish, Andrew and Gopal Samavedam. 2013. Track Buckling Prevention: Theory, Safety Concepts, and Applications. Rep. no. DOT/FRA/ORD-13/16, Federal Railroad Administration.

Klima, K. & Morgan, M.G. 2015. Ice Storm Frequencies in a Warmer Climate. Climatic Change. 2015. 133: 209. https://doi.org/10.1007/s10584-015-1460-9

Kulp, Scott A., Benjamin H. Strauss, CoastalDEM: A global coastal digital elevation model improved from SRTM using a neural network. Remote Sensing of Environment, Volume 206, 1 March 2018, Pages 231-239. https://doi.org/10.1016/j.rse.2017.12.026

Larsen, P. 2016. A Method to Estimate the Costs and Benefits of Undergrounding Electricity Transmission and Distribution Lines. Energy Economics, 60, 47-61.

Larsen, P.H., Boehlert, B., Eto, J., Hamachi-LaCommare, K., Martinich, J. and Rennels, L. 2018. Projecting future costs to U.S. electric utility customers from power interruptions. Energy, 147, pp.1256-1277.

Leopold, L. B. and Maddock, T. J., 1953, Hydraulic geometry of stream channels and some physiographic implications. U. S. Geological Survey Professional Paper 252, 55 p.

Lewkowicz, A.G. 2020. A possible method to model future impacts of permafrost thaw on highways in northern Canada. Unpublished report to Canadian Climate Institute. April 13 2020.

Melvin, A., P. Larsen, B. Boehlert, J. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M. Baumann, L. Rennels, A. Bothner, D. Nicolsky, and S. Marchenko. 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*. 114(2): E122-131. doi: 1611056113.

Neumann, J.E., Price, J., Chinowsky, P. et al. 2015. Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. Climatic Change 131, 97–109. https://doi.org/10.1007/s10584-013-1037-4.

Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich. 2019. Climate effects on U.S. infrastructure: the economics of adaptation for rail, roads, and coastal development, manuscript submitted for review.

Neumann, J.E., J. Willwerth, J. Martinich, J. McFarland, M.C. Sarofim, G. Yohe. 2020. Climate damage functions for estimating the economic impacts of climate change in the United States. *Review of Environmental Economics and Policy*. Available: https://doi.org/10.1093/reep/rez021

Nordhaus, W., and J. Boyer. 2000. Warming the world: economic models of global warming. Cambridge, MA: MIT Press.

NRC (Natural Resources Canada). 2019. The Atlas of Canada. Accessed on Feb 20, 2020 from https://www.nrcan.gc.ca/maps-tools-and-publications/maps/atlas-canada/10784.

NRC (Natural Resources Canada). 2020. Accessed from https://www.nrcan.gc.ca/maps-tools-publications/tools/geodetic-reference-systems/water/16888

O'Neill, H B; Wolfe, S A; Duchesne, C. 2020. Ground ice map of Canada. Geological Survey of Canada, Open File 8713, (version 1). https://doi.org/10.4095/326885 (Open Access).

Obu, Jaroslav; Westermann, Sebastian; Kääb, Andreas; Bartsch, Annett. 2018. Ground Temperature Map, 2000-2016, Northern Hemisphere Permafrost. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.888600

Oswell, J. and J. Nixon. 2015. Thermal Design Considerations for Raised Structures on Permafrost. Journal of Cold Regions Engineering. DOI: 10.1061/(ASCE)CR.1943-5495.0000075.

PBO (Parliamentary Budget Officer), Canada. 2016. Estimate of the Average Annual Cost for Disaster Financial Assistance Arrangements due to Weather Events

Public Safety Canada (2015) "Floods." December 16. Retrieved from https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/ntrl-hzrds/fld-eng.aspx

Roy, Robert Leconte, Francois P. Brissette, and Claude Marche. 2001. The impact of climate change on seasonal floods of a southern Quebec River Basin. Hydrol. Process. 15, 3167–3179 (2001) DOI: 10.1002/hyp.323

S&P Global. 2018. S&P Global Platts Electric Power Services. [online] Available at: https://www.spglobal.com/platts/en/products-services/electric-power [Accessed 15 May 2018].

Shu, J., Qu, J. J., Motha, R., Xu, J. C., & Dong, D. F. 2018. Impacts of climate change on hydropower development and sustainability: A review. IOP Conference Series: Earth and Environmental Science, 163(1).

Smith, M. and D. Riseborough. 2002. Climate and the Limits of Permafrost: A Zonal Analysis. Permafrost and Periglacial Processes. DOI: 10.1002/ppp.410

Sweet, William, Greg Dusek, Jayantha Obeysekera, John J. Marra. 2018. Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086

Singh, Vijay P. 2003. On the Theories of Hydrologic Geometry. International Journal of Sediment Research, Vol. 18, No. 3, 2003, pp. 196-21

Stanton, E. A., Davis, M., & Fencl, A. 2010. Costing climate impacts and adaptation. A Canadian Study on Coastal Zones. A report commissioned for the National Round Table on the Environment and the Economy, Stockholm Environmental Institute.Statistics Canada. (2019). Population Projections for Canada (2018 to 2068), Provinces and Territories (2018 to 2043). Available: https://www150.statcan.gc.ca/n1/pub/91-520-x/91-520-x2019001-eng.htm

Statistics Canada. 2020. Electric power generation, monthly generation by type of electricity. Accessed from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510001501.

Thistlethwaite, J., Henstra, D., Brown, C. et al. How Flood Experience and Risk Perception Influences Protective Actions and Behaviours among Canadian Homeowners. Environmental Management 61, 197–208 (2018). https://doi.org/10.1007/s00267-017-0969-2

Treasury Board of Canada Secretariat. (undated). Safety guide for operations over ice. Retrieved on August 19, 2020, from https://www.collectionscanada.gc.ca/eppp-archive/100/201/301/tbs-sct/tb_manual-ef/Pubs_pol/hrpubs/TBM_119/CHAP5_3_e.html.

U.S. Department of Transportation, Federal Highway Administration, 2006. Longterm Pavement Performance (LTPP) Data Analysis Support: National Pooled Fund Study TPF-5(013) – Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost, Publication No. FHWA-HRT-06-121, November 2006.

U.S. Department of Transportation, Federal Highway Administration, 2015. Gravel Roads Construction & Maintenance Guide. Available at https://www.fhwa.dot.gov/construction/pubs/ots15002.pdf.

U.S. Environmental Protection Agency. 2017. Multi-model framework for quantitative sectoral impacts analysis: a technical report for the Fourth National Climate Assessment. EPA 430-R-17-001. Washington, DC: U.S. Environmental Protection Agency.

U.S. Bureau of Labor Statistics. 2020. Consumer Price Index (CPI) Database. Available at https://data.bls.gov/cgi-bin/surveymost.

Wang, Ting & Harvey, John & Lea, Jeremy & Kim, Changmo. 2014. Impact of Pavement Roughness on Vehicle Free-Flow Speed. Journal of Transportation Engineering. 140. 1-11. 10.1061/(ASCE)TE.1943-5436.0000689.

Wiberg, D. and K. Strzepek. 2005. Development of Regional Economic Supply Curves for Surface Water Resources and Climate Change Assessments: A Case Study of China. The International Institute for Applied Systems Analysis. Paper RR-05-001.

Wilks, Daniel (1993) Comparison of three-parameter probability distributions for representing annual extreme and partial duration precipitation series. Water Resources Research, Vol. 29, Issue10, Pages 3543-3549. https://doi.org/10.1029/93WR01710

Withey, Patrick, Van Lantz, Thomas Ochuodho. 2015. Economic Costs and Impacts of Climate-induced Sea-Level Rise and Storm Surge in Canadian Coastal Provinces: A CGE Approach. Applied Economics Vol. 48, No. 1, 59–71. DOI: 10.1080/00036846.2015.1073843

Wotling, G., Ch. Bouvier, J. Danloux, J.-M. Fritsch (2000) Regionalization of extreme precipitation distribution using the principal components of the topographical environment, Journal of Hydrology, Vol 233, Issues 1–4, 12 June 2000, Pages 86-101. https://doi.org/10.1016/S0022-1694(00)00232-8

WWF (World Wildlife Federation). 2020. HydroAtlas. Accessed at https://www.hydrosheds.org/page/hydroatlas.

Zhai, Li, Blair J.W. Greenan, John Hunter, Thomas S. James, Guoqi Han, Phillip MacAulay, and Joseph A. Henton (2015) Estimating Sea-Level Allowances for Atlantic Canada using the Fifth Assessment Report of the IPCC. Atmosphere-Ocean, 53 (5) 2015, 476–49http://dx.doi.org/10.1080/07055900.2015.1106401Allen, P. M., Arnold, J. G. and Byars, B. W., 1994, Downstream channel geometry for use of in planning-level models. Water Resources Bulletin, Vol. 30, No. 4, pp. 663-671.

Zhang, Merrina, Aliereza Roghani, and Christian Barker. 2018. Track research: longitudinal rail stress management gap analysis research report (phase 1), National Research Council Canada. https://doi.org/10.4224/23004461.

APPENDIX A | CCI NOTE ON CLIMATE SCENARIO SELECTION

Introduction

Climate change impact analyses in Canada frequently uses ensembles of 24 statistically downscaled general circulation models (GCMs) to determine the possible worlds under various emissions pathways. While the 24 model ensemble is useful in capturing average annual changes and general trends, ensembles cannot be used to analyze variability and changes at a daily temporal scale. Further, the use of ensemble distribution slices to capture a range of model outputs can produce incongruent physical realities across the country.

The Canadian Climate Institute is developing an analysis of climate change impacts and associated costs to Canada. The Cost of Climate Change project will require daily precipitation and temperature projections at a national scale in order to model impacts to various infrastructure systems. While the analysis seeks to capture the range of possibilities represented by various GCMs, time constrains limit the ability to run an analysis for each of the 24 statistically downscaled GCMs commonly used in Canada. Herein, the Institute has conducted an analysis to determine if a sample of GCMs can be used to capture the range of model outcomes that is represented in the 24 model ensemble.

Methods

Following the United States Environmental Protection Agency's (EPA) approach to model selection for the Climate Impact and Risk Analysis, the Institute has examined the average annual temperature and average annual precipitation changes projected by 24 GCMs in Canada. Sensitivity analysis was conducted to examine intranational variation as well as model output characteristics at a daily scale.

Average annual precipitation and average annual temperature data was obtained for 24 statistically downscaled GCMs for periods 1971-2000, 2041-2070, and 2071-2100 and for representative concentration pathways (RCPs) 4.5 and 8.5. Additionally, indices for annual days with precipitation >10mm and for 3 consecutive days with temperature >25c was obtained for the RCP 8.5 end of century scenario. Data was obtained from the Canadian Centre for Climate Services.

National analysis was conducted by calculating the delta average annual temperature and delta percent average annual precipitation for each GCM, scenario, and era. Data was plotted on a scatterplot with a y axis of percent precipitation change and x axis of degrees of temperature change (figure 1). Using the EPA Locating and selecting scenarios online (LASSO) technique, a polygon was mathematically drawn around the parameter of the scatterplot, selecting the models that represented the margins of all temperature X precipitation outcomes.

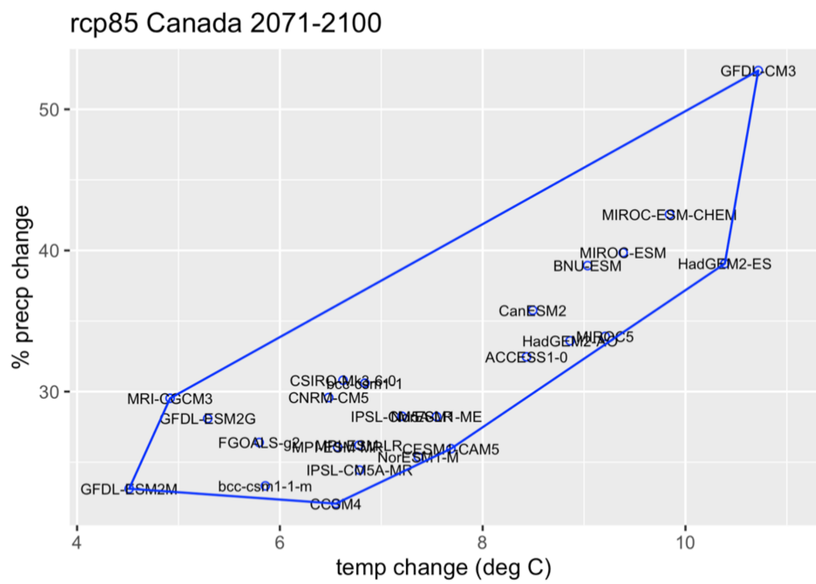


Figure 1

Following the national analysis, an GCM outputs for each province and territory were examined in order to determine the spatial differences of model outcomes. This process ensured that models used for the Cost of Climate Change project would also reflect the range of possible outcomes at a regional scale. For the regional analysis, boundaries of each jurisdiction were used to cut the baseline and future GCM outputs prior to determining the delta. Gridded cells were only included that were fully within the jurisdictional boundaries. Results were then analyzed using the LASSO process (figure 2).

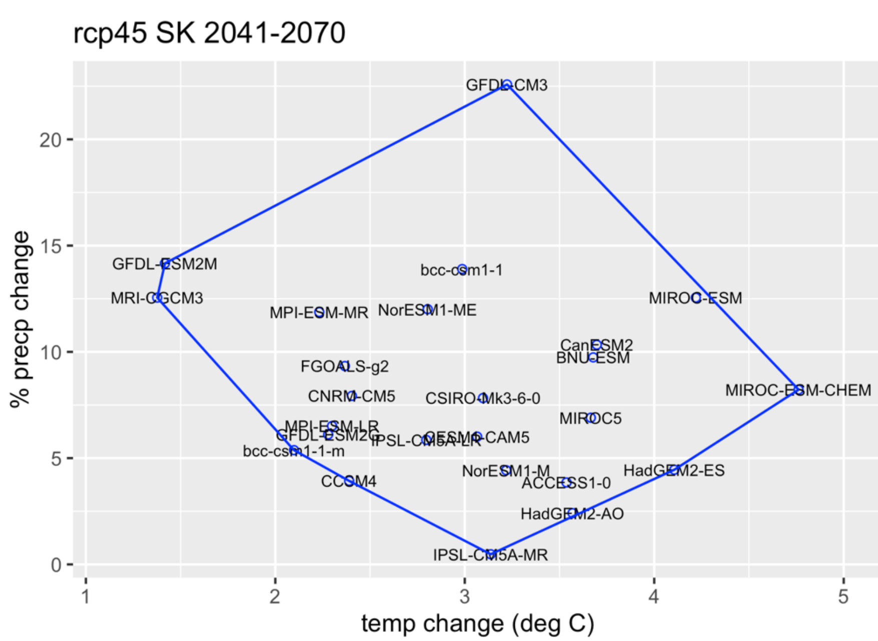


Figure 2

Since the Cost of Climate Change project will be using daily level precipitation and temperature data, it was important that daily variability was analyzed and captured by the selected models. Herein, indices of extreme precipitation and extreme temperature were used to determine the range of projected outcomes. This analysis was only conduced at a national level for RCP 8.5 and for the end of century timeframe. The scatterplot and LASSO technique was similarly used to analyze results (Figure 3).

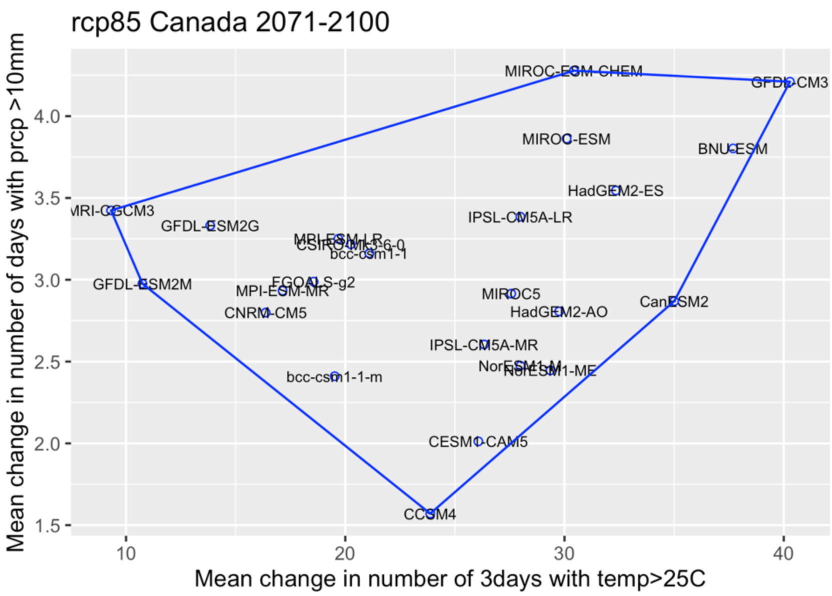


Figure 3

Results

The parameter GCMs for each analysis were compared across temporal (eras of 2041-2070, 2071-2100) and spatial (national and province and territory) scales. We tabulated the number of times each model was selected in the analysis (Table 1). This led to the selection of 7 models that can be effectively used to represent the range of model projections for Canada. These models align with the analysis of interannual variability. We examined each scatter plot then to confirm that even for the scenario or era where a peripheral model was not selected, there was an adequate representation of high temperature and low precipitation, high temperature and high precipitation, low temperature and high precipitation, and low temperature and low precipitation outcomes.

Table 1

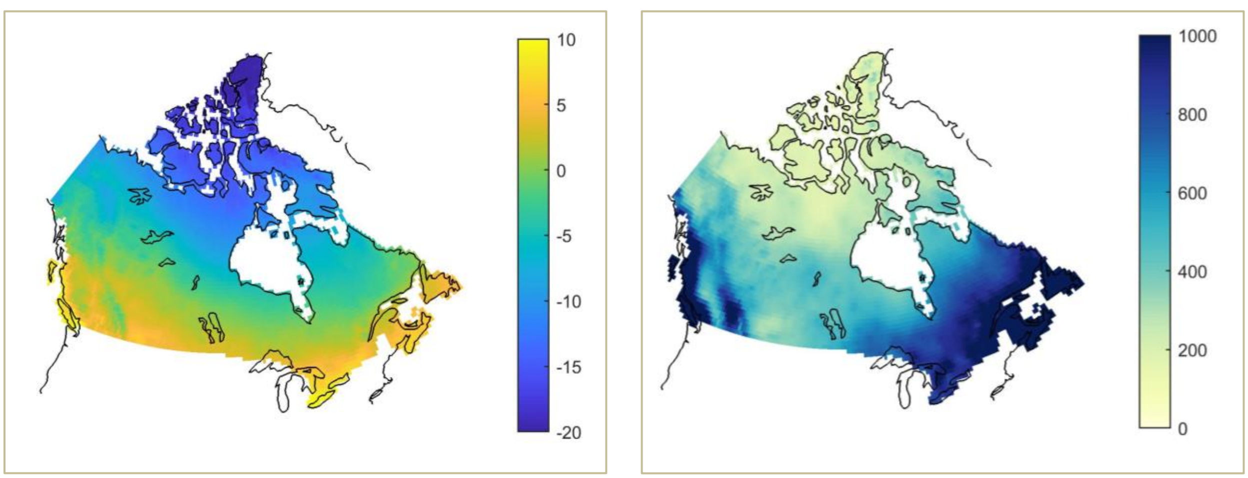
	Canada Analysis							PT 4.5 Analysis			PT 8.5 Analaysis		
	RCP 8.5 Mid	RCP8.5 End	RCP4.5 Mid	RCP4.5 End	Count 4.5	Count 8.5	**Total Count**	**Total Count**	Mid Century Count	End Century Count	**Total Count**	Mid Century Count	End Century Count
ACCESS1-0	0	0	1	0	1	0	**1**	**2**	1	1	**3**	2	1
bcc-csm1-1	0	0	0	0	0	0	**0**	**0**	0	0	**0**	0	0
bcc-csm1-1-m	0	1	1	0	1	1	**2**	**6**	4	2	**5**	4	1
NorESM1-M	0	1	1	0	1	1	**2**	**2**	1	1	**4**	2	2
NorESM1-ME	0	0	0	0	0	0	**0**	**2**	1	1	**1**	1	0
MRI-CGCM3	1	1	1	1	2	2	**4**	**16**	11	5	**20**	10	10
MPI-ESM-MR	0	0	0	0	0	0	**0**	**1**	1	0	**1**	0	1
MPI-ESM-LR	0	0	0	0	0	0	**0**	**2**	2	0	**0**	0	0
MIROC5	0	1	0	0	0	1	**1**	**1**	0	1	**4**	2	2
MIROC-ESM	0	1	0	0	0	1	**1**	**5**	2	3	**3**	3	0
MIROC-ESM-CHEM	0	0	0	0	0	0	**0**	**7**	4	3	**15**	7	8
IPSL-CM5A-MR	0	1	0	0	0	1	**1**	**5**	4	1	**2**	1	1
IPSL-CM5A-LR	0	0	0	0	0	0	**0**	**3**	1	2	**3**	2	1
HadGEM2-ES	1	1	1	0	1	2	**3**	**11**	3	8	**17**	4	13
HadGEM2-AO	0	1	0	1	1	1	**2**	**15**	7	8	**13**	7	6
GFDL-ESM2M	1	1	0	1	1	2	**3**	**22**	10	12	**22**	9	13
GFDL-ESM2G	0	0	0	0	0	0	**0**	**5**	1	4	**4**	4	0
GFDL-CM3	1	1	1	1	2	2	**4**	**19**	10	9	**19**	10	9
FGOALS-g2	0	0	0	0	0	0	**0**	**4**	2	2	**4**	3	1
CanESM2	0	0	0	0	0	0	**0**	**0**	0	0	**0**	0	0
CSIRO-Mk3-6-0	0	0	0	1	1	0	**1**	**11**	5	6	**6**	3	3
CNRM-CM5	0	0	0	0	0	0	**0**	**5**	4	1	**2**	1	1
CESM1-CAM5	1	0	1	1	2	1	**3**	**8**	3	5	**5**	0	5
CCSM4	1	0	0	1	1	1	**2**	**8**	4	4	**13**	7	6
BNU-ESM	0	0	0	0	0	0	**0**	**7**	3	4	**7**	4	3

APPENDIX B | CLIMATE CHANGE PROJECTIONS

The baseline training climate dataset used in this project is a gridded observational dataset produced by Natural Resources Canada (NRCan), available at 300 arc second spatial resolution (1/12° grids, ~10 km) over Canada. The bulk of the daily minimum and maximum temperature, and precipitation amounts were produced by Hopkinson et al. (2011) and McKenney et al. (2011) on behalf of the Canadian Forest Service (CFS), NRCan. Gridding was accomplished with the Australian National University Spline (ANUSPLIN) implementation of the trivariate thin plate splines interpolation method (Hutchinson et al., 2009) with latitude, longitude and elevation as predictors. Precipitation occurrence and square-root transformed precipitation amounts were interpolated separately on each day, combined, and transformed back to original units. Quality-controlled, but unadjusted, station data from the National Climate Data Archive (NCDA) of Environment and Climate Change Canada data (Hutchinson et al., 2009) were interpolated onto the high-resolution grid using thin plate splines. Station density varies over time with changes in station availability, peaking in the 1970s with a general decrease towards the present day (Hutchinson et al., 2009). Thus, the number of stations active across Canada between 1950 and 2011 ranged from 2000 to 3000 for precipitation and 1500 to 3000 for air temperature (Hopkinson et al., 2011).

Figure B-1 shows average annual mean temperature and precipitation for the 1986-2005 period, which is the utilized baseline era for this project.

FIGURE B-1. BASELINE AVERAGE ANNUAL MEAN TEMPERATURE (°C; LEFT) AND ANNUAL PRECIPITATION (MM; RIGHT)



B.1 PROJECTIONS

The statistically downscaled climate scenarios used in this work were obtained from the Pacific Climate Impacts Consortium (PCIC) (Pacific Climate Impacts Consortium, 2019), which used the training data described in the previous section to produce daily climate scenarios at the 300 arc second spatial resolution (1/12° grids, ~10 km) over Canada for minimum temperature, maximum temperature, and precipitation. For more details on the statistical downscaling process, referred to as the bias correction/constructed analogues with quantile mapping reordering (BCCAQV2) method, see the PCIC resource here: https://pacificclimate.org/data/statistically-downscaled-climate-scenarios.

The dataset provides 27 global circulation models (GCMs) for 3 Representative Concentration Pathways (RCPs). Of these, this project used 7 GCMs and 2 RCPs, as listed below in Table B-1. The selection process was conducted jointly by CCI and IEc, and is documented in Appendix A.

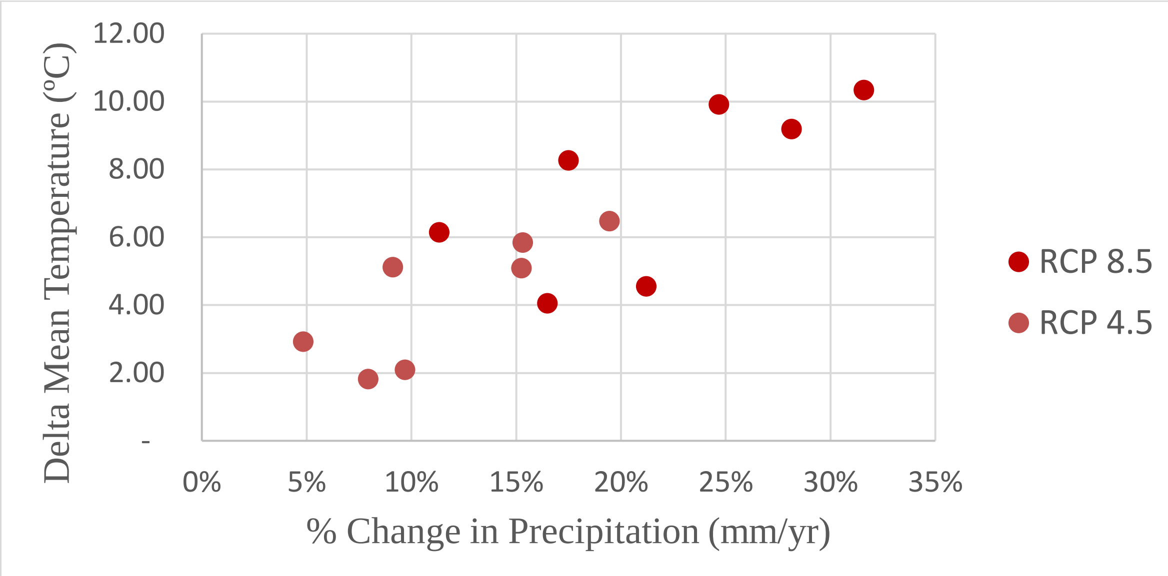
TABLE B-1. MODEL ENSEMBLES

GCM	RCP			Variable		
	2.7	4.5	8.5	tasmax	tasmin	pr
CCSM4	x	✓	✓	✓	✓	✓
GFDL-CM3	x	✓	✓	✓	✓	✓
GFDL-ESM2M	x	✓	✓	✓	✓	✓
HadGEM2-AO	x	✓	✓	✓	✓	✓
HadGEM2-ES	x	✓	✓	✓	✓	✓
MIROC-ESM-CHEM	x	✓	✓	✓	✓	✓
MRI-CGCM3	x	✓	✓	✓	✓	✓

B.2 ADMINISTRATIVE-RESOLUTION RESULTS

On a national scale, these 14 scenarios represent a wide set of potential futures and allow for an understanding of uncertainty in the predictions. Figure B-2 shows the national level change in temperature and precipitation for the 14 unique combinations of 7 GCMs and 2 RCPs. This scatter plot specifically shows the change from the 1986 – 2005 baseline to the 2080s era.

FIGURE B-2. NATIONAL AVERAGE CHANGE IN ANNUAL TEMPERATURE (°C) AND PRECIPITATION (MM/YR) FOR THE 2080S



Tables B-2 and B-3 displays the changes in temperature and precipitation summarized at the provincial spatial resolution (rows) for each era and rcp (columns). These values are averaged across all 7 GCMs.

TABLE B-2. PROVINCIAL AVERAGE CHANGE IN ANNUAL TEMPERATURE (°C) FOR THE 2080S

Province/Territory	change in mean temperature (°C)			
	rcp 4.5, 2050s	rcp 4.5, 2080s	rcp 8.5, 2050s	rcp 8.5, 2080s
Alberta	2.76	3.36	3.62	5.90
British Columbia	3.06	3.71	4.00	6.52
Manitoba	2.52	3.05	3.33	5.38
New Brunswick	2.97	3.47	3.77	5.84
Newfoundland and Labrador	2.35	2.89	3.15	5.10
Northwest Territories	2.97	3.45	3.79	5.87
Nova Scotia	2.73	3.22	3.53	5.54
Nunavut	2.99	3.46	3.81	5.91
Ontario	2.78	3.30	3.62	5.72
Prince Edward Island	2.48	2.99	3.29	5.26

Province/Territory	change in mean temperature (°C)			
	rcp 4.5, 2050s	rcp 4.5, 2080s	rcp 8.5, 2050s	rcp 8.5, 2080s
Quebec	2.87	3.40	3.71	5.87
Saskatchewan	2.72	3.28	3.56	5.73
Yukon	3.18	3.94	4.14	6.86

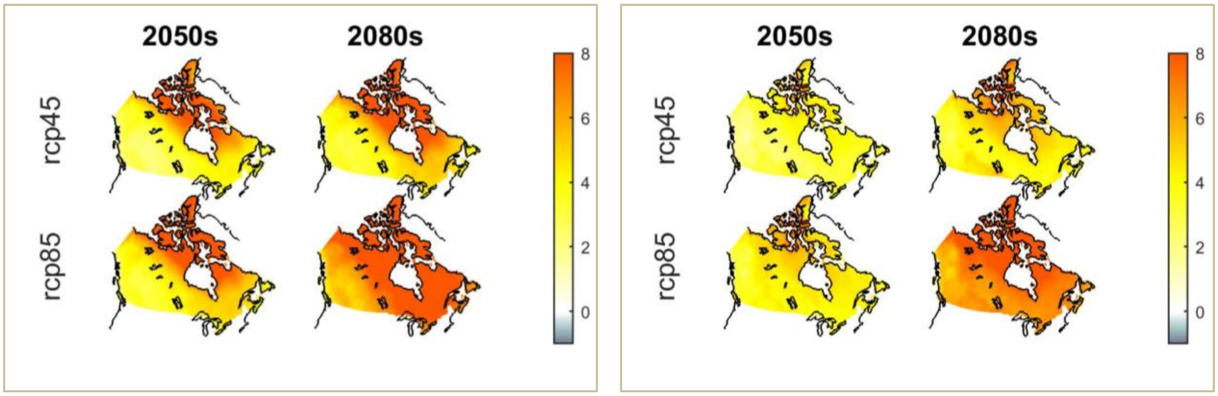
TABLE B-3. PROVINCIAL AVERAGE CHANGE IN ANNUAL PRECIPITATION (MM/YR) FOR THE 2080S

Province/Territory	% change in precipitation			
	rcp 4.5, 2050s	rcp 4.5, 2080s	rcp 8.5, 2050s	rcp 8.5, 2080s
Alberta	3%	6%	5%	13%
British Columbia	14%	17%	18%	26%
Manitoba	5%	7%	8%	12%
New Brunswick	3%	5%	6%	12%
Newfoundland and Labrador	5%	7%	7%	10%
Northwest Territories	5%	7%	6%	10%
Nova Scotia	2%	5%	5%	10%
Nunavut	7%	9%	8%	12%
Ontario	4%	6%	8%	13%
Prince Edward Island	0%	2%	2%	5%
Quebec	4%	6%	7%	14%
Saskatchewan	2%	5%	5%	11%
Yukon	6%	10%	11%	19%

B.3 GRIDDED RESULTS

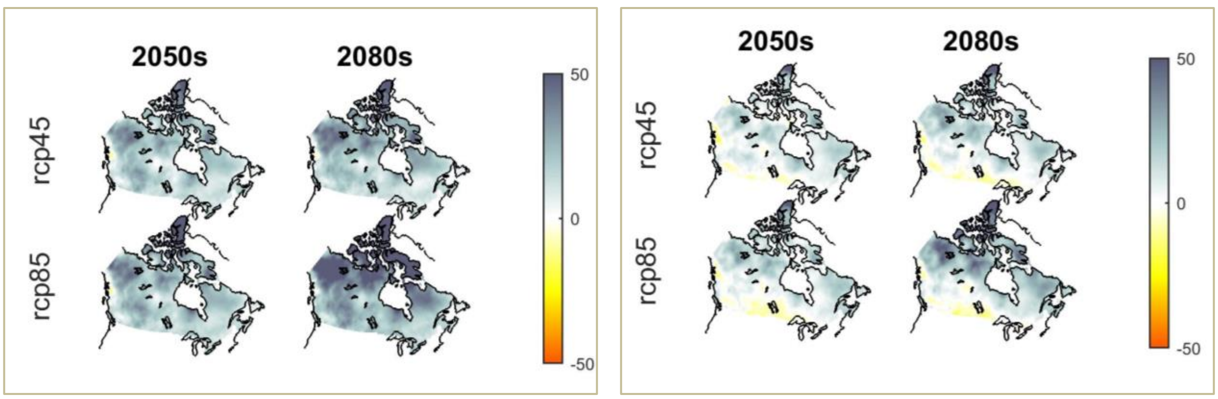
Figures B-3 and B-4 below show changes in temperature and precipitation at a gridded resolution in 2 x 2 panels of two eras, the 2050s and the 2080s, and for two RCPs, RCP 4.5 and RCP 8.5. Shown are a selection of GCMs that capture a wide range of possible futures.

FIGURE B-3. PROJECTED CHANGE IN MEAN ANNUAL TEMPERATURE (°C)



GFDL-CM3 *HadGEM2-AO*

FIGURE B-4. PROJECTED CHANGE IN MEAN ANNUAL PRECIPITATION (MM)



GFDL-CM3 *HadGEM2-AO*

B.4 ADJUSTMENTS

Initial exploration of the provided data revealed a few cases of anomalously high or low values for the maximum temperature variable in the baseline dataset. While these cases were very few in number, they could be problematic in later analysis, and thus needed to be adjusted.

Based on historical records, we chose a minimum feasible temperature of – and a maximum feasible temperature of °C. Any values that fell outside of these ranges were replaced with the average maximum temperature for that month across the baseline dataset.

REFERENCES

Hopkinson, R.F., McKenney, D.W., Milewska, E.J., Hutchinson, M.F., Papadopol, P., Vincent, L.A., 2011. Impact of Aligning Climatological Day on Gridding Daily Maximum–Minimum Temperature and Precipitation over Canada. J. Appl. Meteorol. Climatol. 50, 1654–1665. *https://doi.org/10.1175/2011JAMC2684.1*

Hutchinson, M.F., McKenney, D.W., Lawrence, K., Pedlar, J.H., Hopkinson, R.F., Milewska, E., Papadopol, P., 2009. Development and Testing of Canada-Wide Interpolated Spatial Models of Daily Minimum–Maximum Temperature and Precipitation for 1961–2003. J. Appl. Meteorol. Climatol. 48, 725–741. *https://doi.org/10.1175/2008JAMC1979.1*

Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2006. Hole-filled seamless SRTM data V3.1 available from the CGIAR-CSI SRTM 90m Database.

McKenney, D.W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R.F., Price, D., Owen, T., 2011. Customized Spatial Climate Models for North America. Bull. Am. Meteorol. Soc. 92, 1611–1622. *https://doi.org/10.1175/2011BAMS3132.1*

Pacific Climate Impacts Consortium, University of Victoria, (Feb. 2019). Statistically Downscaled Climate Scenarios. Downloaded from https://data.pacificclimate.org/portal/downscaled_gcms/map/ on July, 2020. Method: BCCAQ v2.