The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions

Social Infrastructure

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Preface

This research was carried out under the CCAF Grant No. A209. Under the same grant, we earlier wrote a review of the literature. It was entitled: *The Costs of Adaptation to Climate Change: a Critical Review,* dated November 15, 2000. The present work should be seen as a continuation of that work.

As with the earlier report, this work should be of interest to three kinds of readers: the specialized climate change scientists and researchers in the field of adaptations and impacts of climate change; readers interested in policy formation, and the top level decision makers. We expect that the scientists and researchers will want to read the entire report. Those interested in policy formation may read the comprehensive summary of each chapter, and the top-level decision makers with very little time may want to read the Executive Summary.

We are again fortunate in receiving assistance from a larger number of people. First we would like to thank all those who responded to our questionnaires, which were followed by emails and phone calls to all managers, engineers, and civil servants who look after Canada's roads and water utilities. We consulted people at the federal, provincial, regional and municipal levels all over Canada. Without their generous support of time and their willingness to share their data this study would not have been possible. At Brock University, we would like to thank Kathleen Jaques Bennett, Indra Hardeen, Mike Patterson, Harvey Stevens, and Klemen Zumer who all worked at one time or the other at the Climate Change Laboratory at Brock University. We would also like to thank Dr.Elaine Barrow, Dr.Eva Mekis, Trevor Murdock, Dr.Elaine Wheaton and Dr.Francis Zwiers. In addition we continued to receive generous help from two librarians at Brock University: Margaret Dore and Moira Russell. As usual, Margaret also did a fair amount of unpaid proof reading and editing. At Environment Canada we would like to thank Indra Fung-Fook, Ash Kumar and Roberta McCarthy. However, the remaining deficiencies are those of the two authors alone.

Executive Summary

Progress to Date on the Estimation of Adaptation Costs

We have made a beginning on the estimation of adaptation costs of climate change for social infrastructure. On roads, we estimate that the cost of constructing an all weather road is $85 000 per km plus an additional $65 000 to $150 000 per bridge. The cost on permafrost is $500 000 per km and $350 000 per km on non-permafrost land. An average coastal bridge will cost $600 000, with a total expected cost of all coastal bridges being around $9 billion. The most important operating cost for roads is winter control, which we estimate to be between $9 and $12 per km.

For water utilities the adaptation costs will be mainly in the form of expanding wastewater treatment capacity. For Toronto, the adaptation costs range from $633 million to $9 billion; for Niagara between $8 and $24 million; for Halifax about $6.5 million. Montreal is an exception as it has excess capacity. These estimates are based on case studies and cannot be extrapolated regionally or nationally because Canada has a number of distinct ecoclimatic zones. We report on other case studies too, covering the entire country, but these case studies need to be extended to other areas.

We must emphasize that all estimates of the costs of adaptation are preliminary and need to be verified and further refined based on more and better data.

What follows is a more detailed Executive Summary.

Detailed Executive Summary

1. The fundamental objective of this report was to collect the micro-level data in order to be able to estimate the costs of adaptation to climate change. For this purpose, a data collection protocol was established. On the basis of this protocol, questionnaires were sent out to determine climate impacts, current expenditures (both capital and operating), and other technical factors relevant to social infrastructure. By agreement, this report is restricted to the costs of adaptation of the road network (roads, bridges, storm water management systems), and water utilities (drinking water treatment plants, and wastewater treatment plants).
2. For the road network and for a representative sample of water utilities, various databases on current expenditures at the provincial, municipal and water-utility level were created. Time series temperature data from CGCM1, GG1 were used as the exogenous factor in simulating the impacts of climate change. Experiments with the downscaling software SDSM were carried out. As SDSM downscaling can only be done on a limited basis so far, we carried out our own downscaling for all the sites of water utilities in our sample. Our downscaled data was then used as the "exogenous shock" in order to simulate the impact of climate change.
3. We tried using SDSM for Toronto. At the time of writing, it was the only locality for which we might be able to use SDSM for downscaling. However, we found that the resulting downscaled precipitation did not differ statistically significantly from the GCM simulated base. We therefore devised our own proportional

downscaling model, using *actual precipitation data* for each of the case studies. However, further research in downscaling is needed (see below).

4. We have argued that social infrastructure is an asset that provides services that can be called intermediate public goods or quasi-public goods. The quality and quantity of public infrastructure has declined over the last 25 years in most OECD countries, including Canada. Adapting this infrastructure to climate change would ideally require determining the original quality some 25 years ago and then estimating what the costs of damage due to climate change would be. In practice this may not be possible. The best we can hope for is to estimate the costs of adaptation that restores the integrity of the services provided by the infrastructure. However only those costs that can be attributed directly to climate change must be included.

The Roads Network

5. The distribution of roads and bridges between the provincial and local governments is quite variable across the country. In Ontario, the regional government assumes much of the responsibilities for road, bridge and storm water management system construction that would otherwise be handled by the province. Other provinces, such as British Columbia, also have a two-tier local government system. Both the municipal and regional levels of government handle roads.
6. About two-thirds of all roads in Canada are under municipal jurisdiction. About a quarter are under provincial and the rest under Federal jurisdictions.
7. Roadways are fairly consistent in their design standards as well. Most provinces use the Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Roads. There are also guides specific to each province, which often exist to accommodate special considerations for climate within the province.
8. About 50 percent of all roads in Canada are gravel roads; about a third are paved roads.
9. The standards for bridge design are fairly consistent across the country, with the Canadian Standards Association guide used in most provinces. A single bridge estimate alone could cost $15,000.
10. Storm water management system guidelines are very diverse across the country. In most provinces, the design of the drainage system and the level of protection provided for the associated road depend upon the type of road. Major highways have more protection against flooding than local roads.
11. Climate affects both capital and operating expenditures. Climate constitutes one component of the deterioration of roads, bridges and storm water management systems; the impact of human activities is the other.
12. The road system in British Columbia, particularly the bridges, is already over-designed for climate factors, as considerations for seismic activity have already been taken into account. In the Northwest Territories, considerations for the behaviour of permafrost add almost 50% to the cost of road building per km. A road built on permafrost costs approximately $500,000 per km to construct; a road

on non-permafrost costs approximately $350,000 per km to construct in the Northwest Territories.

13. There may be changes in the number of freeze-thaw cycles. A change in freeze-thaw cycles is more likely to occur in the eastern half of Canada with fewer cycles on the west coast. GCMs predict an overall increase of approximately 5°C in mean temperature accompanied by an increase of approximately 10% in precipitation. This will change the number of freeze-thaw cycles, which will affect the life of a road.
14. Freeze-thaw cycles and frost heave (temperature effects on soil moisture) require specific depths of well-drained materials below the road surface to prevent deleterious effects on the roadbed. Frost heave depends on the duration of the winter; it is therefore different from a freeze-thaw cycle.
15. The highway expenditures in Canada vary across the country. The lowest expenditures per kilometre of road are found in the Prairie Provinces and the Atlantic Provinces. British Columbia, Ontario and Quebec have the highest expenditures per kilometre. These provinces also have high percentages of paved roads. The percentage of paved roads varies from a low of 5% in the territories (Yukon, Northwest Territories and Nunavut) to a high of 78% in Quebec. The Prairie Provinces generally have a low percentage of paved roads. The provincial expenditures per vehicle do not vary as much as the expenditures per kilometre of road. Some of the differences in provincial road expenditures may be due to higher traffic volumes.
16. Bridges, compared to other structures, are exposed to the most adverse environments of loading and climatic change. The climatic loads that must be considered in bridge design include water loads, ice loads, scour, stream instability, temperature effects, wind effects, frost effects, groundwater effects and soil properties. All of these factors contribute to the cost of bridge construction.
17. About 75 percent of bridges in Canada are old and will require replacing anyway. When they are replaced using the new higher standards, these bridges will be over-dimensioned and will not need any further adaptation to climate change. Therefore the climate change adaptation costs will be near zero for bridges.
18. There are about 10 000 km of ice roads; most of these are in Ontario and Quebec. Therefore these two provinces will incur the highest adaptation costs for ice roads. If, by the year 2100, all of the winter/ice roads that will no longer be in use are replaced with all weather roads and 50% of the winter/ice roads that have restrictions placed on them are replaced with all weather roads, the number of kilometres of roads that will require replacement will be about 10,000 km, costing $908 million.
19. All weather roads are considerably more expensive to build and maintain. In northern Ontario, construction of an all-weather road will cost at least $85,000 per km plus bridges. An average bridge for an all weather road in Ontario will cost between $65,000 and $150,000 per bridge.
20. All roads will be affected by changes in temperature, particularly as these temperature changes relate to freeze-thaw cycles and frost heave. It can be

expected that due to increased temperatures, the maintenance costs for roads will change in different parts of the country.

21. Roads on permafrost will be affected by greater capital expenditures as the permafrost melts. This impact will be felt mostly in the discontinuous permafrost zone in northern Canada. After the permafrost has disappeared, however, it can be expected that capital expenditures for new roads will decrease. The presence of permafrost increases the cost of road building; it is only the transitional period while the permafrost is melting that will result in higher capital costs for roads. The General Circulation Model that we used predicts that the permafrost will disappear in most of the discontinuous permafrost zone over the next 100 years. The cost of replacing ice roads and permafrost roads is expected to be about $0.5 million per km.
22. Climate change could severely affect coastal bridges. If the sea level rises much, then this could have a major effect on the bridges in the Atlantic Provinces where there are many coastal roads and many coastal bridges. The loss of navigational clearance is expected to result in the need to replace a large proportion of the bridges in Newfoundland, Nova Scotia, New Brunswick and Prince Edward Island. Bridges along the lower St.Lawrence, in Quebec, could also be affected by a rise in sea level. In general it is cheaper to replace a bridge than attempt to raise a bridge. The average replacement cost of a coast bridge is $600 000. As there are about 3000 coastal bridges in Canada, we estimate the costs of adaptation for coastal bridges to be about $9 billion.
23. The capital costs for all storm water management systems will be affected by climate change, as the frequency of extreme events is expected to change. However, these costs are expected to be small, as they typically represent about 10 percent of the total road maintenance budget. While the cost of increasing or decreasing culvert sizes and ditch depths is not large, the cost of altering storm water detention ponds and dams may be quite a bit larger. An increase in the frequency of extreme events will result in more debris clogging the system and more siltation in the water retention areas.
24. One of the largest components of costs is winter control (snow clearance, sanding, salting etc.), which can be as high as 50 percent of the roads maintenance budget. Winter control costs for roads, bridges, ditches and drains will change with the amount of snow and ice formation. The costs of climate change adaptation for winter control will decrease overall, as temperature is expected to rise. There may be local increases in winter control costs as more snow falls in areas that have previously been too cold or too dry. Our regression results show that winter control costs will change by $9 to $12 per km of road.

The Water Utilities

25. The timing and regional patterns of precipitation will change, and more intense precipitation days are likely. General circulation models used to predict climate change suggest that a 1.5 to 4.5 degree C rise in global mean temperature would increase global mean precipitation about 3 to 15 percent. Some of this is due to the conversion of snow into rain.

26. Although the regional distribution is uncertain, precipitation is expected to increase in higher latitudes, particularly in winter. Potential evapotranspiration rises with air temperature. Consequently, even in areas with increased precipitation, higher rates may lead to reduced runoff, implying a possible reduction in renewable water supplies.
27. More annual runoff caused by increased precipitation is likely in the high latitudes. In contrast, some lower latitude basins may experience large reductions in runoff and increased water shortages as a result of a combination of increased evaporation and decreased precipitation. Flood frequencies are likely to increase in many areas, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins. Floods may become less frequent in some areas.
28. The frequency and severity of droughts could increase in some areas as a result of a decrease in total rainfall and more frequent dry spells. The hydrology of arid land is particularly sensitive to climate variations. Relatively small changes in temperature and precipitation in these areas could result in large percentage changes in runoff, increasing the likelihood and severity of droughts and floods.
29. It seems reasonable to expect seasonal disruptions in the water supplies of mountainous areas if more precipitation falls as rain than snow and if the length of the snow storage season is reduced.
30. The Great Lakes impact assessments suggest global warming will result in a lowering of water supplies and lake levels and in a reduction of outflows from the Basin. Some projections show a lowering of lake levels by up to a meter or more by 2050. A one meter drop in the levels of Lakes Michigan and Huron in thirty years would have a severe impact on Lake St. Clair and Lake Erie, whose levels would drop by about 2 feet. A lake level drop of one meter in Lake Michigan could cause thousands of municipal water intakes and wells to be moved or extended.
31. We reported on several case studies of water utilities in the different ecoclimatic zones of Canada, focusing on the question of the impact of climate change on the availability of drinking water supply and capacity for treating wastewater. For Toronto, precipitation is expected to increase, and so it is unlikely that Toronto will experience a water supply problem. The City draws its water supply from Lake Ontario, and even supposing that lake levels drop by a metre in the future time periods, intake pipes are deep enough, and far enough into the lake. Maximum precipitation in Toronto is expected to increase from the baseline period to the 2020 period by a factor of 4. The standard deviation increases by a factor of 1.7 from the baseline period to the 2020 period. We conclude that the City of Toronto will face adaptation costs for wastewater treatment from a low of $633 million to a high of $9.4 billion, depending on how risk averse they are.
32. In the region of Niagara, our analysis shows a wet autumn, followed by a wetter winter. Wastewater treatment capacity will have to increase. We estimate the costs will be in the range of $8 million to $24 million.
33. We found that Montréal was an exception to the general eastern seaboard case studies. Montreal has a great deal of excess treatment capacity already built into the system. Based on our analysis, Montréal will not have climate change

adaptation costs associated with drinking water supply and wastewater treatment. Its drinking water source is the St. Lawrence River, which of course relies on the Great Lakes for water supply.

34. In the case of Halifax, our projections show that maximum precipitation increases a dramatic 315% from the baseline period to the 2020 period. It remains 149% to 232% higher in the subsequent periods. The standard deviation also increases in the future time periods from the baseline. At present, Halifax discharges 16 mega gallons of untreated sewage per day into the Halifax Harbour. However, new planned treatment capacity will come on stream in 2003. Based on this information and our regression analysis, it appears that Halifax will experience a wastewater treatment capacity shortfall in the future scenarios. The costs associated with climate change adaptation will include those that expand treatment capacity, and a rough estimate of this cost is $6.5 million.
35. We also did a sample of Prairie cities and towns. We considered Regina, Swift Current, Humboldt, and Lethbridge. For all these prairie studies there is a need to study the effects of a change in rain to snow ratio for all prairie settlements that rely on rivers originating in the mountains. Changes in rain to snow ratios will impose additional adaptation costs. We expect that vulnerability of water supply is likely to be most acute in the Prairie Provinces.
36. Our West coast case studies included Prince George and Penticton. Our analysis indicates that existing wastewater treatment capacity in Prince George seems adequate for the near future. Therefore, based on this analysis, there will be no adaptation costs associated with wastewater treatment due to climate change.
37. However in the case of Penticton, we find that the city will face a wastewater treatment capacity shortfall. The costs associated with climate change adaptation range from $15 million to $28.5 million.
38. In Northern Canada, we included Yellowknife and Norman Wells. Because Yellowknife draws its water directly from the Yellowknife river and the pipes are buried below the permafrost, there does not appear to be a water supply problem, nor a cost associated with damaged pipes due to disappearing permafrost. For wastewater treatment, Yellowknife has 10 to 12 months of wastewater storage, so an increase in precipitation is not expected to exceed treatment capacity.
39. The case of Norman Wells is more complicated. Because Norman Wells is in the discontinuous permafrost zone, the main factor affecting possible climate change adaptation costs is the disappearance of the permafrost due to higher temperatures. However, Norman Wells will not be facing a water supply shortage as its water is supplied by the Mackenzie River, which is a large enough source for a small population. Wastewater treatment capacity also appears to be adequate, as years of wastewater retention are provided by the natural wetlands.

Directions for Future Research

40. Some directions for the future include policy oriented research to indicate ways of eliminating existing distortions in the tax structure of fuel prices and property, that currently lead to the highways being overused and the rail network underused. A proper study could identify which taxes are distortionary and what

tax structure would be equitable so that the rail sector is not disadvantaged. This should be part of the National Transportation Strategy that is now being developed.

41. Further research needs to be done to determine the cost of road deterioration due to changes in (a) freeze-thaw cycles, and (b) frost- heave. These are both climatic factors that will affect either the operating costs of roads, or the capital costs, depending on the severity of the problem.
42. The pricing policy of water should also be studied to encourage conservation and reduce wasteful usage of water. The differential impacts of different water pricing policies should also be studied.
43. A further research task on drinking water supply is to expand the coverage to include more case studies in Quebec, northern Ontario, New Brunswick, Manitoba and Newfoundland. In this report we studied Montreal because of its large urban population and investment in infrastructure, but we need to include more rural locations in Quebec such as Sagard and St. Adolphe. Places like Val d'Or and Chicoutimi can be included based on geographic location. The coverage should include a sample of First Nations Reserves in Ontario, Saskatchewan, B.C., and Quebec.
44. There is a need to carry out further experiments in downscaling using other methods. We need to do experiments with a number of different downscaling techniques: dynamic downscaling, synoptic weather typing and stochastic weather generation. When a new release of SDSM is available, we propose to try regression-based downscaling with the possibility of using dummy variables. Ideally, trying a number of downscaling methods might help discover whether the projections converge to some common set, or whether there is a large divergence between them. With an ensemble of experiments, it might be possible to see if the various methods lead to convergent results or not.
45. From the experiments reported here we have excluded the implications of evaporation and evapotranspiration. That could also be investigated for completeness.
46. For the prairies, we need to explore the downscaled data on snow pack and ratio of rain to snow. Winter snow accumulation is a key surface water supply source for Canada, and for much of the U.S. Snow pack accumulations may in future vary substantially, due to changes in long-term wintertime synoptic scale precipitation combined with regional warming. All this may increase the rain to snow ratio. Snowmelt contributes more effectively to stream flow than does rainfall. Hence, conversion of winter snowfall to liquid precipitation will probably result in declining runoff. We are aware of research completed for an alpine watershed in southwestern Alberta that combined a wide area assessment of forecast changes in wintertime synoptic precipitation with the meso-scale alpine hydrometeorology, to evaluate the impact(s) of forecast climate change on mountain snow packs. The results show that modest increases in winter precipitation will not compensate for regional changes in the rain to snow ratios. The net result is a decline in winter accumulations of precipitation as snow; and, we expect, a decline in surface water supply. In summer, higher volumes of water vapour in the atmosphere, together with a magnified greenhouse effect and

warmer summer temperatures, will probably result in greater occurrence and severity of thunderstorms. These storms could tax the capacity of existing storm water pipe networks; and will result in greater stress on water quality and treatment facilities, particularly in regions with combined sewer systems.

47. The cumulative effects of climate change on water resources may include an increase in urban floods, increasing groundwater recharge during winter, and a decline in average spring runoff. This means that there will be less riparian flow to dilute contaminants. Thus there is a need to study the effects of a change in rain to snow ratio for all prairie case studies that rely on rivers originating in the mountains. Changes in rain to snow ratios will impose additional adaptation costs. *For this reason, we believe that it would be unwise to assume that the CGCM1 projections of precipitation (which we relied on for this report) exhaust the research. On the contrary all our Prairie and Western Canada case studies show a heavy dependence on snowpack as sources of water for rivers and basins.*
48. Therefore our results reported here should be seen only as a first experiment, and as soon as better and more reliable data on snowpack becomes available, the case studies reported here should be re-examined. We know that vulnerability of water supply is likely to be most acute in the Prairie Provinces. Perhaps pooling resources and establishing research links with agencies such as the International Joint Commission and the National Water Resources Institute of Canada may also be necessary. In the short period of time available to us, it was not possible to establish these links.
49. The research on wastewater treatment can be expanded by gathering information on land prices for retention tanks and lagoons for major urban areas like Toronto. We also need to estimate the costs of adaptation in other parts of the country, using location-specific costs. In order to improve the estimates of the costs of adaptation, the costs of more efficient treatment technologies such as biological nutrient removal and UV disinfection techniques need to be included. Thus much needs to be done to understand the costs of adaptation to climate change for water utilities, and this report should be seen as an important and, we hope, useful beginning.
50. As promised in our proposal, we give the upper and lower 95 percent confidence limits of the estimates. We have made no assumptions about risk aversion, and no discounting has been used.
51. We emphasize that all results reported here are subject to the limitations of the available data and therefore should be regarded as preliminary. However, we believe that municipalities and the appropriate authorities with jurisdiction over roads should be preparing business plans for the year 2020, and the figures given here represent a start. These business plans should then be revised as better data and improved estimates become available.

Chapter 1: Data Collection Protocol

1.1: Introduction

A comprehensive review of the literature *(Dore and Burton, 2001)* indicated the methodological shortcomings in the literature in measuring the costs of adaptation to climate change. There is a need to collect data at the micro level. Our own approach is described in this Data Collection Protocol (DCP), which reflects the need to do a systematic study of adaptation costs, sector by sector. Completing all the adaptation costs for Canada sector by sector will require several years of work. In this report, we concentrate on the costs of adaptation for some publicly provided social infrastructure.

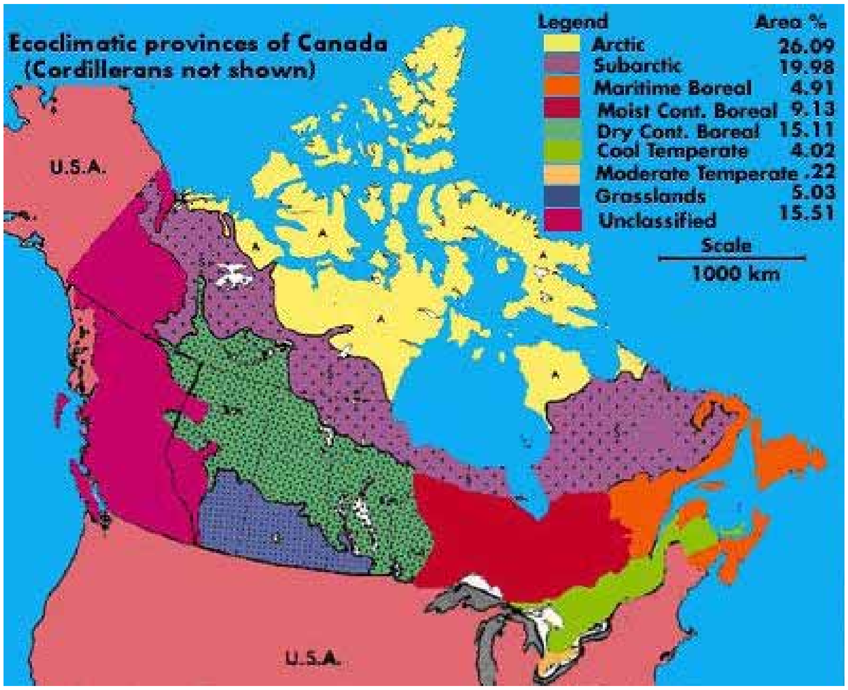
Social infrastructure is provided by the federal, provincial, regional and municipal levels of government and consists of roads, bridges, dams, dikes, ditches, break walls and shoreline protection, water supply, sewers and wastewater treatment plants. Each level of government provides separate portions of this infrastructure and each level must therefore be considered separately for completeness. There is, however, much commonality in the manner in which the data are collected for different levels of government. We began with the finest level of aggregation for social infrastructure, namely the municipalities. We found that the best way of covering the whole of Canada was to obtain data from the Canadian census subdivisions for 1996, of which there are 5562. Each subdivision has a wealth of data, which can be utilized later in our research: income, population, number of dwellings, area, population density and type of subdivision. Using a geographic information system (GIS) format, all the census subdivisions can be displayed over a map of Canada. We then obtained information on climatic factors from the Canadian Institute of Climate Studies (CICS) on their Canadian General Circulation Model 1 (CGCM1) with greenhouse gases (GG1). This model projects climate change scenarios for Canada for the years 2020, 2050 and 2080 from a climate information base period of 1961-1990. We have chosen this model as it is highly regarded in the international climate-change science community. We chose not to use another version of this model (GAX) which includes compensation for the effects of sulphur aerosols, because the scientific community is not agreed on whether aerosols have a damping effect or whether they tend to amplify the forcing effect. In any case, GG1 is one particular realization, which is as good as any other, and so we have chosen to base our experiments on this model only. The model has been disaggregated into 455 grid boxes, where each grid box is 3.75 degrees latitude by 3.75 degrees longitude. Each grid box varies from a maximum of about 130,000 square km in the southern part of the country, to a minimum of approximately 15,000 square km in the northern part of the country (longitudinal distances diminish as one approaches the north pole). The advantage of a GIS format is that these grid boxes can be overlaid onto our 5562 census subdivisions of Canada. These subdivisions correspond fairly closely to Canadian municipal boundaries. We then collected the municipal capital and operating budgets for all municipalities for all provinces and territories of Canada for 1997, 1998 or 1999. We obtained climate assessments for 1997, 1998 and 1999 so that we may evaluate these years in terms of "normal" Canadian climate. Every attempt was made to ensure that we did not utilize data from an anomalous year. Some tradeoffs between the need for recent municipal expenditure data and impact of unusual weather may have to be accepted for this study, however, as data for 1998 was occasionally used. In terms of mean annual temperature, 1998 was the warmest year in the last 50 years of Canadian meteorological data. All this information for all the provinces and territories has been collated and collected into searchable databases at the Climate Change Laboratory at Brock University.

Each grid box of the climate change model contains projections for a number of relevant climatic factors for each of the climate change scenarios. There are 18 climatic factors that are currently available in GG1. These climatic factors are: mean temperature, maximum temperature, minimum temperature, diurnal temperature range, precipitation, snow water content, relative humidity, specific humidity, sea ice, mean sea level pressure, vapour pressure, surface temperature, incident solar radiation, wind speed, evaporation, potential evapotranspiration, soil moisture and fractional cloud cover. We have added a few variables, such as atmospheric carbon dioxide, sea level, lake levels and lake ice where reliable projections exist. Next, we drafted questionnaires on the cost breakdowns and climate impacts for various aspects of social infrastructure such as roads and bridges, and water utilities. We tailored these questionnaires to include the climate change factors that will affect a particular portion of the budget. For example, a winter control question was included in the section on roads. We have also utilized national and provincial codes and standards for construction and operation, the Canada Country Study and other background information to arrive at the relevant climate change factors and to determine where these factors will have an impact. The similarities and differences in these codes and standards across the country were also an indication of potential differences in the impact of climate change. The climate change scenarios provided by the CGCM1 model have given us a potential range for the climate changes that we may expect for each census subdivision. We began by aiming for at least 10 percent of the population of Census Subdivisions by first stratifying and obtaining an unbiased sample.

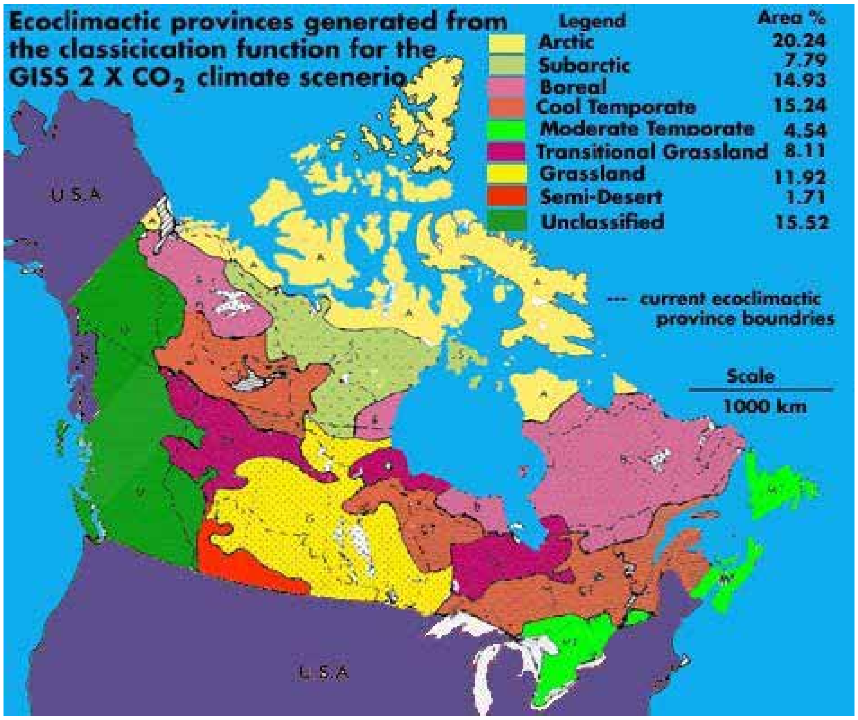
However, our response rate was only about 15 percent for the cost breakdown for roads, bridges and storm water management systems. Nevertheless we had at least 100 municipalities that responded and these were well distributed throughout Canada. We therefore have a fair degree of confidence in our sample. The questionnaires covered the break down in capital and operating costs for roads, bridges and storm water management systems. These breakdowns were necessary as the capital and operating expenses for roads, bridges and storm water management systems will all be affected differently by climate change. This breakdown gave us a base to assess cost increases and decreases that can be attributed to climate change. One area, winter control, was almost always maintained as a separate budget item by the municipalities and provinces. This is most likely because winter control can consume a large portion of the costs for road networks in Canada.

For water utilities, it became clear early that most averages would be meaningless, as Canada is a vast country with a large number of climatically different regions. We therefore chose to do case studies, taking care that these case studies were broadly representative of these ecoclimatic provinces (Figure 1.1.1).

Figure 1.1.1: Ecoclimatic Provinces of Canada and Projected Shifts Under a Scenario of Doubled Atmospheric Carbon Dioxide



http://www.ec.gc.ca/water/images/nature/clim/a9f1e.jpg



http://www.ec.gc.ca/water/images/nature/clim/a9f2e.jpg

Thus our primary source of data was drawn from the questionnaires on roads and bridges, provincial budgets, municipal budgets and water utilities. We then used standard statistical methods to estimate the costs of adaptation for the two main categories of data for social infrastructure.

The main orientation of this protocol has been to identify where the shifts and changes in climate will occur, how intense these changes will be and what the costs will be to Canadians in order to adapt to these changes, where possible. This data collection protocol is designed to be consistent with our critique of the methods of estimating adaptation costs that was reported in the literature review and to be consistent with the economic theory outlined therein. In Part 4 of the literature review, we stated our direction in costing adaptation to climate change in Canada:

> *"We hope to show that the optimal adaptation will be based in a theory of investment in a context of preserving natural and human-made capital. Thus we shall shift the focus from consumption benefits to a theory akin to portfolio choice in the theory of finance. Specifically, our aim will be to show that the optimal adaptations will be a function of the climate change scenarios, and not on the level of theoretical abstraction. The uncertainty or variation in the level of adaptation must depend on statistical properties of climate change and not be based on treating climate change as a marginal project."*
>
> *(Dore and Burton, 2000).*

We therefore propose to assess climate adaptation costs in Canada in terms of what would be required to preserve our portfolio of assets (our present structures). As indicated earlier in the literature review, we are critical of the use of the marginal benefit equals marginal cost rule (MB = MC) in our estimations for costing adaptation. We assess our adaptation costs in terms of the climate change scenarios that have been presented to us by the members of the scientific community that are involved in modeling climate change for Canada. Costs that are assessed at the micro level are more easily adapted to modifications in climate change scenarios for the future; aggregated costs may change but the costing base should remain the same and the data collection protocol will remain constant.

> *"From a perspective of "no regrets policy" and the precautionary principle, it is best not to bank on gains from climate change at the aggregate level. Instead, it would be wise to concentrate on the micro level and attempt to estimate adaptation costs. This can be done by…building a systematic record of physical adaptations and their respective costs, sector by sector."*
>
> *(Dore and Burton, 2000)*

This data collection protocol has, accordingly, been designed to establish the manner in which these adaptation cost figures will be established for two key components of social infrastructure, namely the road network (roads, bridges and storm water management), and water utilities covering both the production of drinking water and the treatment of wastewater.

In addition to the extra adaptation and impact costs associated with climate change, there may be benefits and reduced costs in some sectors for some climate change factors. The impact of climate change on sectoral costs may be classified into long-term effects, accompanied by ongoing costs, or short-term effects that may be associated with a single adaptation cost for each effect. The cost of adaptation to climate change for highway bridges, for example, may involve a reduction or increase in the yearly application of road salt as winter conditions change. This is an ongoing cost. The cost of adaptation to climate change for highway bridges over rivers may also involve the addition of bank stabilization materials such as gabions/rip rap as the intensity of water action (scour) on the substructure of the bridge increases. This is a single adaptation cost. However, in this report is was not possible to consider such a fine level of analysis, and carrying that out would require a great deal of time and a lot of data; it cannot be done in one year covering the entire country.

We collected data with the intention of developing sufficient detail, so that broad categories of expenditures can be identified. For roads, we collected expenditure data on operating costs and capital costs. Operating costs were broken down into expenditures by municipality (in each grid box) on roads, bridges, ditches and drains, and winter control. Capital costs were broken down into expenditures on roads, bridges and ditches and drains. For water utilities, we chose several representative case studies from different ecoclimatic regions of Canada. Our chosen case studies are: Toronto, the Regional Municipality of Niagara, Montreal, Halifax, Regina, Swift Current, Humboldt, Lethbridge, Prince George, Penticton, Yellowknife, and Norman Wells.

For water utilities, we confined ourselves to two crucial aspects only for adaptation: the supply of raw water for the production of drinking water, and the treatment of wastewater. We considered the impacts of climate change on the sources of the supply of raw water, and the implications of changes in precipitation patterns predicted by CGCM1 for the 2020s, 2050s and 2080s. It should be pointed out that CGCM1 does not contain realized data, but only simulated data, which is one possible realization. The climate modellers have argued that these data must then be downscaled for each locality in each particular grid box. The next chapter discusses the issue of downscaling, and how it was most important for us to use real downscaled data rather than simulated data for the costs of adaptation for the case studies in water utilities. The relevant climate factors that will affect roads will be discussed in detail. The calculation of costs has sufficient reliability and breadth that it may accommodate changes in projected climate scenarios as climate models are modified. The costs associated with new development required by population growth will be particularly affected by changes in codes and standards in response to climate change and may be assessed separately. We are primarily concerned with each sector as it currently exists and the adaptation costs over the next 100 years. The structures (homes, roads, pipelines, satellites, factories) and activities (maintenance, equipment operation, manufacturing processes) of humans interact with the climate and this interaction will change with climate change.

1.2: Anticipated Effects of Climate Change

It is anticipated, depending upon the climate model that is utilized and the amount of increase in carbon dioxide, that global warming averaging 4-5^{o} C over the next 80-100 years will occur. An increase in precipitation of approximately 10% may also occur and increases in humidity are expected. Lake and sea ice will be decreased and snow cover will be reduced. New information suggests that sea level may increase but the increase is likely to be moderated by the decline in the ice sheets, as these sheets had a gravitational pull. Without this pull, sea levels are now expected to be higher around the equator than in the northern latitudes. Lake levels may drop due to increased heat and evaporation (see Chapter 5). Climatologists expect changes in the number of days below freezing and the number of freeze-thaw cycles. In addition, the frequency of extreme events, such as ice storms, high winds and heavy rainfall, will likely increase. More rain will fall but there will not necessarily be more rainy days as the hydrologic cycle accelerates. In view of this, changes to the design of infrastructure, such as bridges and roads, must be made. Maintenance on existing and new structures may be higher and replacement of existing structures may have to occur more frequently. In some local areas, the climate may become more benign and costs may drop. Changes in costs may arise from either direct effects, such as extreme events, increased heat, loss of permafrost, more oscillations in temperature, or from indirect effects, such as the increased or decreased use of road salt.

1.3: Methodology

The methodology of the data collection protocol has been designed to recognize the distinctiveness of different sectors and the different climate change impact that may affect each sector and various subsectors. The intensity and costs associated with changes in a single climatic factor vary between sectors. .

1.3.1: Definitions of Sectors of the Economy

The sectors of the economy may be divided into nine major NAICS groups (two-digit codes). These codes identify all of the human activities that form part of the economy. The nine NAICS groups are as follows:

1. Code 11 corresponds to primary production sectors such as agriculture, forestry and fisheries.
2. Code 21 includes extraction sectors such as mining and petroleum, Code 22 is utilities and Code 23 is construction.
3. Codes 31 to 33 refer to the manufacturing sector.
4. Code 41 includes wholesale trade, Codes 44-45 are retail trade and Codes 48-49 are transportation and warehousing.
5. Code 51 is information and cultural industries, Code 52 is finance and insurance, Code 53 is real estate, rental and leasing, Code 54 is professional, scientific and technical services, Code 55 is management of companies and enterprises and Code 56 is administrative and support, waste management and remediation services.
6. Code 61 is educational services and Code 62 is health care and social assistance.
7. Code 71 is arts, entertainment and recreation and Code 72 is accommodation and food services.
8. Code 81 is other services (except public administration).
9. Code 91 is public administration.

We have chosen social infrastructure as the initial area to estimate climate change adaptation costs. This area was identified in the original research contract (Schedule A of the contractual agreement with the Government of Canada). Social infrastructure consists of the activities associated with the public administration codes (Code 91) in providing Canadians with various structures such as roads, bridges and water supply. Social infrastructure includes publicly owned and maintained structures and systems such as roads, bridges, drains, docks, airports, water utilities, sewage treatment facilities, dikes, dams, breakwaters and storm water management systems. These systems and structures are publicly funded and utilized by the public at large.

Social infrastructure can be subdivided into subsectors based on political boundaries; services may be provided on a municipal, regional, provincial and federal level. Each level has its own responsibilities and distinctive budgets for the various sorts of social infrastructure. For example, each level of government provides some types of social infrastructure, such as roads and bridges; some are handled at only one level. In addition, there may be separate agencies, such as the conservation authorities and the Seaway Commission, that handle specific forms of social infrastructure (flood control and canals). These intermediate levels change from one province to the next. The budgetary allocation for the types of social infrastructure provided by each level of government or agency may be handled differently (roads may be included with bridges for example). Different provinces may require their municipalities to aggregate the expenditures for social infrastructure differently. Ontario municipalities do not necessarily track their expenditures in the same manner as British Columbia municipalities. In order to determine the optimum data collection protocol, each sector must be assessed separately and, for social infrastructure, each subsector must also be assessed separately. The subsectors can then be aggregated if necessary.

We conducted an information review of each sector with a focus on standard practices/procedures/codes for each sector to determine what changing climatic factors will have an impact on the sector (structures, maintenance and operations). We compiled a list of relevant standards for the province and country. As a check, we conducted local telephone consultations to verify and expand on the changing climatic factors that will have an impact for the sector/subsector.

We researched climate change scenarios from the Canadian model of global warming (CGCM1 –GG1) as source factors involved in climate change scenarios. We researched and utilized other sources of information such as the Canada Country Study and Environment Canada website as a source for climate change scenarios for factors not modelled in CGCM1. We added other climatic factors as indicated in the literature review of standard practices/procedures/codes for each sector where reliable climate change scenarios could be obtained.

We compiled databases that can be used as a basis for the aggregation of adaptation costs. For social infrastructure, for example, expenditure information may be available for many areas affected by climate change. Other studies of adaptation to climate may be used as a framework.

The acquisition of climate change factors and a reasonable estimate of how much each factor might be expected to change over various time frames will allow us to simulate present and future climates for various geographic areas such as census subdivisions and for various structures such as bridges and roads. Bridges are long-lived structures (at least 50 years by 1991 design standards) and their longevity may be affected by climate change. Other structures are much shorter-lived. These structures are not likely to be affected as much, if at all, by climate change during their normal life cycle although new construction may be altered. Codes and standards for long-lived structures may have to be altered substantially now, but codes and standards for short-lived structures may not have to be changed much or not changed until later. The early imposition of increased standards for bridge design may represent a considerable cost for new construction but a savings in the future, as the bridge will not have to be replaced as quickly as it might have been under the old standards. In some cases, it may be possible to reduce costs due to reduced climate impact.

1.3.2: Sampling Structure

The sampling structure that was utilized in the application of the data collection protocol has been designed to devise stratified unbiased samples. In the data collection we tried to provide maximum geographic, demographic and ecoclimatic spread. Such a spread will allow for the establishment of differences in the adaptation costs between the three sectors for different areas.

For social infrastructure, samples were obtained that are representative of the level of jurisdiction in the public sector (municipal, regional, provincial, federal, other agencies). The samples reflect differences in the size of the area of jurisdiction, differences in the climate for various parts of Canada, differences in population and differences in the quality and quantity of social infrastructure that is provided by each government agency. There were differences in standards, codes and practices across the country for the various aspects of social infrastructure.

1.3.3: Spatial Methods

For social infrastructure, and possibly for other sectors, the data will be tied to a geographic base; the use of a geographic base and a geographic information system (GIS) facilitates overlaying various climate change scenarios on the different levels of government that are involved in providing social infrastructure. In this manner, our sample can be checked for an appropriate distribution. Various climate change scenarios can be overlaid on existing municipal, regional, provincial and federal expenditures, and the resulting costs for a climate change scenario specific to the municipality, region, province, or watershed can be generated. This will be particularly useful in aggregating costs for areas that may sustain high adaptation costs. It will also allow anomalous data to be more easily seen by viewing neighboring areas and areas with similar population and social infrastructure. Census data, municipal financial information, hydrology and a range of natural and demographic data are currently available from Statistics Canada, Geologic Survey Canada and over the Internet. The use of a GIS gives us access to much more information and facilitates the use of that information.

1.3.4: Quantitative Estimation Methods

The fundamental objective of this report was to collect the micro-level data in order to be able to estimate the costs of adaptation to climate change. This report is restricted to the costs of adaptation of the road network (roads, bridges, storm water management systems), and water utilities (drinking water treatment plants, and wastewater treatment plants). The first important task is to try to identify the climate change impacts. For the road network, these impacts are indeed complex and required some detailed engineering information about the effects. We then tried to quantify the costs of these impacts. For the road network we utilized a variety of information, both from the CGCM1 and from other sources. The quantification of costs included the use of standard statistical methods including linear regression analysis. For water utilities, we confined ourselves to two simple impacts: a possible change in water availability for the production of drinking water, and the possible change in precipitation that might change the amount of wastewater that will have to be treated. We considered the CGCM1 projections for annual precipitation for the time periods of 2010 to 2039, 2040 to 2069, and 2070 to 2099. As shown in Chapter 2, we carried out our own downscaling in order to provide the projections for the water utilities in our sample. We then considered the implications of these projections both for the supply of drinking water and wastewater treatment capacities. For at least one case study (Toronto), we outline a model for the determination of the optimal adaptation costs in the form of increased wastewater treatment capacity. For the rest, where increases in wastewater treatment capacity seem warranted, we present a "rule of thumb" estimate of the adaptation cost of the increase in treatment capacity. For the Prairie case studies, a further study at the watershed level will be needed in order to establish the adaptation costs with any degree of reliability.

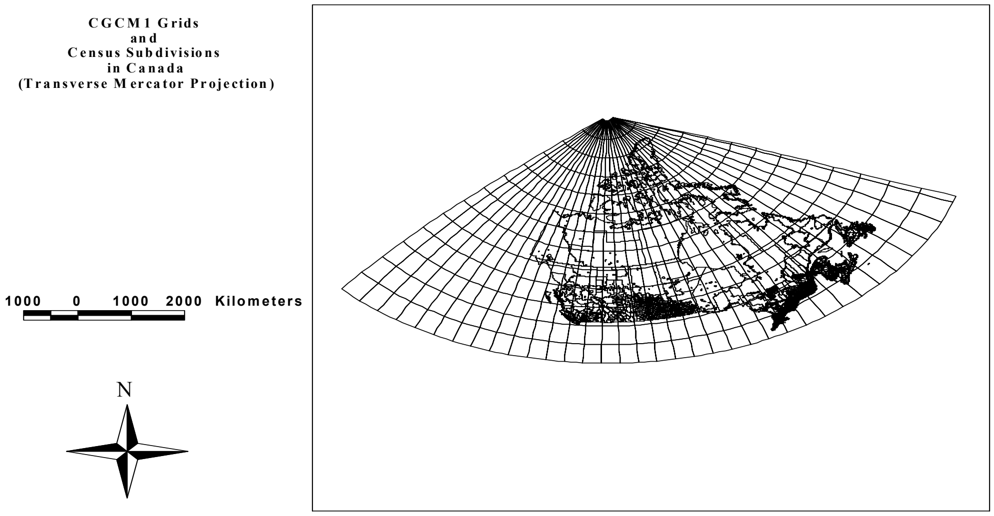
In the analysis of water utilities, again extensive use is made of regression analysis as well as mixed-integer programming models for the determination of the optimal adaptation costs.

1.3.5: Base Maps

A demographic base map for cost aggregation has been prepared from a geographically registered database of the census subdivisions for Canada. The census subdivision base map allowed us access to all of the demographic data that was collected by the Canadian census in 1996. It also allowed us to overlay the anticipated changes for all of the parameters that have been modelled for climate change in Canada. We were able to utilize information on area and population, plus a small amount of contact information. Other demographic information, particularly information based on municipalities, regions or provinces can be tied to the census subdivision units. Census subdivision units closely resemble municipalities. There have been some changes in the boundaries since 1996 and these were taken into consideration when other, post-1996, databases were acquired and merged with the census subdivisions.

A climate change base map was developed from the Centre for Climate Studies data. We successfully downloaded and overlaid the grid boxes and grid points for the climate change scenarios developed for the Canadian General Circulation Model 1 (CGCM1) GG1 model. Figure 1.3.1 shows the CGCM1 grid boxes overlaid onto a map of the Census Subdivisions. Various data for the actual climate change scenarios and the time series were downloaded and converted into database files. The variables that were considered to be the most relevant to costing adaptation to climate change for social infrastructure included minimum, mean and maximum temperature and precipitation.

Figure 1.3.1: CGCM1 Grid Boxes Overlaid on Census Subdivisions



Grid boxes are numbered from “1” in the upper left corner (North Pole) to 455 (east of the Maritimes) in the lower right hand corner. In Figure 1.3.1, the last column on the right has been shortened.

Although cost prohibited their use, digital maps of the Canadian road network are available. These maps are available as CD ROMs of single 1:50,000 sheets. Detailed

road information could then be overlaid onto the Census Subdivision map and the CGCM1 climate grid map to arrive at the climate change scenario for each amount of road kilometrage for each municipality. We could do this kind of detailed work later if requested to do so.

1.3.6: Codes and Standards

A database of various standards and codes that may be affected by climate change was compiled. The Canadian Standards Association, Techstreet Publishers, university libraries and various provincial experts have been utilized as a source of information. Separate files for international, national and some provincial codes of practice were assembled. These codes include, but are not limited to, the design, construction and operation codes for housing, bridges, electrical work, plumbing work and shipping. Many of these codes and standards have climate factors built into their specifications. For structures, such as bridges, buildings and roads, the codes and standards are a reflection of the expected longevity of the structure under a given set of climatic conditions. The full list of relevant codes and standards for Ontario and Canada has been compiled. A full list of the codes and standards for roads, bridges and storm water management systems has been acquired for the country. We examined the standard codes for many structures and determined what the costs or savings will be under a new climate regime for a specific area in co-operation with cost engineers familiar with the codes. Codes and standards are particularly important in establishing the costs of new and replacement structures. Changes in loads, such as occur with wind and snow, and changes in the substructure, such as occur with permafrost and soil moisture, are particularly important with buildings and bridges. Thermal expansion is important for bridges and roads. Drainage and storm runoff, in particular, affect most structures. Codes and standards for design often do not factor into maintenance costs and these must be assessed separately. Operating codes may also be involved in the assessment of the cost of climate change adaptation as climate may alter practices such as ship operation.

1.3.7: Climate Change Factors

We assembled a list of climate change factors that affect adaptation costs. As stated above, we decided to use the CGCM1, GG1 model for our base, as this model is highly regarded in the international climate change science community. There are 18 climate change factors that have been modelled by the CGCM1. Other general circulation models are located at the website of the University of Victoria, Canadian Institute for Climate Studies. These factors include:

- Mean Annual Temperature
- Annual Minimum Temperature
- Annual Maximum Temperature
- Annual Incident Solar Radiation
- Annual Wind Speed
- Annual Diurnal Temperature Range
- Annual Relative Humidity
- Annual Vapour Pressure
- Annual Sea Ice
- Annual Snow Water
- Annual Soil Moisture
- Annual Fractional Cloud Cover
- Annual Evaporation
- Annual Specific Humidity

- Annual Precipitation
- Mean Annual Sea Level Pressure
- Annual Surface Temperature
- Annual Potential Evapotranspiration

The CGCM1 model offers climate change scenarios for a base (1961-1990) and three projected scenarios (2020, 2050, 2080) for the entire country. The data files for each factor include values for 455 grid boxes for each month of the year, aggregations of months and an annual total. The information on changes in the climate change factors is given at a very general level (grid size 3.75 degrees of latitude by 3.75 degrees of longitude). The 18 variables can be merged with the GIS to give us current and projected climate change scenarios for grids that vary in size from approximately 130,000 square km to approximately 15,000 square km. According to the CICS, a finer grid (0.5 degrees of latitude by 0.5 degrees of longitude) will be ready shortly. This refined grid will be an interpolation of the existing grid information and will not represent more localized information on climate change for Canada. Downscaling models are being developed, but at the moment only one is available. There is evidence that a large amount of heterogeneity exists within a 3.75 x 3.75 degree unit and downscaling may be necessary to develop better cost estimates. Downscaling is discussed in Chapter 2.

In addition to the climate factors derived from the CGCM1 model, there are other factors that we have added where reliable information has been available. These include:

- Sea Level
- Inland Water Level
- Inland Ice Cover
- Atmospheric Carbonation Increase
- Frequency of Natural Catastrophes

There are additional climatic factors that will change with global warming and probably should be included in this study. Values for many of these factors can only be acquired either through interpretation of daily climatic data or as combinations of various climatic and non-climatic factors. These include:

- Frost-free Period
- Amount of Spring Runoff
- Frequency of Freeze-Thaw Cycles
- Frequency of Wet-Dry Cycles
- Intensity of Frost-Heave
- Atmospheric Particulates
- Water Turbulence
- Slope Stability
- Seawater Salinity

At present, we do not have a satisfactory means of determining reasonable change scenarios for many of these factors. Projections for future years for factors that are derived from daily climatic data, such as freeze-thaw cycles and wet-dry cycles, are not currently available. There are indications that changes in these factors have already occurred and may be affecting buildings and other structures *(Joan Klaassen, Meteorological Service of Canada, personal communication).*

As reliable climate change scenarios are not available for many factors, we are not able to determine the size of the range that must be included with each climate change factor in order to determine its impact. We have used statistical proxies to arrive at reasonable cost estimates for adaptation to changes in these variables. There are also indications that cost estimates derived from a general model and cost estimates derived from a group of regional models for the same area will be substantially different for some types of adaptation *(Linda Mearns, NCAR, Laval workshop presentation).* It can be seen from the downscaling work that is being done, and comparisons of costs that have been conducted from the general climate and the regional climate models, that more heterogeneity is present at the regional level than at the general level and the difference in costs derived from the general model base to the regional model base can be substantial.

1.3.8: Statistics Canada Census 1996

Information from the 1996 census for Canada has been acquired as a spreadsheet and can be attached to the census subdivision map in the GIS. This information includes such variables as the type of census subdivision (town, county, municipality, etc.) population, area and number of dwellings. There are 5562 census subdivisions for 1996 and they correspond very closely to municipalities. We used this as a base to compile information on websites, telephone numbers, addresses and contacts within each census subdivision (municipality).

It should be noted that there are 8373 polygons in the GIS base map provided by Statistics Canada. This is because there are census subdivisions that contain several islands and the GIS software handles each island separately. Spatial analysis may be complicated because of this.

1.3.9: Municipal Financial Information

We obtained budget information at the municipal (census subdivision) level for the following provinces and territories:

Ontario, 1997
Alberta, 1997
British Columbia, 1997
Saskatchewan, 1998
Newfoundland, 1996/1997
Manitoba, 1998

Nova Scotia, 1997/1998

New Brunswick, 1998

Quebec, 1996

PEI 1999

Northwest Territories 1999

Nunavut – not available

Yukon – not available

The level of detail in this information is fairly broad but does give a breakdown in municipal costs for such areas of expenditure as roads, sewers and water supply. The choice of year for budget information may have to vary, as years that involve local disasters will likely be reflected in government budgets. The year 1998 may not be appropriate for Ontario or Quebec due to the ice storm in eastern Ontario and western Quebec. The year 1996 involved flooding and mudslides in parts of Quebec and 1996 and 1997 involved flooding in Manitoba.

The level of information contained in municipal financial statements is fairly coarse (road expenditures are often rolled up with bridges, ditches and drains) but the municipal treasurers were consulted for more detail. Regional revenues and expenditures are included in this information for some provinces. Provincial/territorial budgets for some provinces/territories were acquired. For many municipalities, the information on expenditures is broken down by capital and by operating expenses, partly because this is the required reporting procedure for the provincial accountants and partly because different municipal departments are responsible for capital expenditures and operating expenditures.

The municipal, regional and provincial budgets provide valuable information for costing the social infrastructure sector. The codes and standards for the province (and the country in many cases) provide us with a basis to determine where, and possibly by how much, the operation and maintenance expenditures may increase or decrease with climate change, although the codes and standards are more valuable in costing the impact of climate change adaptation on new structures. This information was incorporated with questions posed directly to the relevant departments within the government.

1.3.10: Historical Climate Information

An overview account of the climate information for the country has been obtained for 1997, 1998 and 1999. This information was utilized to establish the general weather conditions for municipal, regional, provincial and federal financial information. This information is very coarse but it gives an indication as to whether the expenditures (or any other information that we gather) for any given year are representative of an average year climatically. The year 1997, for example, was the 14th warmest for the country in 50 years of data collection; 1998 was the warmest year on record to date.

1.4: Directions for Future Research

During the course of data collection for this sector, it was noted that data collection could be enhanced for some aspects of the project. These areas included data that were completely missing or unavailable, data that were inadequate in their scope and data that were incomplete. These data have been broken down into climate data, census subdivision data, government financial data and data from other sources.

1.4.1: Climate Data

Climate data are fairly complete for basic climate parameters at a coarse spatial and temporal level. However, for the adaptations and impact research community, downscaled data at a finer spatial level is required. Downscaling will give more accurate information spatially. It may be difficult to compensate for the temporal averaging that characterizes the climate data available for analysis. Daily, and even hourly, data are necessary in the calculation of the costs of certain climate change adaptations. Culvert sizes are a prime example. A culvert capacity can be exceeded easily within a few hours of heavy precipitation. This is equally true for wastewater treatment as shown in Chapter 5. In the end, adaptations must be carried out for extremes. But this information is lost within monthly, and even daily, averages.

1.4.2: Census Subdivision Data

Census subdivision data are complete for the country for 1996 and could be used in their present form for another year. A new census is scheduled to begin in June 2001. Consequently, the old information will not be valid when this information becomes available. Some census subdivisions could not be sampled since there has been considerable amalgamation between municipalities in some parts of the country (Ontario and Quebec, particularly) and it was too difficult to relate costs for the individual municipalities to the costs for the amalgamated municipalities. Several of the municipalities involved in amalgamation declined to participate in the survey as they did not have enough data from previous years to give an estimate of their budget breakdowns.

1.4.3: Government Financial Data

Government financial data were handled at a fairly coarse level. Many of the activities handled under the operating budget for roads were lumped together, even though climate may affect these activities differently. Vegetation control will likely have its own associated climate change costs apart from road maintenance costs. Traffic signals may also be affected differently from the road surface. These costs were not treated separately even though other aspects of road maintenance may be affected by climate change.

Financial information is not complete. While much information was available online, many municipalities and provinces do not, as yet, provide the level of detail in expenditures that is necessary to calculate climate change adaptation costs. In addition, costs are not always aggregated similarly for roads, bridges and storm water management. While the financial reporting system for the municipalities to the provinces is fairly consistent, the municipalities do not keep their records for budget allocations in the same format. The provinces and federal government do not necessarily store their financial information in the same format either. Many of the questionnaires were incomplete for this reason and the provincial online information required clarification.

1.4.3.1: Municipal Financial Information

The sample size for municipal financial information was very small; the response to the questionnaires was not high. More telephone follow up would probably increase the response. Additional contact information could be acquired and more questionnaires could be sent out.

1.4.3.2: Provincial Financial Information

Provincial financial information is not complete for the country. More information is required on various capital and operating expenditures relevant for adaptation costs.

1.4.3.3: Federal Financial Information

Federal financial information was not obtained in detail for road, bridge, storm water management and winter control expenditures. There are a number of international "commissions" that are responsible for bridges, such as the Peace Bridge Commission. These commissions should be contacted separately for future work.

1.4.3.4: Other Government Agencies

Other government agencies that are involved in the construction and maintenance of social infrastructure include the conservation authorities and other intermediate government agencies. There are water authorities in Manitoba and, possibly, similar watershed-based government agencies in a number of provinces. These agencies are often responsible for major storm water management facilities such as dams. Financial information from these agencies and data on how many structures are managed was not acquired.

1.4.4: Other Data Sources

Other data sources, such as the Updated Roads Network provided on CD ROM by Natural Resources Canada, were not utilized. This digital information would have facilitated analysis on the roads network as kilometres and types of roads could be attached to each climate change grid box. Each CD ROM is equivalent to the information provided on a 1:50,000 National Topographic Service (NTS) sheet. Using a GIS, this information could have been merged with the census subdivisions, to give an idea of how many roads of all levels existed within a census subdivision, or merged with the climate change grid boxes to determine how many roads would sustain any particular climate change.

1.5: Summary

- The fundamental objective was to collect the micro-level data in order to be able to estimate the costs of adaptation to climate change. This report is restricted to the costs of adaptation of the road network (roads, bridges, storm water management systems), and water utilities (drinking water treatment plants, and wastewater treatment plants).
- For road and water utilities, various databases on current expenditures at the provincial, municipal and water-utility level were created.
- Time series temperature data from CGCM1, GG1 was downloaded and used to simulate freeze-thaw cycles and frost heave. For freeze-thaw cycles, oscillations above and below freezing for each 30-year climate change scenario block were used as a statistical proxy. For frost heave, the number of months below freezing was used as a statistical proxy. However, these data need to be validated as no statistically significant relationships for adaptation costs could be established in this phase of the work.
- Time series precipitation data from CGCM1, GG1 was downloaded. Experiments with the downscaling software SDSM were carried out. As SDSM downscaling can only be done on a limited basis so far, we carried out our own downscaling for all the sites of water utilities in our sample. Our downscaled data was then used as the "exogenous shock" in order to simulate the impact of climate change.

- There are a number of data gaps that could be filled in at a future date. These data gaps exist for climate data, census subdivision data, financial data and other types of data.

Chapter 2: Climate Change Projections

As indicated Chapter 1, we have used the scenarios generated by the CGCM1, GG1, as the exogenous shock representing climate change. The assumption is that if the climate change scenarios turned out in fact to be real, then the infrastructure under study would be affected and in order to preserve them as assets, or in order to adapt our capital assets to the new climatic conditions, some adaptive actions would have to be taken.

Our key variables of climate change for social infrastructure are taken to be precipitation and temperature. The preliminary question is how the output or projections of precipitation and temperature in CGCM1 can be made useful, knowing that both the base year and the projections in the time series portion of the model represent simulated data. Consider precipitation first as the climatic factor most likely to affect water utilities, both at the production of drinking water stage and the treatment of wastewater stage.

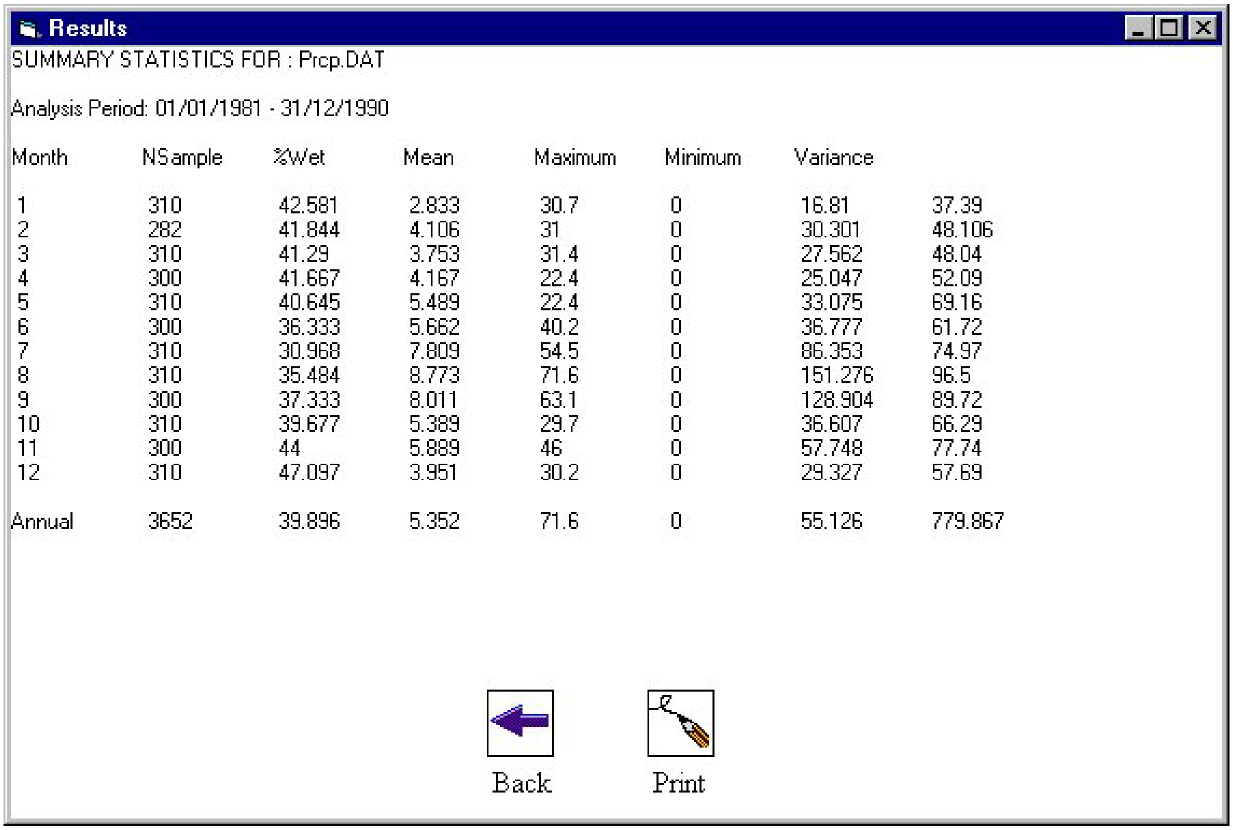
It has been stated that the CGCM1 projections for precipitation would have to be downscaled for particular localities. In the next section we describe our learning experience and our attempts to meet our data needs for projecting climate change and its impact on water utilities.

2.1: Downscaling Experiment with SDSM

To the best of our knowledge, at the time of writing this report (March 2001) very little work has been done on downscaling. Canadian Climate Impact Scenarios (CCIS) group very kindly made some shareware available to use for downscaling. This software is called Statistical Down Scaling Model *(Wilbey et al, 2001)*, which we shall refer to as SDSM. In this section we describe our experiments in downscaling, which were done with the help of Dr Elaine Barrow of CCIS. First, it must be acknowledged that SDSM is in the early stages of development, and at the time of writing could only do the downscaling for sites contained within the CGCM1 grid box centred on 42.68°N, 78.75°W (this includes Toronto). Another limitation is related to the limited amount of large-scale observed climate data which was available when SDSM was first developed; at the moment only 10 years of daily large-scale climate data are available (for the period 1981-1990) and this means that only the corresponding 10 years of daily station data (e.g. precipitation) can be used in SDSM, regardless of whether a longer station record is available.

We carried out the experiment in FOUR steps. The first step was to obtain statistics of the observed precipitation data for Toronto (1981-1990); these were monthly statistics from daily data on percentage of wet days, the mean, the maximum and minimum precipitation and its variance. This is shown in Table 2.1.1 given below.

Table 2.1.1: from SDSM: Daily Precipitation Data for Toronto, 1981-1990



```
SUMMARY STATISTICS FOR : Prcp.DAT

Analysis Period: 01/01/1981 - 31/12/1990

Month    NSample  %Wet     Mean     Maximum  Minimum  Variance

1        310      42.581   2.833    30.7     0        16.81     37.39
2        282      41.844   4.106    31       0        30.301    48.106
3        310      41.29    3.753    31.4     0        27.562    48.04
4        300      41.667   4.167    22.4     0        25.047    52.09
5        310      40.645   5.489    22.4     0        33.075    69.16
6        300      36.333   5.662    40.2     0        36.777    61.72
7        310      30.968   7.809    54.5     0        86.353    74.97
8        310      35.484   8.773    71.6     0        151.276   96.5
9        300      37.333   8.011    63.1     0        128.904   89.72
10       310      39.677   5.389    29.7     0        36.607    66.29
11       300      44       5.889    46       0        57.748    77.74
12       310      47.097   3.951    30.2     0        29.327    57.69

Annual   3652     39.896   5.352    71.6     0        55.126    779.867
```

In step two we carried out multiple linear regression (MLR) equations derived using observed precipitation data for Toronto and National Centers for Environmental Prediction (NCEP) reanalysis data (namely the gridded observed data set), providing large-scale information, with "global" independent variables, such as airflow, F, and vorticity, Z. In this case eight independent variables were used in the model, since all eight resulted in the best fit, with the maximum amount of variance explained. The kurtosis parameter (which describes the distribution of the residuals of the MLR model) was altered to represent a leptokurtic distribution. The default value in SDSM is 12, which represents a normal distribution. We replaced it with 60, using trial and error, to improve the statistics of the synthetic precipitation data so that they more closely matched the observed statistics. The parameter file obtained when fitting the multiple linear regression models contains the coefficients for the MLR equations. This parameter file is used, in conjunction with the independent variables, to generate synthetic precipitation data for Toronto.

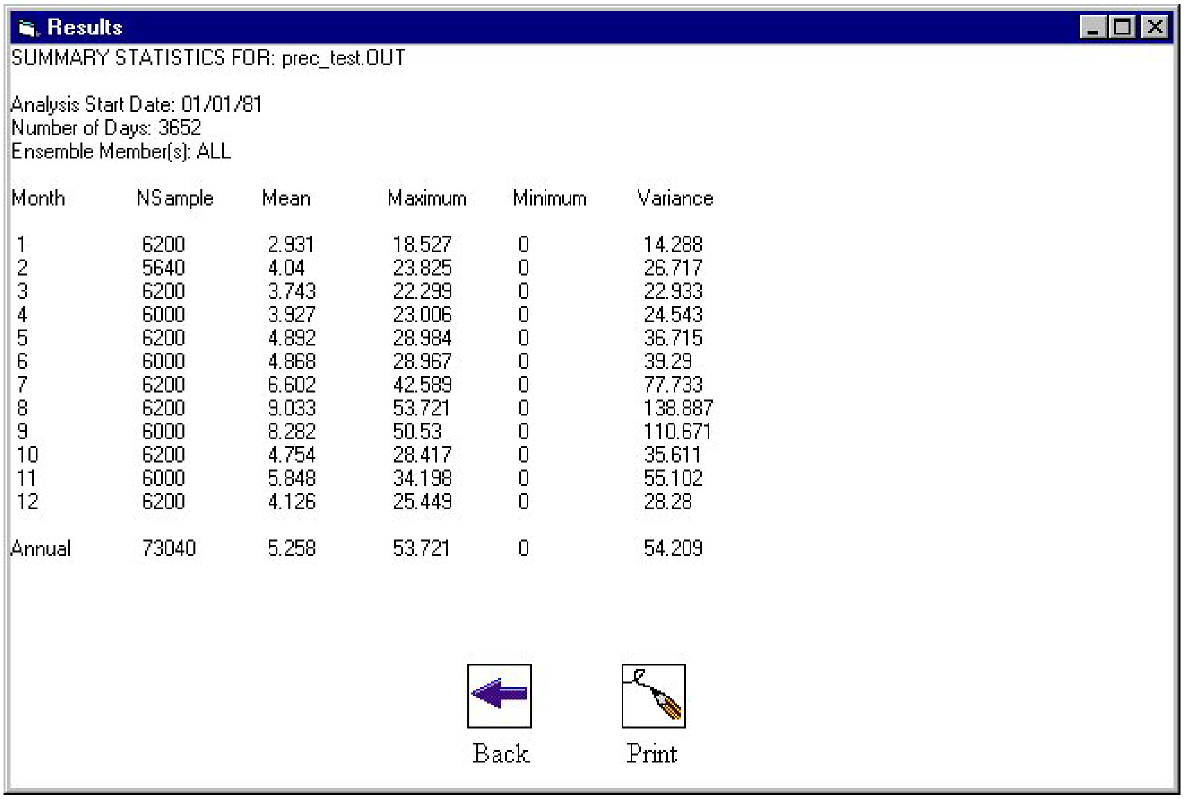
The MLR equations have the form:

Station precipitation = f(independent variables) + error term

If station precipitation generated using the above equation is very close to the observed statistics in step 1 above, then we are confident that we have derived significant relationships between the local and large-scale (NCEP data), particularly if the large-scale (independent) variables explain a large proportion of the variance in station data.

Step 2 indicates the statistics of the station precipitation data that were derived using the MLR equation above and the NCEP independent variables. The objective is to check whether the model is working well or not. Ideally we would have used some independent NCEP data to drive the MLR equations, but in this case only data for 1981-1990 is available, so the same data are being used again. The results are shown in the Table 2.1.2.

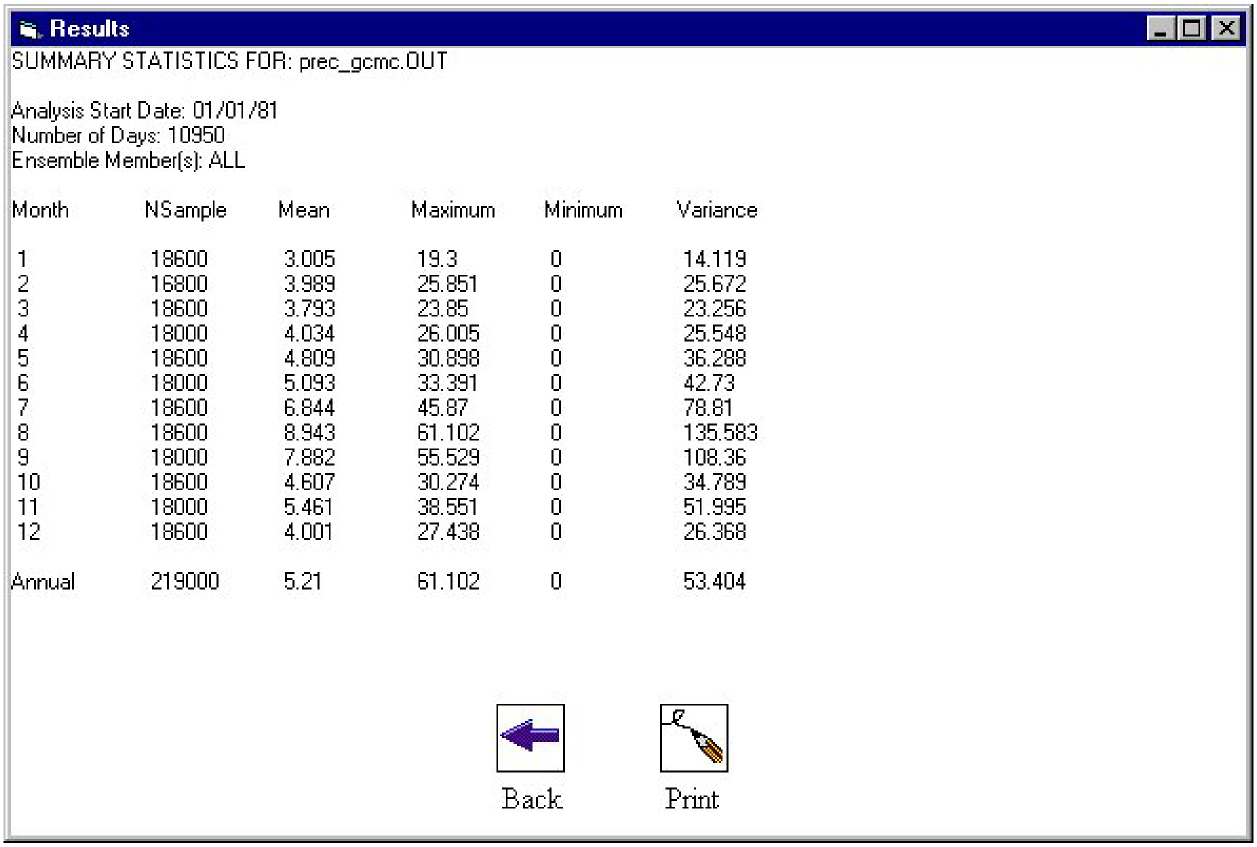
Table 2.1.2: Testing the Toronto Data



```
SUMMARY STATISTICS FOR: prec_test.OUT

Analysis Start Date: 01/01/81
Number of Days: 3652
Ensemble Member(s): ALL

Month     NSample   Mean     Maximum   Minimum   Variance

1         6200      2.931    18.527    0         14.288
2         5640      4.04     23.825    0         26.717
3         6200      3.743    22.299    0         22.933
4         6000      3.927    23.006    0         24.543
5         6200      4.892    28.984    0         36.715
6         6000      4.868    28.967    0         39.29
7         6200      6.602    42.589    0         77.733
8         6200      9.033    53.721    0         138.887
9         6000      8.282    50.53     0         110.671
10        6200      4.754    28.417    0         35.611
11        6000      5.848    34.198    0         55.102
12        6200      4.126    25.449    0         28.28

Annual    73040     5.258    53.721    0         54.209
```

The third step is to obtain station precipitation statistics by using independent variables derived from GCM data for the current baseline period (1961-1990). This gives an indication of the GCM performance: if the statistics are similar to the observed statistics, then we can be reasonably "confident" that the relationships between the GCM independent variables are similar to those of the real data (but see the discussion below). These are summary statistics of the actual daily output from SDSM using GCM independent variables for the period 1961-1990. These are shown in Table 2.1.3.

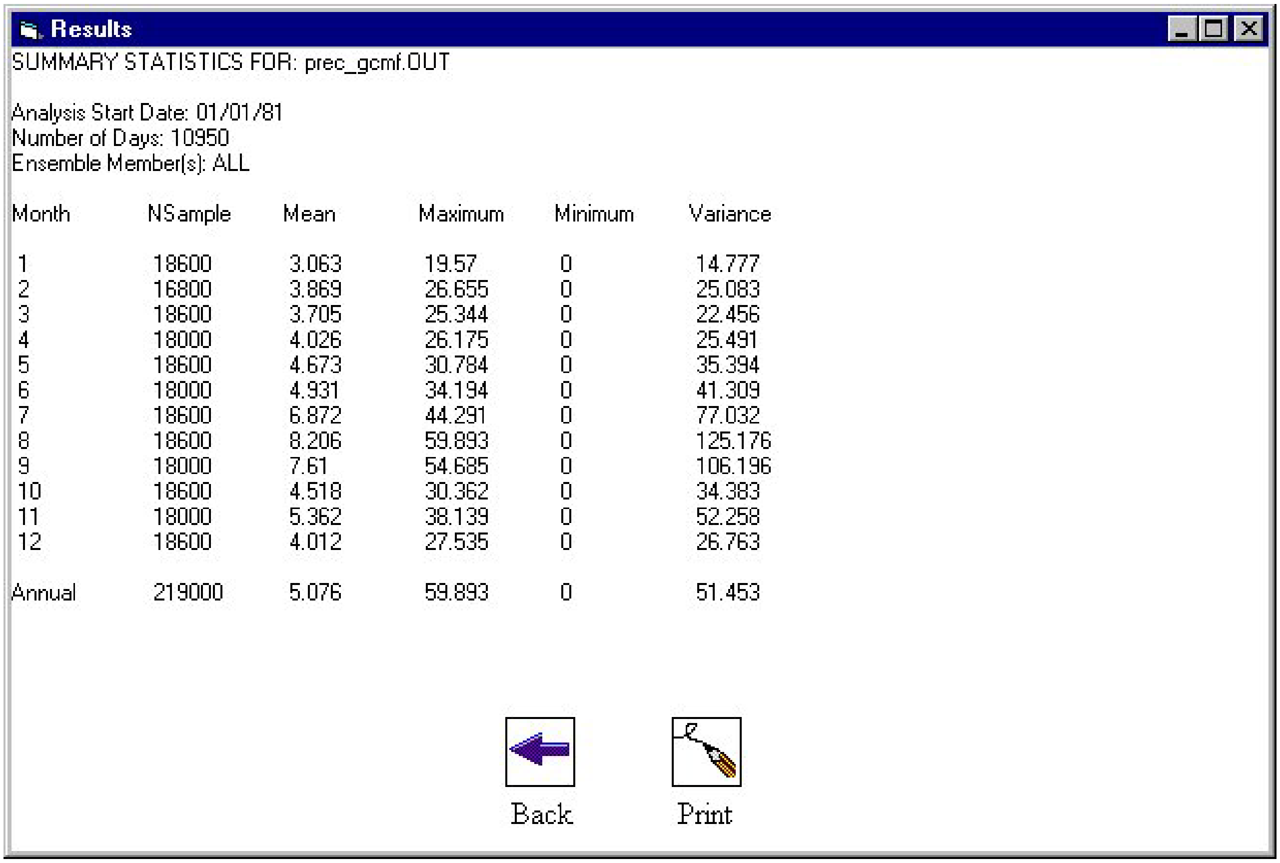
Table 2.1.3: SDSM Summary Statistics using GCM Independent Variables



```
SUMMARY STATISTICS FOR: prec_gcmc.OUT

Analysis Start Date: 01/01/81
Number of Days: 10950
Ensemble Member(s): ALL

Month       NSample     Mean        Maximum     Minimum     Variance

1           18600       3.005       19.3        0           14.119
2           16800       3.989       25.851      0           25.672
3           18600       3.793       23.85       0           23.256
4           18000       4.034       26.005      0           25.548
5           18600       4.809       30.898      0           36.288
6           18000       5.093       33.391      0           42.73
7           18600       6.844       45.87       0           78.81
8           18600       8.943       61.102      0           135.583
9           18000       7.882       55.529      0           108.36
10          18600       4.607       30.274      0           34.789
11          18000       5.461       38.551      0           51.995
12          18600       4.001       27.438      0           26.368

Annual      219000      5.21        61.102      0           53.404
```

The fourth and final step is to obtain SDSM projections for precipitation for Toronto for the period 2040-2069. Recall that we used the GCM independent variables for the 2040-2069 period to drive the MLR equations and to forecast daily precipitation data for Toronto corresponding to the 2050s period. These are the final summary statistics for the downscaled scenario. These final results are given in Table 2.1.4

Table 2.1.4: Summary Statistics for the Projected Precipitation for Toronto, 2050s



```
SUMMARY STATISTICS FOR: prec_gcmf.OUT

Analysis Start Date: 01/01/81
Number of Days: 10950
Ensemble Member(s): ALL

Month      NSample    Mean      Maximum    Minimum    Variance

1          18600      3.063     19.57      0          14.777
2          16800      3.869     26.655     0          25.083
3          18600      3.705     25.344     0          22.456
4          18000      4.026     26.175     0          25.491
5          18600      4.673     30.784     0          35.394
6          18000      4.931     34.194     0          41.309
7          18600      6.872     44.291     0          77.032
8          18600      8.206     59.893     0          125.176
9          18000      7.61      54.685     0          106.196
10         18600      4.518     30.362     0          34.383
11         18000      5.362     38.139     0          52.258
12         18600      4.012     27.535     0          26.763

Annual     219000     5.076     59.893     0          51.453
```

When we carried out the downscaling of precipitation for Toronto, the linear regression yielded an R^2= 0.26, which was not a particularly good fit. Not surprisingly, the downscaled data generated from SDSM were not statistically significantly different from the simulated GCM data for the current baseline period, 1961-1990. The statistical properties of the SDSM downscaled data were virtually identical to the properties of the GCM data for 1961-1990. Naturally we could not use that set of data. Furthermore we would not have wanted to rely on SDSM anyway, since at the time of writing, only 10 years of data were available to calibrate the model, although SDSM could be used for any site located within the CGCM1 grid box centred on 42.68°N, 78.75°W. We therefore had to develop our own methods of downscaling, which are described in Section 2.2. We end this section by making some observations about SDSM, which might be helpful to the software developers as they prepare newer releases of SDSM for use by the adaptations and impact research community. We emphasize that this report is not the place for a full evaluation or critique of all downscaling methods. We are also aware that some of the limitations of all downscaling techniques are fully known to the authors of SDSM *(see Wilby et al., 2001)*. Thus what follows refers exclusively to SDSM.

First, we are not persuaded that the arbitrary trial-and error correction of the kurtosis parameter is theoretically valid. To support our argument, consider the following example. A Russian statistician Eugen Slutzky *(1937)*, who made major contributions to quantitative analysis in economics, took the last two digits of the Russian lottery and generated from it a time series that "looked" like the fluctuating GDP of the UK. He had thus generated a time series of business cycles for the UK. The point about this example is that any time series that merely looks like any other cannot be a proxy for it. For business cycles it would be legitimate to look at the theory and propose the governing mechanism of the business cycle *(see Dore, 1993)*. The governing mechanism will give the model or the set of equations of motion that "govern" the business cycle. In the case of weather data such as precipitation, we know that the latter is a product of complex and nonlinear deterministic and stochastic factors acting together. But as adaptation analysts, we are not competent to claim what the governing mechanism of precipitation is, and nor are we really interested in it! We want to be able to represent climate change with a plausible changing distribution of precipitation that is consistent with other exogenous statistical evidence. We are of the view that the kurtosis parameter that can be changed in SDSM only covers two moments of a given distribution. It would be good to have software that can capture the moments higher than two. Higher moments would enable the analyst to experiment with a wider variety of admissible distributions.

Second, in SDSM, the explanatory variables are restricted to physical variables only, like vorticity and airflow. From our own experience, (see below) dummy variables representing the months of a year, or the number of seasons, should also be allowed by the software, since we are concerned with discerning a changing distribution as a result of climate change.

Third, while recognizing the "low-tech" nature of SDSM based on regression as a merit, it is unclear to us that the 10-year base is adequate to capture long-term secular trends in climate change data. Even a 30-year base that we tried showed only a weakly rising trend in precipitation. It was nevertheless perceptible (see below). And yet it is clear that even with a long enough base, there must be room for the GCM forcings to affect the projected scenarios of precipitation for the next 100 years.

Therefore, in the absence of any reliable and usable downscaling of precipitation, we developed our own proportional downscaling method. It is described in the next section.

2.2: Proportional Downscaling

As noted above, SDSM utilized a 10-year daily precipitation data time series as the base, and then the (global) forcing functions project the data for the next three time slices, 2010 to 2039, 2040 to 2069, and then finally 2070 to 2099. We used a 30-year base of actual precipitation for 1961 to 1990. We refer to the GCM base as the simulated base, and use the subscript *sb*. We replace the GCM base with real and actual precipitation for 1961 to 1990 and use the subscript *rb*.

In the GCM, let the subscript *i* represent the year and the subscript *m* represent the month; hence $p_{i,m}$ is precipitation in year *i* in the month *m*. In addition, let:

gg = greenhouse gases
wv = water vapour
sv = solar variability
ve =volcanic eruptions
ae =aerosols

Then the linearized global forcing functions are:

$$p_{i,m} = f_1(gg) + f_2(wv) + f_3(sv) + f_4(ve) + f_5(ae) + p_{sb,m} \qquad (2.1)$$

$$p_{i,m} = \sum_{r=1}^{5} f_r(\bullet) + p_{sb,m} \qquad (2.2)$$

Next assume that the result of the global forcing is proportional to the simulated base: i.e.

$$\frac{p_{i,m}}{p_{sb,m}} = \sigma_{i,m} \qquad (2.3)$$

Then it follows from the proportionality assumption that our projected downscaled precipitation pp is:

$$pp_{i,m} = p_{rb,m} \bullet \sigma_{i,m} \qquad (2.4)$$

In the case studies of water utilities in Chapter 5, we use Equations (2.1) to (2.4) to generate the downscaled precipitation in which the actual and real base of the precipitation data for the particular locality is used and equation (2.4) is derived for the appropriate GCM grid box. Thus for each particular GCM grid box, we utilize the forcings from that grid box but use the actual and real precipitation data for the base.

We accept that the model given in Equation (2.1) to (2.4) is by no means perfect for proper downscaling. But it shares the "low-tech" property with SDSM. And yet we found (see below) that the precipitation projections based on that simplified model yielded plausible results that could be validated by the statistical properties of exogenous precipitation data.

We are reminded of the dictum:

> If you don't do the best with what you happen to have, you will not do any better with what you should have had!

In fact this dictum is proof by contradiction of Bellman's *Principle of Optimality*. We did not have all the data, because it is not yet available. We did not have time (or the budget) to study and evaluate all the downscaling. So we followed Bellman's Principle in making our downscaled projections.

2.3: Understanding Climate Change

The key question is how do we *understand* climate change in a concrete sense that drives adaptation expenditures. We have done a number of statistical experiments with the projections of the Canadian General Circulation Model (CGCM1), GG1. This particular CGCM1 experiment can be understood as a *particular realization* of climate. Econometricians are wedded to *real and actual* data, be it for precipitation or temperature, or anything else. However, a general meta-principle is that even actual data is only one particular realization. It is a particular realization because it is non-repeatable. An analogy might help. In chaotic dynamics, if a polynomial governing limit cycles has an irrational root, we know that even when the governing mechanism is completely deterministic, the irrational root means that the cycle will *never* repeat: it will be unique, like finger prints, or the fractal structure of snow flakes. Thus we propose that most climate patterns are in the final analysis governed by complex nonlinear interactions among the actual time series, be it precipitation or temperature, and are non-repeating.

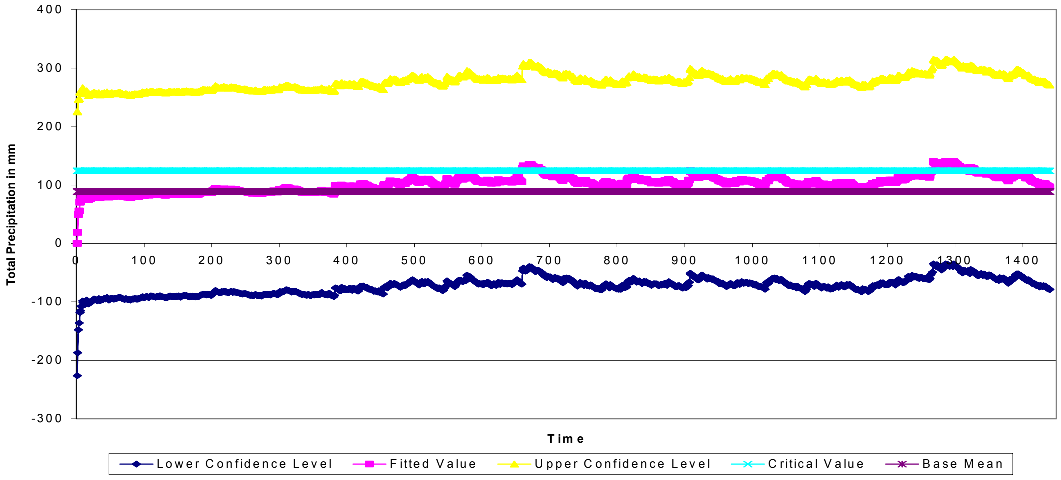
Returning to the projections of GCMs, the particular experiment (GG1) of the particular model (CGCM1) is one possible realization. Therefore actual data has no greater merit than a possible realization of a GCM experiment, *except that actual data will reflect the statistical properties of a given locality.* We could view the GCM experiment as a possible realization of future climate, but naturally it does not include all the forcings and feedbacks which occur in the real world, due to modelling constraints and to our limited knowledge of the forcings and feedbacks. So one could argue that the actual data has more worth than the GCM data since it does include all these forcings and feedbacks, although we cannot identify them all. Indeed, if we could, we would be able to forecast the weather much better and generate future climate with greater confidence.

Thus, it was necessary to use actual data to help with downscaling. In our experiments, we learned that the GCM projections were "too abstract", representing an average of a large grid box, and naturally the projections did not reflect the statistical properties of any particular locality within the grid box. The greater the topographical diversity of the locality, the greater the departures of the statistical properties of the actual data from that of the statistical properties of data generated by the GCM experiment. We found this to be the case for Toronto.

As a result of that finding, we had to "downscale" the projections for all the grid boxes of interest to us. We showed in Section 2.2 that the downscaling from the SDSM did not reflect the statistical properties of local Toronto precipitation data. Therefore we carried out our own downscaling. The theory behind our downscaling was described in Section 2.3.

Having obtained our downscaled projections for Toronto, we set about trying to learn from this data what the distribution was like and what its properties were. We found that our own downscaling led to a very plausible realization that seemed to be consistent with the stylized facts of global warming and the actual data reported by CDIAC. We found that over future time slices, the mean precipitation was rising slowly, and that the variance was also increasing. We tried out an ARIMA fit on our downscaled data, in case the time series was nonstationary. Letting p be the order of autoregressive terms, d the number of times the data is differenced, and q the order of the moving average terms, we found that the (p,d,q) of the best model was (1,0,1). This indicated that differencing was not required (i.e. d= 0), indicating that the projected 100 year time series was stationary. And yet when we plot the ARIMA fitted values (See Figure 2.3.1), we observe a slight upward "drift." This reflects the rising means.

Figure 2.3.1: Fitted Values With 95% Confidence Intervals for ARIMA (1,0,0) Model



The next question is to suppose our downscaled projections are "valid", i.e. they are a particular realization, which is at least better and closer to *actual* data than anything we might obtain from the GCMs. In that case, how do we *understand the changing distribution of precipitation*, a defining characteristic of climate change? As the time series was stationary and yet there was a perceptible upward drift in the means of the time slices, we adopted the following linear regression model to *bring out the changing distribution of precipitation.* We regressed precipitation on a constant and eleven dummy variables. The constant "picks up" the January precipitation mean. The coefficient of the first dummy variable, D1, then yields the *marginal contribution of* the month of February, added to the January mean. The coefficient of the second dummy variable, D3, gives the marginal contribution of the month of March. And so on to December. In this way, we "see" how the monthly pattern of distribution of precipitation is changing over the four time slices.

Note that as scientists engaged in the "art of adaptation to climate change", we are not interested in *explaining* why the monthly pattern of rainfall is changing; the dummy variables are not 'explanatory' variables in this sense. For this reason we do not report the coefficient of variation (R^2), which would be meaningless anyway. But we do report the t statistic for each coefficient. And naturally the overall F statistic for the regression is significant. To repeat, the objective of the regressions is to see how the monthly pattern of rainfall is changing. For Welland, for example, we found that climate change means a wetter spring and a drier summer, followed in the 2040-2079 period with an even wetter winter! We think that this is a very plausible scenario of climate change.

2.4: Summary and Directions For Future Research

In this chapter, the main concern was how to understand and represent climate change as the required shock in the analysis of this report. We accept that the precipitation data from the GCM must be downscaled for the particular localities in which we were interested for estimating adaptation costs. We tried using SDSM for Toronto. At the time of writing, it was the only locality for which we might be able to use SDSM for downscaling. However, we found that the resulting downscaled precipitation did not differ statistically significantly from the GCM simulated base. We therefore devised our own proportional downscaling model described in equations (2.1) to (2.4).

The direction for future research here is clear: we need to do experiments with a number of different downscaling techniques: dynamic downscaling, synoptic weather typing, stochastic weather generation, and when a new release of SDSM is available, try regression-based downscaling with the possibility of using dummy variables. Ideally, trying a number of downscaling methods might help discover whether the projections converge to some common set, or whether there is a large divergence between them.

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Chapter 3: The Theory Of The Optimal Production Of Public Goods And Its Application To Social Infrastructure

In economic theory, the roads network and the water utilities (the subject of this report) would be classified as local public goods, a subclass of public goods. In this report we shall refer collectively to the road network and the water utility network as social infrastructure. But it is the service that is provided by social infrastructure that is the public good, not the capital expenditures. It is the capital assets such as the road network and the water utility network of a country that provide the flow of services that are classified as public goods, including local public goods. The costs of adaptation to climate change can be defined as follows: all expenditures (capital or other) that would be required for the preservation of the same quality and quantity of services provided by social infrastructure. In what follows we review very briefly some elements of the economic theory of public goods to provide the context.

Modern economics defines a pure public good as follows:

1) The use of a good by one consumer does not exhaust the good, so that others can also "consume" and enjoy its benefits. Furthermore, it is impossible in any practical sense to charge a user fee or a price for the use of the good. Thus the good is non-rival and non-excludable in consumption.

2) The cost of producing the good cannot be divided among consumers. If the cost of the good is indivisible, then its marginal cost – the cost of providing one additional unit of the good - must be zero.

Standard examples of public goods that meet the above definition are national defence, flood control, public health programs such as vaccinations and health education. (See below for other examples).

First consider as an example the services of the cable television industry. It is characterized as follows:

1) It is possible to charge those who derive benefit from the use of the good. Moreover, those who do not pay can be excluded from the use of the good.

2) The marginal cost – the cost of providing one additional unit of the good - is positive, and determined by the service and maintenance cost of the extra cable required to service the area, but probably below its average cost, as the cable companies are oligopolies.

We can see that the cable TV does not qualify as a public good; it is in fact a private good. But there are ambiguous examples, such as educational programs for children and for schools.

Next consider non-commercial broadcasting as an example. Non-commercial broadcasting is a pure public good. With commercials we have the case that some beneficiaries can be charged but others cannot. Those who tune in cannot be charged, and the marginal cost of advertised broadcasting to them is zero. But advertisers can be charged and those charges cover the costs. The marginal cost of such advertised broadcasting is positive, not zero.

Somewhere between the two extremes of pure public goods and private goods falls the case of quasi-public goods. A quasi-public good is characterized as follows:

1) It is difficult and perhaps costly to charge those who benefit from the use of the good in some or all cases, but some can be charged.

2) The marginal cost of the good is less than the average cost (there are economies of scale) but it is not zero.

Now consider social infrastructure and its services. Social infrastructure can be considered a quasi-public good. There are economies of scale in the operation of water utilities and also in the construction and operation of a road network. In the case of the latter, on some routes it would be feasible to install a mechanism (electronic or other) for the collection of user fees or tolls. But for most large urban road networks it might be easier to collect the "tolls" through vehicle licencing, or gasoline taxes. In the case of water utilities, the installation of water meters makes it simple to charge user fees, and discriminatory pricing is a widespread practice. Some of these practices in Canada amount to a subsidy for some large industrial users, with a consequent wasteful use of water. But to the extent that water is a public good that promotes health, it may not be wise to cut off water supply to an individual resident who fails to pay. Typically such a resident's water costs would be covered through some other program.

3.1 The Optimal Quantity of a Public Good

In much of economics, the theory of perfect competition is used as an "ideal" type, like frictionless space. Under certain specified assumptions, a perfectly competitive economy results in an optimal allocation of resources. Among the required assumptions is that the exclusion principle holds, as explained above. That is to say, whether or not a person consumes a good depends on whether or not he or she pays the price. Those who pay for the good can consume it, while those who do not pay cannot consume it; that is, the exclusion principle holds for all consumption goods. Second, it is assumed that the benefits from a good flow to the particular consumer who has paid the price. Thus, the consumption of a particular good is rivalrous. If one person consumes a particular good, someone else cannot consume it as well.

But not all goods have both of these characteristics. Goods that do not have the second characteristic - rivalry in consumption - are called public goods. One person can enjoy such goods without reducing the enjoyment they give to others, who may not have paid the price. The classic example is that of the uncrowded bridge. If one individual crosses the bridge, this does not interfere with another individual's ability to cross it. Thus the use of the bridge is a public good.

It is important to note that the market mechanism will not work properly for a public good even if it conforms to the exclusion principle. For example, in the case of the uncrowded bridge, it is perfectly feasible to charge a fee for crossing the bridge and to prevent people who do not pay from crossing it. But it would be inefficient to do so, since excluding those who do not pay reduces their satisfaction but does not increase the satisfaction of others. In the economics jargon, it is Pareto inefficient. Thus although the market mechanism may be applied, it is not optimal to use the market mechanism in distributing public goods, because to do so is inefficient.

If resources are to be allocated efficiently, what is the socially optimal quantity of a public good that should be produced? In the case of a private good, under conditions of perfect competition the optimal output of the private good is at the point where the marginal benefit each consumer would obtain from an extra unit of the good just equals the (marginal cost) of providing that good. The market demand for the good is considered to be the sum of the individual demands. In the case of a public good, the individual consumers consume the total amount of the good and the combined price paid by the individual consumers is the sum of the prices paid by each one. That is to say, optimal output is where the marginal social benefit equals the marginal social cost.

Whereas economic efficiency requires that each consumer's marginal benefit equal marginal cost for a private good, it requires that the sum of the marginal benefits of all consumers equal marginal cost for a public good. But when consumers feel that the total output of the good that will be publicly supplied will not be affected significantly by the action of any single person, they are likely to make no contribution to producing that public good. But they will use whatever output of the good is forthcoming, or become "free riders". Of course this analysis is of limited use for practical decision making since individual demand curves will not be revealed.

The answer to the question of the socially optimal output of a public good is complicated. Public goods are a kind of nonconvexity, and nonconvexities have no 'interior' optimal solutions. Frequently, if the public good is produced under conditions of increasing returns, the social optimum quantity is a "corner solution": produce as much of it as is required given the available tax dollars.

3.2 The Changing Nature of a Public Good

There was a time when it was thought that the set of public goods was large: national defense, health, education, broadcasting, flood control, courts and correctional facilities, and public utilities such as water, telephones, gas and electricity supply, roads, and urban transportation were all treated as public goods. Of these, only national defense, health, education and flood control can still be called "pure" public goods. Technological change has influenced what was previously considered public goods. For example, scrambling devices mean that broadcasting is no longer a public good; even the globally respected BBC Television and Radio are now distributed by private companies. In Britain, many prisons and correctional facilities have been privatized. While urban gas pipelines and the telephone wires may be treated as public "utilities" (only one set of pipelines and one set of telephone lines make sense), deregulation has enabled a number of marketers to use the same hard infrastructure. In the case of telephones, the development of wireless technology means that there is no justification for thinking of telephones as a “public utility”, as there can be a number of suppliers of a wireless telephone service. Electronically detected tolls on roads, such as those on the new 407 ETR in Ontario mean that all publicly provided roads could in principle apply the exclusion, so that the services provided by roads are no longer pure public goods. In Britain even water utilities have been privatized.

The private sector is already involved in education in Canada, although education is a public good in that the benefits of education are not confined to the person who is educated - there are large social gains from an adequate and well-designed educational network of schools, colleges, universities and technical institutes. A well-educated and well-trained labour force benefits private companies as well, and this is well recognized. The same is true of the public provision of healthcare, as a healthy workforce leads to fewer lost production days. But in a publicly provided healthcare system, there is a problem of free riders.

The air traffic control system is clearly a public good, as it makes sense to have one authority providing the service, because of the nature of the costs, and private competition in it would be socially harmful. The administration of justice is clearly a public good, as privatized courts could not dispense justice. Similarly drug safety regulations cannot be in private hands, and this is also a public good. No technological developments have affected or changed the nature of these public goods.

The key question for any good is always the price that will be charged and the quantity that will be supplied, if a good is left to the market place. A single private supplier would supply at a monopoly price by limiting the quantity supplied. That is why the older privately owned utilities (such as telephone monopolies like Bell Canada and AT & T in the United States) were subject to a rate of return regulation, and price increases had to be approved by a regulatory body (the CRTC in Canada and the FCC in the United States).

In this report we are concerned with social infrastructure, such as roads, bridges and water utilities as candidates for the title of local public goods. The dividing line between national and local public goods is not hard and fast. For example, the Trans-Canada Highway is both a local public good and a national public good, irrespective of who finances it. Local public goods such as roads and bridges are subject to "congestion" costs, when inappropriate pricing leads to overuse of a highway, such as the 401. Even with high gasoline taxes, drivers on the 401 do not pay the "full price" for the operation of the 401, and a lot of freight that uses the 401 could, from the point of view of society, be beneficially diverted to the rail network. Unfortunately the tax structure provides a hidden subsidy to users of the 401, which also puts the railway network at a tax disadvantage *(Eric Reguly, The Globe and Mail, March 17, 2001)*. However, the subject of this report is not the question of the socially optimal pricing of highways and water utilities, although we shall return to that below as a possible adaptation measure. The question in this report concerns the costs of adapting this infrastructure to climate change. Traditional economic theory might still be inclined to treat infrastructure as a local public good, and in so far as the road and water network help industry, both have the characteristic of an intermediate public good, sometimes also called a quasi-public good.

As stated above, the road network belongs to the class of local public intermediate good. Such a good can be used as an input in production, and the input can be used simultaneously by a group of firms. Jointness in use prevents the market from extracting a price from firms unless certain firms can be excluded. But even if they can be excluded, they ought not to be on efficiency grounds, as argued above. Informational problems regarding the benefits generated by public intermediate goods are prevalent but the problems may not be insurmountable. As Musgrave *(1959)* points out, the benefits of public intermediate goods may accrue to firms as pure profits or rents and these may be in principle observable.

As argued above, roads could be considered intermediate public goods or quasi-public goods, as it does not make sense to provide more than one direct road from point A to point B. Similarly a water utility is a natural monopoly, with the obvious economies of scale in production. Therefore its output is also a intermediate public good.

Since there are economies of scale, the marginal cost curve is downward sloping, and as the marginal cost of the good is less than its average cost, the optimal quantity cannot be defined. As the optimal quantity cannot be determined, neither can the optimal price. Thus we are again led to view the optimal solution as a corner solution to a nonconvex problem.

Another interesting feature is that the nature of a quasi-public good changes if we introduce a budget constraint in the form of the total allocation given to a local authority or any other jurisdiction. Suppose that a municipality has a given fixed budget, and is required to fulfill its mandate within the constraints of the budget. Then this becomes a problem of the theory of the Second Best. In this theory all simple rules, such as pricing on the basis of marginal costs no longer apply. In this situation, the local authority will attempt to work out what level of road services, etc. it can supply within the budget and what prices it will have to charge in order to fulfill its mandate.

3.3 Climate Change and Social Infrastructure

The question of whether social infrastructure is a local public good, a quasi-public good or an intermediate public good is relevant to the question of whether the services of the social infrastructure should be publicly provided or whether provision should be left to the market place. We have argued that when there are nonconvexities, the social optimum cannot be determined. A fortiori the market place will not be able to provide those services and there is a prima facie case for public provision. However, once the social infrastructure exists, these assets must be preserved when damaged by climate change, whether they are in the private sector domain or in the public domain. It is these additional costs designed to maintain the integrity of the portfolio of social assets that must be identified as the costs of adaptation to climate change. Some would argue that as these adaptation costs would be additional or marginal, the optimal adaptation costs should be determined by the rule that the marginal costs should just equal marginal benefits. In our literature review, we have argued against this rule, in part on the ground that the rule is valid only if we can view climate change as additively separable and therefore marginal. All the evidence it that climate change is NOT marginal.

Finally, there is mounting evidence *(Sturm, 1998)* that in all the OECD countries including Canada, there has been a dramatic decline in public capital expenditure in the maintenance of all avenues of public concern. Thus in Canada there have been declines in real expenditures in health, education, culture, and in social infrastructure. The quality of roads has declined, and as the quality of a road declines, it is used less by the public; the decline in use then enables the authorities to downgrade the classification of the road and reduce maintenance expenditure even further. With enough time, this downward spiral can be documented over and over in Canada. The decline in expenditure has also taken the form of "downloading", i.e. the Federal authorities delegate the responsibility for roads to the provinces, which in turn download the fiscal responsibility to the regional authorities, which in their turn download the fiscal responsibility to the municipalities. Many of the municipalities just do not have the tax base to assume the full financial burden.

The decline in expenditures partly explains the decline in government regulation and quality control. There is a strong argument that the Walkerton disaster in Ontario in 2000 could be partly explained by lack of government supervision following drastic cuts to the budget of the Ontario Ministry of the Environment.

Thus, ideally, the cost of adaptation must be determined on the basis of maintaining the integrity of the service of social infrastructure. In practice, what the quality and level of service would have been without this deterioration may not be easy to establish.

While restoring the integrity of the social infrastructure should form the basis of estimating the costs of adaptation, it is also clear that some structural reforms would also help the adaptation process, by reducing the overuse of highways and reducing wasteful use of water. For roads, Eric Reguly *(op. cit.)* has argued that rail transportation is five times more efficient than trucking freight on the highways. Removing the distorting effects of all taxes taken together would reduce freight traffic on some of Canada's busiest roads and also reduce wear and tear. For water, it has been argued that the declining water price schedules for large industrial users leads to a wasteful use of water. Reducing wasteful use would also reduce the costs of wastewater treatment. As Chapter 5 shows, some of the most important adaptation costs faced by water utilities are in the area of wastewater treatment.

In the two chapters that follow (Chapters 4 and 5) we present our estimates of the costs of adaptation for the road network and for the case studies of water utilities. Except when stated, all dollar figures are current 2001 dollars. Throughout this study, no use of discounting is used. For a justification, see Dore and Burton (2000, Section 2.7 pp39-46). Furthermore, no assumptions about risk aversion are made.

3.4 Summary and Directions for Future Research

We have argued that social infrastructure is an asset that provides services that can be called intermediate public goods or quasi-public goods. The quality and quantity of public infrastructure has declined over the last 25 years in most OECD countries, including Canada. Adapting this infrastructure to climate change would ideally require determining the original quality some 25 years ago and then estimating what the costs of damage due to climate change would be. In practice this may not be possible. The best we can hope for is to estimate the costs of adaptation that restores the integrity of the services provided by the infrastructure. However those costs that can be attributed directly to climate change must be included.

Some directions for future research include:

Measures of adaptation to climate change should also include "demand management", whereby existing distortions in the structure of fuel prices, property and other taxes lead to overuse of highways and underuse of the rail network. A proper study could identify which taxes are distortionary and what tax structure would be equitable so that the rail sector is not disadvantaged. This should be part of the National Transportation Strategy that is now being developed.

The pricing policy of water should encourage conservation and reduce wasteful usage of water. The differential impacts of different water pricing policies should be studied. A good beginning would be to eliminate the declining price schedules faced by large industrial users.

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Chapter 4: Roads and Bridges in Canada

This chapter deals with the main impacts of climate change on road infrastructure and the required adaptation costs. We have broken the road system into its three main components: roads, bridges and storm water management systems. We suggest that the main impacts of climate change will be different for each of these components. For roads, the main impact will be on (a) operating costs such as road repair and winter control and on (b) capital costs to replace temporary winter/ice roads with permanent roads and replace roads on permafrost. For bridges, the main impact will be on (a) capital costs to replace coastal bridges and (b) operating costs for changes in road salt application. Storm water management systems are a small component of the overall costs for the road network. The direct impact of climate on the storm water management system is small; the indirect effect of road washouts is much larger but requires assessment in terms of the frequency of heavy precipitation. Section 4.1 gives an introduction; Section 4.2 gives basic climate information and Section 4.3 covers the jurisdiction of roads, bridges and storm water management systems in the country. Section 4.4 covers the design codes and standards for road, bridge and storm water management design. Section 4.5 provides details of the major components of costs and their associated climate factors and Section 4.6 gives the costs of adaptation. The chapter ends with suggestions for directions for future research and a comprehensive summary of the material covered in the chapter.

4.1: Introduction

There are 900,000 to one million km of roadways in Canada and the expenditures exceed $1 billion Canadian per year to maintain, upgrade, replace and build roadways. The road transportation system moves 90% of the Canadian populace and 70% of freight by revenue (*PaulDeLannoy, MSC, personal communication*).

The road system in Canada can be broken into several components, all of which would be expected to sustain different levels of climate impact and would incur different costs of climate adaptation. Roadways consist of roads, bridges and a drainage system (ditches and drains). Bridges are special structures to carry roadways over various impediments. The drainage system includes both existing waterways and the runoff from the roadway itself. Bridges and culverts may be included as part of the drainage system. The structures and practices associated with roadways have two purposes:

1) Provide safe use of the roadway
2) Ensure the longevity of the road system

These two purposes are often at odds with one another. Safety provisions, such as the application of more than 4.7 million metric tonnes of salt yearly *(Paul DeLannoy, MSC, personal communication)* has a tremendous impact on the longevity of some of the components of the roadway. Safe stopping distances must be maintained, but at a price. Concrete structures (bridges are a prime example) are subject to greater breakdown due to salt application. Bridges not only deteriorate due to salt but, due to increased susceptibility to icing, are also more heavily salted. Climate factors heavily into salt application. Salt is applied to roadways under very specific climatic conditions (below freezing but above –10 degrees C). Federal, provincial, regional and municipal governments are constantly working to balance their capital costs for replacement of existing structures against the costs of maintenance for deterioration of these structures and maintenance for safe operation. In addition, there is wear and tear on roadways from traffic and from climate itself. Roads must be kept free of potholes in order to allow safe driving and the concrete spalling on bridges must be repaired to prevent deterioration of the rebar that provides strength and integrity to the structure. Ditches and drains must be maintained to allow precipitation to flow off the roadway and not become a hazard to driving. They must be designed to handle even rare events; otherwise the structure of the roadway and its safety may be compromised.

Roads, bridges and storm water management systems are designed and constructed at the federal, provincial or territorial, regional (if it exists) and municipal level in Canada. Each level of government has its own road system with associated bridges and storm water management system. Although these systems are usually distinct, there may be some overlap in terms of cost sharing for maintenance or construction. The various levels of government recognize that a single road may carry benefit for transportation locally, regionally, provincially/territorially and nationally. All provinces and territories have roads and bridges that are federally maintained, provincially/territorially maintained and municipally maintained. In some provinces, a regional level of government exists as well, but this is not consistent across the country. The disparity in government structure across the country has resulted in very different distributions of responsibilities for road and bridge construction and maintenance across the country. A very different picture of road and bridge construction and maintenance has emerged as a result. In addition, different codes and standards for roads, bridges and storm water management system construction are in place across the country. Most municipalities and regions follow the provincial standards for road and bridge construction; no federal standard currently exists for road, bridge or storm water management system construction. Municipalities and regions are not required to follow these standards, but they usually do. The more populous municipalities usually employ their own engineers; the less populous municipalities usually employ engineering firms to do the design and construction for them. Maintenance procedures for roads, bridges and storm water management systems are fairly consistent across the country.

4.2: Basic Climate Information

Global warming will benefit winter transportation in most parts of Canada. Reduced winter snowfall will reduce snow removal, salt/sand application and road maintenance in much of southern Canada. However, the risk of increased freezing rain conditions in winter could pose a problem. Melting permafrost in northern areas could also pose transportation problems since the ground must be frozen to allow unrestricted travel. This could shorten the land transportation season in the North and increase costs *(Environment Canada, http://www.ec.gc.ca/climate/primer/sec-6.htm#12).*

Overall, there will likely be a loss of extreme temperatures and less impact on all structures. Climate change appears to be resulting in a loss of the lows but not necessarily gains of higher temperatures *(Phil Jarrett, Environment Canada, personal communication).* There may be changes in the number of freeze-thaw cycles. A change in freeze-thaw cycles is more likely to occur in the heartland with fewer cycles on the west coast *(PaulDeLannoy, MSC, personal communication).* An overall increase of approximately 5°C is expected to occur, accompanied by an increase of approximately 10% in precipitation. Sea level is expected to rise by approximately one metre, due to the melting of the ice cap but more recent research indicates that the rise may be less in the northern latitudes, as the gravitational pull of the ice caps is reduced.

4.3: Roads, Bridges and Storm Water Management Jurisdiction in Canada

There are currently 2,400 km of roads under federal jurisdiction in Canada. There are also 33 bridges and tunnels throughout the country that are maintained by the federal government. The national highway system includes 24 international crossings, roads and bridges under Parks Canada, roads and bridges under Public Works Canada, roads and bridges under the National Capital Commission and roads maintained by the Department of Indian and Northern Affairs. The federal government also contributes to the provincial highway system *(Transport Canada, http://www.tc.gc.ca/pol/en/Report/Highway_Historical _Look/Chapter2.htm)*.

The provincial and territorial governments are responsible for most of the main thoroughfares in the country. The distribution of roads and bridges between the provincial and local governments is quite variable across the country (Table 4.3.1 and Table 4.3.2). In Ontario, the regional government assumes many of the responsibilities for road, bridge and storm water management system construction that would otherwise be handled by the province. Other provinces, such as British Columbia, also have a two-tier local government system. Both the municipal and regional levels of government handle roads.

Table 4.3.1: Road Jurisdiction in Canada (2-lane equivalent)

Province/Territory	**Federal Roads (km)**	**Provincial Roads (km)**	**Municipal Roads** (including Regional) **(km)**	**Total Roads (km)**
Alberta	4,076 (3,973)	18,767 (18,292)	163,307 (159,172)	**186,150** (181,437)
British Columbia	2,626 (2,050)	54,161 (42,279)	27,413 (21,399)	**84,200** (65,728)
Manitoba	2,784 (1,740)	(21,628)	(64,500)	(87,868)
New Brunswick	400 (219)	**21,300** (18,480)	3,671 (3,185)	25,371 (21,884)
Newfoundland	500 (207)	**9,000** (8,747)	4,246 (4,127)	13,746 (12,081)
Nova Scotia	500 (291)	**26,000** (23,371)	2,592 (2,330)	29,092 (25,992)
Ontario	4,939 (2,346)	(28,458)	(137,087)	(167,891)
Prince Edward Island	100 (57)	**5,660** (5,128)	554 (502)	6,314 (5,687)
Quebec	2,536 (534)	**70,000** (29,344)	**92,000** (90,000)	**164,536** (119,878)
Saskatchewan	3,939 (3,181)	32,441 (26,200)	213,620 (172,522)	**250,000** (201,903)
Northwest Territories	800 (351)	**4,400** (3895)	813 (720)	6,013 (4,966)
Nunavut	200 (39)	(412)	(70)	(521)
Yukon	600 (94)	(4,696)	(278)	(5,487)
Total	**24,000** (15,082)	(230,930)	(655,892)	(901,904)

Figures in bold are actual numbers for 2000. Figures in brackets are numbers for 1995. All other figures are estimates.

AB http://www.gov.ab.ca/aboutalberta/index.cfm
BC Annual Report 1999-2000 pg17
NB http://www.gov.nb.ca/dot/mt/maint.htm
NF Gary Goss, Newfoundland Works, Services and Transportation, personal communication
NS http://www.gov.ns.ca/tran/whoweare/tpwglance.stm
PE Helen Blake, Prince Edward Island Transportation and Public Works, personal communication
PQ http:www.mtq.gouv.qc.ca/regions
SK http://www.touryorkton.com/about_body.html

( ) Bracketed data are for 1995; other data are for 2000. The 1995 data are from following sources:
Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

Table 4.3.2: Bridge Jurisdiction in Canada*

Province/Territory	**Provincial Bridges (number)**	**Municipal Bridges (including Regional) (number)**	**Total Bridges (number)**
Alberta	3,800	8,700	12,500 (>1.8m)
British Columbia	3,000	500	3,500
Manitoba	2,400	5,800	8,200 (>2m)
New Brunswick	2,800	150 (est)	2,950 (>3m)
Newfoundland	1,900	100	2,000 (>6m)
Nova Scotia	3,540	280 (est)	3,820
Ontario	2,600	10,000	12,600 (>3.5m)
Prince Edward Island	1,200	50	1,250
Quebec	4,700	3,800	8,500 (>4.5m)
Saskatchewan	950	100	1,050
Northwest Territories	47	3	51
Nunavut	10	0	10
Yukon	100	1	100
Total	**27,047**	**29,484**	**56,531**

**There are an additional 33 bridges and tunnels maintained by the federal government*

AB Alan Kwan, Alberta Infrastructure, personal communication
BC Bill Szeto, British Columbia Ministry of Transportation and Highways, personal communication
MB Wayne Kapar, Manitoba Highways and Transportation, personal communication
NB http://www.gov.nb.ca/dot/mt/maint.htm including causeways
NF Peter Lester, Newfoundland Works, Services and Transportation, personal communication (exclusive of causeways)
NS http://www.gov.ns.ca/tran/whoweare/tpwglance.stm
ON David Lai, Ontario Provincial Ministry of Transportation, personal communication
PEI Ken Hoy, Prince Edward Island Transportation and Public Works, personal communication
PQ http:www.mtq.gouv.qc.ca/regions
SK Howard Yee, Saskatchewan Highways and Transportation, personal communication
NT Larry Purcka, Northwest Territories Transportations, personal communication
NA Doug Sitlin,, Nunavut Community and Transportation, personal communication
YK Bernie Cross, Yukon Community and Transportation Services, personal communication
Canadian federal government (http://www.tc.gc.ca/pol/en/Report/Highway_Historical_Look/Chapter2.htm).

Roads and bridges may be municipal, regional, provincial or federal. The federal bridges are often under the jurisdiction of separate bridge commissions. There are 24 international crossings (bridges or tunnels) under federal jurisdiction. The federal government also owns four intraprovincial bridges, Arthur Laing, Dinsmore (Vancouver), Jacques Cartier and Champlain (Montreal via the St.Lawrence Seaway Authority). The federal government operates the roadway portion of the Victoria Jubilee (Montreal). Through the St.Lawrence Seaway Authority, the federal government owns and operates the Thousand Islands International Bridge (Gananoque), Seaway International Bridge (Cornwall), Beauharnois Tunnel and the St.Louis and Larocque Bridges over the Beauharnois Canal (Valleyfield) and the Townline Tunnel (Welland). Blue Water Bridge Authority (federal) owns the Canadian half of a toll bridge between Point Edward (near Sarnia) and Port Huron (MI) *(Transport Canada, http://www.tc.gc.ca/pol/en/Report/Highway_Historical _Look/Chapter2.htm)*.

In Ontario, the province downloaded a number of bridges to the regions in 1997 and the regions subsequently downloaded a number of bridges to the municipalities in 2000. Following the downloading, several Ontario municipalities have indicated that their bridges may not be in good condition. Some municipalities have posted low load designations rather than rehabilitate or replace their deteriorated bridges. The jurisdiction for a bridge, in most cases, follows the jurisdiction for the associated road (i.e. a bridge on a municipal road is considered to be a municipal bridge).

4.4: Roads, Bridges and Storm Water Management System Design Codes and Standards

The design of roads, bridges and storm water management systems (ditches and drains) varies across the country. Bridges are more consistent in their design standards, roads are fairly consistent but storm water management standards are quite variable, province-by-province. Municipalities are not necessarily required to follow the provincial guidelines but, as many regions and municipalities hire consulting engineers to design their roadways, the provincial standards would be expected to reflect the standards for all roads, bridges and storm water management systems within each provincial boundary. Consulting engineers normally follow accepted provincial practice in order to avoid the issue of liability should there be a problem with their structure in the future. Bridge design standards are fairly consistent across the country at present and, with the completion of the new Canadian Highway Bridge Design Code (CHBDC), will be uniform for all Canadian bridges in the near future. The CHBDC, which has utilized the Ontario Highway Bridge Design Code (OHBDC) will replace all existing Canadian codes including the current CHBDC, CSA Standard CAN/CSA-S6-88, Design of Highway Bridges, its supplement, CAN/CSA-S6S1-1990, Existing Bridge Evaluation, to CSA Standard CAN/CSA-S6-88, Design of Highway Bridges and the commentary S6.1-M1990.

This does not imply that all bridges will adopt the same design, but that the consideration for different factors, including climatic load factors, will be standard. Bridges are large, expensive and (usually) long-lived structures. The results of a bridge failure may be catastrophic, in terms of loss of life and property damage. Consequently, bridges are designed both carefully and consistently in order to avoid this occurrence. The current standards for bridge design and construction are intended to provide a minimum of 50 years' life for a bridge. In fact, most bridges last much longer. The new standards that will become effective with the revised CHBDC (currently undergoing the approval process) are directed toward a 75-year minimum life expectancy. Most of the improvements in longevity are through improvements in materials, many of which have been designed to resist or avoid the effects of de-icing road salt, a major cause of the deterioration of bridges.

Roadways are fairly consistent in their design standards as well. Most provinces use the Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Roads. There are also guides specific to each province, which often exist to accommodate special considerations for climate within the province. Alberta and Saskatchewan have their own guides and Manitoba utilizes the US guidelines in addition to the TAC guide. Roads are often classified by traffic volume and speed and the design follows these classifications. Pavement surfaces are fairly specialized and undergoing constant change, often due to advances in surfacing materials. With pavement surfaces, the ability to handle high traffic volumes (durability of surface) may be compromised by adaptation to higher temperature (less viscous binders). Roads are currently designed to last between 15 and 25 years. The lifespan of a road does not appear to vary much across the country. Much of the difference in longevity between any two roads may be related to traffic volumes.

Storm water management is not standardized across the country and probably reflects the different population densities, history of flooding and normal precipitation for each province. Some provinces have periodic flooding in areas of high population density and have made provision, at least in these areas, for these occurrences. The storm water management systems are usually integrated with bridge and culvert design and with any flood control structures, such as dams and dikes, in these areas. If this practice were not followed, then a storm water management system associated with a highway could potentially compromise the effectiveness of a dam or dike.

4.4.1: Roads

Road design usually follows the Transportation Association of Canada Geometric Design Guide for Canadian Roads. Other standards, such as the American Association of

State Highway and Transportation Officials (AASHTO) "Green Book" are also used. Some provinces have developed their own guides in order to adapt the TAC guide to their specific weather and traffic considerations. Construction practices for each type of road are different. Some provinces have a higher percentage of one type of road than another. Different road types are not evenly distributed across the country (Table 4.4.3).

Table 4.4.3: Road Type Distribution in Canada (1995)

Type	Total Km	Percentage
Freeway	16,571	1.84
Paved	301,348	33.41
Gravel	442,408	49.05
Treated	69,292	7.68
Earth	66,829	7.41
Other	5,455	0.61
Total	901,903	100

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.1: Alberta

Alberta provincial transportation design engineers usually use Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Roads for the structure of the roadway. They also utilize the Alberta publication, "Highway Geometric Design Guide". This guide also takes Alberta weather into consideration for structural aspects of road design. In Alberta it was discovered, for instance, that the super-elevation on curves was too high for Alberta winter conditions. Rather than using a super-elevation of 8%, a 6% increase in elevation around the outside of curves has been stipulated *(Peter Ho, Alberta Infrastructure, personal communication).* Highways are expected to last approximately 50 years in Alberta *(1999/2000 Annual Report, Alberta Infrastructure, pg84)*, although the lifespan of the pavement may be considerably less.

The highway includes the original pavement, roadbed, drainage works and traffic control devices. The road type distribution in Alberta is given in Table 4.4.4.

Table 4.4.4: Road Type Distribution in Alberta (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		3,178	
Paved	631	12,330	25,840
Gravel	2,903	2,426	110,045
Treated	148	282	8,500
Earth	225		13,210
Other			
Total	3,973	18,292	159,172

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.2: British Columbia

British Columbia provincial transportation design engineers usually use the TAC Geometric Design Guide for Canadian Roads *(Patrick Bolger, personal communication)*. There is an additional manual produced by the BC government that is being phased out. There have been some design deviations from the TAC guide. The super-elevation has also been lowered from 8% to 6% for highways in BC as in Alberta *(Gerry Fleming, British Columbia Ministry of Transportation and Highways, personal communication)*.

The road type distribution in British Columbia is given in Table 4.4.5.

Table 4.4.5: Road Type Distribution in British Columbia (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		1,219	
Paved	560	19,094	18,836
Gravel	654	17,670	2,375
Treated	716	2,982	
Earth	120		99
Other			
Total	2,050	42,279	21,399

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.3.1.3 Manitoba

Manitoba provincial transportation design engineers use the TAC Geometric Design Guide for Canadian Roads supplemented with the American Association of State Highway and Transportation Officials (AASHTO) "Green Book" Design of Highways and Streets. The classification of the roadway determines what storm water management considerations are put in place *(Eric Christiansen, Manitoba Highways and Transportation, personal communication).* The road type distribution in Manitoba is given in Table 4.4.6.

Table 4.4.6: Road Type Distribution in Manitoba (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway			
Paved	99	7,915	3,225
Gravel	1,358	6,212	61,275
Treated	10	4,720	
Earth	273		
Other		1,640	
Total	1,740	21,628	64,500

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.4: New Brunswick

New Brunswick provincial transportation design engineers use the TAC Geometric Design Guide for Canadian Roads *(Neil Gilbert, New Brunswick Department of Transportation, personal communication).* The road type distribution in New Brunswick is given in Table 4.4.7.

Table 4.4.7: Road Type Distribution in New Brunswick (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		494	
Paved	89	4,393	2,263
Gravel	94	4,730	
Treated	26	8,863	922
Earth	10		
Other			
Total	219	18,480	3,185

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.5: Newfoundland

Newfoundland uses the TAC Geometric Design Guide for Canadian Roads *(Garry Goss, Newfoundland Works, Services and Transportation, personal communication)*. The road type distribution in Newfoundland is given in Table 4.4.8.

Table 4.4.8: Road Type Distribution in Newfoundland (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		110	
Paved	162	6,393	3,116
Gravel	32	2,241	1,011
Treated	2		
Earth	11		
Other			
Total	207	8,747	4,127

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.6: Nova Scotia

Nova Scotia provincial transportation design engineers use the TAC Geometric Design Guide for Canadian Roads *(Tom Gouthro, Nova Scotia Transportation and Public Works, personal communication).* The road type distribution in Nova Scotia is given in Table 4.4.9.

Table 4.4.9: Road Type Distribution in Nova Scotia (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		1,518	
Paved	141	12,377	2,209
Gravel	108	9,476	121
Treated	0		
Earth	42		
Other			
Total	291	23,371	2,330

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.7: Ontario

Ontario provincial transportation design engineers use the TAC Geometric Design Guide for Canadian Roads. The primary road-building design guide in Ontario is the provincial publication, Geometric Design Standards for Ontario Highways, which was last updated in 1994 *(Michael Thomas, personal communication)*. Some modifications have been made to the TAC standard, including a reduction in the super-elevation from 8% to 6% for most roads. In Ontario, only roads that will have high levels of de-icing chemicals applied on a regular basis will have the higher super-elevation level built into the road *(Darsham Bhatia, Ontario Ministry of Transportation, personal communication)*. Pavement lasts approximately 15 years in Ontario, if properly maintained *(Ontario Ministry of Transportation, http://www.mto.gov.on.ca/english/about/quickfacts.htm)*. The road type distribution in Ontario is given in Table 4.4.10.

Table 4.4.10: Road Type Distribution in Ontario (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		3,868	
Paved	343	20,418	47,965
Gravel	1,308	900	60,225
Treated	271	3,272	25,550
Earth	424		3,236
Other			
Total	2,346	28,458	137,087

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.8: Prince Edward Island

Prince Edward Island provincial transportation design engineers use the TAC Geometric Design Guide for Canadian Roads. Roads have a 15 to 25 year life span in Prince Edward Island *(AlAiken, Prince Edward Island Transportation and Public Works, personal communication).* The road type distribution in Prince Edward Island is given in Table 4.4.11.

Table 4.4.11: Road Type Distribution in Prince Edward Island (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway			
Paved	41	3,618	502
Gravel	8	254	
Treated	0		
Earth	8		
Other			
Total	57	5,128	502

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.9: Quebec

Quebec provincial transportation engineers use their own standards for road design. These standards were developed within the province *(Darsham Bhatia, Ontario Ministry of Transportation, personal communication).* The road type distribution in

Quebec is given in Table 4.4.12.

Table 4.4.12: Road Type Distribution in Quebec (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		4,707	
Paved	294	22,231	66,000
Gravel	194	2,406	24,000
Treated	6		
Earth	40		
Other			
Total	534	29,344	90,000

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.10: Saskatchewan

Saskatchewan provincial transportation design engineers use the TAC Geometric Design Guide for Canadian Roads. This guide is augmented with Saskatchewan's own design manual. Saskatchewan has many roads of low traffic volume, which must be designed for high speed, the cold conditions and snowfall. The terrain is also very flat. There are four classifications of roads in Saskatchewan. Roads are generally designed to last approximately 15 years. The temperature range in Saskatchewan is very high and is hard on the durability of roads but the traffic volumes are usually fairly low *(SukhyKent, Saskatchewan Highways and Transportation, personal communication)*. The road type distribution in Saskatchewan is given in Table 4.4.13.

Table 4.4.13: Road Type Distribution in Saskatchewan (1995)

Type	Federal Km	Provincial Km	Municipal Km
Freeway		49	
Paved	80	11,525	8,021
Gravel	2,281	5,847	116,600
Treated	19	8,729	2,175
Earth	801		45,700
Other		50	
Total	3,181	26,200	172,522

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"

Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.11: Northwest Territories

In the Northwest Territories, road design engineers use the TAC Geometric Design Guide for Canadian Roads. The road surface in the Northwest Territories may last 15 years, which is comparable to the rest of the country. The roadbed itself often has a shorter lifespan, though, than the rest of the country. Due to the problems with high soil water content and permafrost changes, roadbeds in the Northwest Territories may only last 25 years. Roadbeds in other parts of the country will last up to 50 years. The Alberta provincial road design guide is also used *(Larry Purcka, Northwest Territories Transportation, personal communication)*. The Northwest Territories is very dependent upon temporary winter roads for transportation. The road type distribution in the Northwest Territories is given in Table 4.4.14. These figures have been adjusted for the change in road jurisdiction that occurred when the territory of Nunavut was formed. All of the paved roads are found within the Northwest Territories. Approximately 90% of the other types of roads remained within the Northwest Territories after the creation of the territory of Nunavut *(Larry Purcka, Northwest Territories Transportation, personal communication).*

Table 4.4.14: Road Type Distribution in Northwest Territories (1995)

Type	Federal Km	Territorial Km	Municipal Km
Freeway			
Paved	0	187	90
Gravel	296	1492	630
Treated	0	322	
Earth	55		
Other		1894	
Total	351	3895	720

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.1.12: Nunavut

There is no standard for road construction in Nunavut. There are no hard-surfaced roads; all roads are graveled *(Doug Sitlin, Nunavut Community and Transportation, personal communication).* The road type distribution in Nunavut is unavailable for 1995, as Nunavut was part of the Northwest Territories at that time. According to Doug Sitlin, all roads are gravel in Nunavut. According to Larry Purcka *(Northwest Territories Transportation, personal communication)* the division of roads between the Northwest Territories and Nunavut was approximately 9:1 (90% of the roads remained under the jurisdiction of the Northwest Territories after Nunavut separated). An approximation of the road distribution in Nunavut is given in Table 4.4.15.

Table 4.4.15: Road Type Distribution in Nunavut (1995)

Type	**Federal Km**	**Territorial Km**	**Municipal Km**
Freeway			
Paved	0	0	0
Gravel	33	166	70
Treated	0	36	
Earth	6		
Other		210	
Total	39	412	70

Derived from Northwest Territory figures

4.4.1.13: Yukon

Design engineers in the Yukon utilize the TAC Geometric Design Guide for Canadian Roads *(Bernie Cross, Yukon Community and Transportation Services, personal communication)*. The road type distribution in the Yukon is given in Table 4.4.16.

Table 4.4.16: Road Type Distribution in Yukon (1995)

Type	Federal Km	Territorial Km	Municipal Km
Freeway		3	
Paved	0	263	94
Gravel	86	2,744	137
Treated	8	1,686	47
Earth	0		
Other			
Total	94	4,696	278

Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

4.4.2: Bridges

Bridges are structures that vary in definition across the country. Bridges may include culverts and range in span from 1.8 m span in Alberta to 4.5 m span in Quebec (provincial designation). The standards for bridge design are fairly consistent across the country, with the Canadian Standards Association guide, CAN/CSA-S6-88, used in most provinces. Ontario has developed its own standard, the Ontario Highway Bridge Design Code, which will form the basis of the new Canada-wide standard, the Canadian Highway Bridge Design Code (CHBDC). In addition to the OHBDC, many provinces also refer to the American Association of State Highway Transportation Officials (AASHTO).

4.4.2.1: Alberta

Alberta provincial transportation engineers use the CAN/CSA-S6-88 as their standard for bridge construction with some reference to AASHTO and the OHBDC. Alberta climatic data are also employed in the design specifications *(Raymond Yu, Alberta Infrastructure, personal communication)*. Bridges in Alberta are expected to last 50 years *(1999/2000 Annual Report, Alberta Infrastructure, pg84).* Alberta bridges are those structures (including large culverts) that are greater than 1.8 metres in diameter *(Alan Kwan, Alberta Infrastructure, personal communication)*.

4.4.2.2: British Columbia

British Columbia provincial transportation engineers use the CAN/CSA-S6-88 as their standard for bridge construction. There are also considerations made for earthquakes in bridge design. In BC, engineers may often refer to the Ontario Highway Bridge Design Code (OHBDC) as well *(Patrick Bolger, British Columbia Ministry of Transportation and Highways, personal communication)*.

4.4.2.3: Manitoba

Manitoba provincial transportation engineers use the CAN/CSA-S6-88 and the AASHTO Bridge Design Code in the design of their bridges *(Greg Hamilton, Manitoba Highways and Transportation, personal communication).* In Manitoba, bridges are considered to be those structures that are greater than two metres span.

4.4.2.4: New Brunswick

New Brunswick provincial transportation engineers use the CAN/CSA-S6-88 in the design of their bridges. A culvert exceeding a three-metre span is considered to be a bridge *(Neil Gilbert, New Brunswick Department of Transportation, personal communication).*

4.4.2.5: Newfoundland

Newfoundland provincial transportation engineers use the CAN/CSA-S6-88 in the design of their bridges. They also utilize the OHBDC for some aspects of bridge design, such as the substructure, which is over designed by the specifications in the CAN/CSA-S6-88. The substructure ends up being too large using the CAN/CSA-S6-88 guidelines. Newfoundland currently builds its bridges to a minimum life expectancy of 75 years.

Improvements, such as the use of silica fume concrete, are already being employed. Wind is a major factor in bridge design in Newfoundland. The wind loading factors are double the value of wind loads in other parts of the country. Bridges are normally considered to be those structures that exceed six metres in span *(Peter Lester, Newfoundland Works, Services and Transportation, personal communication)*.

4.4.2.6: Nova Scotia

Nova Scotia provincial transportation engineers use the CAN/CSA-S6-88 in the design of their bridges *(Mark Purdes, Nova Scotia Transportation and Public Works, personal communication).*

4.4.2.7: Ontario

Ontario provincial transportation engineers use their own standard, the Ontario Highway Bridge Design Code, in the design of their bridges. Ontario is experimenting with the use of silica fume concrete. In Ontario, bridges include structures such as culverts that exceed three metres span *(David Lai, Ontario Ministry of Transportation, personal communication).* This code is being used as a basis for the new Canadian standard that will be ready in 2001. Ontario provincial bridges are inspected every year. Regions and municipalities in Ontario may inspect every year, but often less frequently *(Ralph Scholtz, Regional Municipality of Niagara, personal communication).* In Ontario, bridges must be rehabilitated every 25 to 40 years and replaced every 75 years *(http://www.mto.gov.on.ca/english/about/quickfacts.htm)*.

4.4.2.8: Prince Edward Island

Prince Edward Island provincial transportation engineers use the CAN/CSA-S6-88 in the design of their bridges *(AlAiken, Prince Edward Island Transportation and*

Public Works, personal communication).

4.4.2.9: Quebec

Quebec provincial transportation design engineers use the CAN/CSA-S6-88 in the design of their bridges *(Michael Thomas, Ontario Ministry of Transportation, personal communication)*. They also have design guides for structures such as bridges. Manual de Conception des Structures – Tome 1, Tome 2 are used as guidelines. Quebec also uses a 4.5 metre span to define a bridge versus a culvert, rather than the three-metre span common to most of Canada.

4.4.2.10: Saskatchewan

Saskatchewan provincial transportation engineers use the CAN/CSA-S6-88 in the design of their bridges. They also use the AASHTO Bridge Design Code, which approximates the OHBDC. In Saskatchewan, provincial bridges are inspected once every five years. On a heavily travelled road, provincial bridges are inspected every two to five years *(Howard Yee, Saskatchewan Highways and Transportation, personal communication)*.

4.4.2.11: Northwest Territories

Design engineers in the Northwest Territories use the Ontario Highway Bridge Design Code (OHBDC) plus the CAN/CSA-S6-88 in the design of their bridges *(Larry Purcka, Northwest Territories Transportation, personal communication)*.

4.4.2.12: Nunavut

In Nunavut, all bridge construction is site-specific. Most bridges are steel girder with wood decking and may span 100 metres. In Nunavut, there are no bridge piers situated in the water *(Doug Sitlin, Nunavut Community and Transportation, personal communication)*.

4.4.2.13: Yukon

Consultants construct most bridges in the Yukon. The CAN/CSA-S6-88 is usually used as the standard for construction *(Bernie Cross, Yukon Community and Transportation Services, personal communication)*.

4.4.3: Storm Water Management

Storm water management system guidelines are very diverse across the country. In most provinces, the design of the drainage system and the level of protection provided for the associated road depend upon the type of road. Major highways have more protection against flooding than local roads. The storm water management system that is designed for major highways will usually have more, and larger capacity, structural components.

4.4.3.1: Alberta

Storm water management in Alberta is based on best practice. Highway culverts are normally designed for one in 25 year flooding, bridge culverts are normally designed for one in 50 year flooding and major span bridges are designed for one in 100 year flood events *(Alan Kwan, Alberta Infrastructure, personal communication).*

4.4.3.2: British Columbia

British Columbia provincial transportation engineers use higher levels of flood protection for their storm water management systems than other parts of the country. Enclosed systems utilize a five-year return period, low volume roads utilize a 50-year period and normal roads use a 100-year return period. Highways and special areas identified by the BC Ministry of the Environment are subject to a 200-year protection level *(Gerry Fleming, British Columbia Ministry of Transportation and Highways, personal communication)*.

4.4.3.3: Manitoba

Manitoba provincial transportation engineers use a number of standards. Primary highways are protected from 2% floods (1 in 50 year events). All flood control structures are at least 0.3 m above the flood level. Secondary roads, which are gravel in Manitoba, are protected from 3% floods. Culverts are sized so as to not be completely underwater. These sizes are determined by the federal/provincial design standards. The exceptions to these standards are the flood-prone areas around the Red River valley. Protection in these areas is designed for a 1% (1 in 100 year) flood. All flood protection structures are to be at least 0.6 m above the flood level. Storm water systems are designed so as not to interfere with the flood protection structures such as dikes *(Ron Richardson, Manitoba Highways and Transportation, personal communication).*

4.4.3.4: New Brunswick

New Brunswick provincial transportation engineers use a TAC hydraulics design manual originating in the 1960s *(Neil Gilbert, New Brunswick Department of Transportation, personal communication)*.

4.4.3.5: Newfoundland

Newfoundland does not have specific standards for storm water system design. Currently the culverts on most roads are designed to handle a one in 25 year flood event. Bridges are designed to handle a one in 100 year event *(Garry Goss, Newfoundland Works, Services and Transportation, personal communication)*.

4.4.3.6: Nova Scotia

Nova Scotia provincial transportation engineers do not utilize any particular manual or standard in their storm water system design. Although 1 in 100 year flood levels may be utilized, best practice guidelines for the area are usually employed *(Tom Gouthro, Nova Scotia Transportation and Public Works, personal communication)*.

4.4.3.7: Ontario

Ontario provincial transportation engineers use a set of standards outlined in the Storm Water Management guidelines posted on the Ontario Ministry of Transportation site. These guidelines are specific to the road classification *(Michael Thomas, Ontario Ministry of Transportation, personal communication)*. According to PHY Directive B100, the Ontario guidelines for storm water management systems, the road classification determines the design flood criteria. There are four classes of roads, urban arterial (freeway), rural arterial (collector road), local road and depressed roadways (subways). Each class of roadway has specifications for associated bridges, culverts, storm drainage systems and stream channels in terms of return periods for precipitation events. The larger, more heavily travelled roadways have greater protection built into their design. Across Ontario there are 3 sets of standards for regulatory storms, the 1/100-year flood (modelled), Hurricane Hazel (1954) and the Timmins Storm (1961). Hurricane Hazel and the 1/100-year flood are used in southern Ontario. The Timmins Storm and the 1/100-year flood are used in northern and central Ontario. The 1/100-year flood is used in eastern Ontario.

4.4.3.8: Prince Edward Island

Prince Edward Island transportation engineers use what they call the Rational Method for designing their storm water management systems. These guidelines are based on 1 in 100 year floods for major roads and one in five or 10-year floods for local roads *(Al Aitkin, Prince Edward Island, personal communication)*. The Rational Method calculates the peak flow rate at a particular location in a catchment due to the runoff contributed from the entire upstream catchment area. The Rational Method utilizes a runoff coefficient, the rainfall intensity and the area of the contributing catchment to calculate peak flow (Q).

$Q = 0.0028\ C\ i\ A$

Where:
C = the runoff coefficient (Refer to *DMM* Design Chart 1.07);
i = the rainfall intensity (mm/hr) (Refer to DMM Design Charts 1.01(a)-(r)); and
A= the area of the contributing catchment (m^2).

(http://www.mto.gov.on.ca/english/engineering/drainage/section10.htm#rational)

4.4.3.9: Quebec

Storm water management in Quebec follows guidelines set out by the Quebec provincial government *(Darsham Bhatia, Ontario Ministry of Natural Resources, personal communication)*.

4.4.3.10: Saskatchewan

Saskatchewan provincial transportation engineers use their own hydraulic manual for storm water management. There are two primary considerations in culvert size. A one in 25 year return period is normally employed with a rider for instantaneous peak flows. The instantaneous peak can be as much as 100% of the one in 25 year standard. This has proven to be very effective in designing culverts. Sask Water (Moose Jaw), the provincial agency responsible for flood monitoring, water supply and sewage for parts of the province, has software that is specific to the design of the culvert size *(Sukhy Kent, Saskatchewan Highways and Transportation, personal communication)*.

4.4.3.11: Northwest Territories

In the Northwest Territories, ditching is designed such that the culverts will handle approximately three times the normal flow. Only when roads are built on rock, is proper grading of the drainage system done for a road. Permafrost thawing is a major problem and often the ditch between the culverts settles and pools before an extreme rainfall event causes any problem *(Larry Purcka, Northwest Territories Transportation, personal communication)*.

4.4.3.12: Nunavut

Storm water management is handled on an ad hoc basis in Nunavut. The roads are not paved surface and ditches are built as required. There are no permafrost heaving problems in Nunavut *(Doug Sitlin, Nunavut Community and Transportation, personal communication)*.

4.4.3.13: Yukon

There are no standards for storm water management system design in the Yukon. There is very little permafrost shifting in this part of the country as well *(Bernie Cross, Yukon Community and Transportation Services, personal communication).*

4.5: The Major Components of Costs and Associated Climate Factors

Costs associated with roads, bridges and storm water management systems can be broken down into two major components, capital costs and operating costs. While there is a certain amount of flexibility in the manner in which these costs are aggregated and reported for roads, bridges and storm water management systems, the financial reports of the municipal and regional governments to the various provincial and territorial governments are fairly consistent in the manner that costs are broken down for roads. The financial statements issued by the provincial and territorial governments are also fairly consistent. Operating costs are those costs associated with maintaining the roads, bridges and storm water management systems as they currently stand. Capital costs are those costs associated with new construction and expansion of the road network with its associated bridges, ditches and drains. Capital costs may also include major road and bridge reconstruction; major reconstruction often involves upgrading. For the purposes of this study, no attempt has been made to correct for slight differences that may exist between municipalities, regions or provinces in their aggregation of these costs. Whether a bridge is repaired (operating costs) or replaced (capital costs) to a large degree appears to be dependent upon the amount of funds that are available for the work, the urgency of the work and the presence of various subsidy programs by one level of government to assist another. Bridges and roads are inspected constantly to determine their condition and assess the need for repair or replacement. In Ontario, all provincial bridges are inspected annually. The Regional Municipality of Niagara inspects its bridges biannually. Local inspection may vary considerably; the municipality of Niagara-on-the-Lake has recently undertaken a bridge inspection for the first time in 25 years. Information on bridge costs (and road costs) varies considerably in its reliability. Inspection reports will usually determine whether repair (operating cost) or replacement (capital cost) is warranted. As the live loads (traffic) are responsible for much of the wear and tear on roads and bridges, the longevity of a road or bridge may be extended through the use of "low load" designations. This prolongs the years of service for a bridge or road and defers capital costs, in many cases, for at least a while. Deterioration of the road network, through lack of capital and operating expenditure, may have occurred and would not be captured by this study. Capital expenditures may vary considerably from year to year and bridge and road inspections only produce a very rough indication of the expenditures that may be required. The costs determined by inspection are usually plus or minus 20% plus an additional 10% for other costs, such as expropriation. Engineering costs must also be added in (an additional 15%). A single bridge estimate, which is usually performed before any work is undertaken, may cost $15,000.

Climate affects both capital and operating expenditures. Climate and other environmental factors constitute one component of the deterioration of roads, bridges and storm water management systems; the impact of human activities is the other. These two major impacts are expressed in terms of “loads” when roads, bridges and storm water management systems are designed. The “live load” is an expression of the impact of human use on a particular structure. Often, the impact of the passage of trucks and cars over a particular structure far outweighs the load imposed by the environment. This may not be true in special instances where the climate, or another environmental factor, is extreme. Designing the components of the road network to withstand earthquakes or permafrost subsidence may far exceed the impact imposed by the “live load” component. At this point, often the judgment of the engineer and an analysis of the risk of failure determine how much extra structural stability must be incorporated into the design of the road, bridge or storm water management system. The road system in British Columbia, particularly the bridges, are already over-designed in terms of climate factors, as considerations for seismic activity must be taken into account already. In the Northwest Territories, considerations for the behaviour of permafrost add almost 50% to the cost of road building per km. A road built on permafrost costs approximately $500,000 per km to construct; a road on non-permafrost costs approximately $350,000 per km to construct in the Northwest Territories *(Larry Purcka, Northwest Territories Transportation, personal communication)*.

4.5.1: Capital Costs

Capital costs are those costs based on new construction. For roads and bridges, there is often a tradeoff between bridge rehabilitation and bridge replacement. Bridge rehabilitation costs are often almost as high as bridge replacement costs. For this reason, it is often more cost effective to replace a bridge, rather than repair it, if inspection indicates that the bridge is badly deteriorated. If the substructure is sound, often only the bridge deck will be replaced, with some savings on the cost of the substructure. Road surface replacement often occurs after the road surface has been repaired a number of times. Road replacement can involve replacement of the surface pavement if the roadbed is still sound or replacement of the sub grade as well if the roadbed is no longer stable. Ditches, drains and other components of the storm water management systems are installed as part of the initial road construction in order to protect the roadbed and to ensure that the road surface does not become submerged and difficult to travel on. Bridges may form part of this system. Capital cost allocation to ditches and drains is generally low (often only 5% of the total roads capital budget) but the impact of an inadequately designed or poorly maintained road system is high.

4.5.1.1: Roads

Roads are designed to withstand the impact of traffic. They are also designed to allow for the safe passage of vehicles at a predetermined speed. Roads have two structural components, the roadbed (sub grade) and the pavement (surface). Both components must be designed to perform the two functions of a road and it is not always possible to accomplish both safety and longevity without tradeoffs in a single design. Road construction involves excavation, the deposit and compaction of underlay, the grading of the surface of the underlay, the application of the pavement surface (gravel, asphalt, concrete), sealing, grading of embankments and stabilization, the construction of curbs and sidewalks and the installation of road signs. Gravel and dirt roads may be only graded. Longevity may have to be compromised for safety. A harder surface allows for safe operation of vehicles at higher speeds but the surface is more susceptible to the effects of freeze-thaw cycles that result in cracking and rutting. One environmental effect may be sacrificed for another; a harder surface may withstand the impact of traffic but may not withstand large diurnal temperature fluctuations. Cost is often a factor in the ability of a road to withstand traffic weight; a deeper sub grade may be constructed and will be much less susceptible to frost heave but the cost of fill can be prohibitive.

The capital costs that are associated with road design result from traffic type and volume, climate conditions and the terrain. High traffic roads must be banked on the curves for safe operation of the vehicles. Wide roads must be sloped to accommodate runoff to prevent water and ice buildup and resulting accidents. While the two major components of road construction are the underlay (sub grade) and the surface material (pavement), the structure of the road may or may not include shoulders, curbs, sidewalks and traffic controls as part of the design of the roadway. Ditches and drains are part of road construction.

The climatic effects on road construction include temperature effects (minimum, maximum, duration and range) and the precipitation effects on the drainage system associated with the roadway. Sidewalks are affected by the same climate components as roads. High heat, extreme cold and fluctuations between the two extremes can do a great deal of damage to both roads and to sidewalks. The type of paving material, particularly the binders that are used, is a function of the temperature.

"Highways and roads are damaged by excessive heat. Asphalt roads soften. Concrete roads have been known to "explode" lifting 3-4 foot pieces of concrete. During the 1980 heat wave, hundreds of miles of highways buckled." *(Adams, C.R. http://www.esig.ucar.edu/socasp/weather1/adams.html).*

Appropriate paving materials and sub grade depths must be used to accommodate the effects of temperature. Freeze-thaw cycles and frost heave (temperature effects on soil moisture) require specific depths of well-drained materials below the road surface to prevent the deleterious effects of these climatic phenomena on the roadbed. Areas with poor drainage may require coarser materials under the road surface to allow water to drain away. Water expands when it freezes and when it melts; water achieves its maximum volume at slightly above 0°C. This property causes problems when soil moisture freezes and thaws, disrupting the stability of the sub grade and causing the pavement to crack. Both the type of material and the depth of the sub grade are important to preventing this effect.

Precipitation affects the capital costs of roads in terms of the drainage system for the road system. Excess precipitation may wash out the road shoulder and undercut the roadbed. Roads do not normally deteriorate as a result of excess rainfall or dryness. If the drainage system for a roadway is properly designed, the water will not affect the road surface or sub grade. Torrential rainfalls may cause washouts when culverts are not designed to accommodate water flow. Precipitation may affect road-building costs directly when it falls as snow in mountainous areas. Avalanches are a climatic occurrence that result from a period of good snow followed by a freeze-thaw cycle, followed by a heavy wet snow. One metre of snow exerts a force of two kPa on a surface

(Phil Jarrett, Environment Canada, personal communication). Roads are often designed with structures (snow sheds) to prevent the blockage of the road where avalanches may become a problem. Climate change may factor heavily into the occurrence of avalanches, particularly in the Rocky Mountains and foothills in British Columbia, Alberta and the Yukon. Snow sheds are common along the Trans Canada Highway in British Columbia. These structures deflect the moving snow from avalanches. Canadian Pacific Railways occasionally constructed their rail lines through tunnels in the mountains where slopes were steep. This was one way of avoiding the blockage of track by avalanches and the maintenance of snow sheds, which could become very costly.

Roads are divided into a number of categories based on the surface type and the traffic volume. Roads may be concrete, asphalt, gravel, surface-treated (oiled, in many cases), earth and winter/ice roads. Roads may be divided into freeway, arterial, collector and local roads based on traffic volume. Freeways are fully controlled access roads designed exclusively for traffic. Arterial roads are roads designed for through traffic. Collector roads are those roads on which traffic movement and access to property have similar importance. Local roads are designed for access to property. The function and volume of traffic that a road sustains may determine the surface type. Freeways and arterial roads are usually hard-surfaced with a concrete, asphalt or asphalt-concrete surface. Collector and local roads may have any type of surface. Concrete and asphalt are more expensive roads to build but they will sustain higher volumes of traffic traveling at higher speeds. Gravel, surface-treated and earth roads do not allow for high speeds and may not allow heavy trucks. Winter/ice roads are temporary in nature and utilize a snow/ice/dirt surfacing material. Road jurisdiction may be public or private. Within the public sector, roads may be maintained by the federal, provincial/territorial, regional or municipal governments. Certain types of roads may be built largely by one level of government versus another but this is not always consistent. Provincial/territorial roads are often concrete or asphalt, largely because this level of government maintains a network of roads that service a large area and large volumes of traffic. Municipal governments are very diverse in the types of roads that they maintain; large cities may have roads under their jurisdiction that sustain the volumes of traffic that provincial/territorial roads sustain. Municipal governments may also maintain only a few earth roads or none at all. The federal government in Canada maintains only a small network of roads for very specialized purposes.

The federal government develops and maintains a road network in the National Parks system (no capital expenditures, just upgrades) including significant highway assets such as the Trans-Canada Highway in Banff, Glacier, Yoho, and Revelstoke Parks, the Yellowhead Highway in Jasper National Park, the highways in Terra Nova, Gros Morne, Cape Breton Highlands, Riding Mountain and Kootenay National Parks. The federal government maintains highways associated with historic Canals, the Chambly and Lachine Canals and the Rideau and Trent-Severn Canals (19 structures). The federal government maintains road network in the National Capital (Commission). The federal public works and government services are also responsible for the capital, operation and maintenance of the British Columbia portions of the Alaska Highway and Haines Road.

Regional governments and a regional level of roads have evolved in some parts of the country. Regional roads are usually intermediate in traffic volumes and road surface types between the municipal and provincial government roads. Different road surface types are usually a reflection of the capital expenditures; concrete and asphalt roads are more expensive to construct than surface treated, gravel and earth roads. Roads may evolve from earth to gravel or surface-treated to asphalt and concrete as the road is more heavily used and the type of traffic changes. Local roads become regional roads as traffic volumes increase. This evolution involves capital expenditure and, as climate changes across the country, there must be different expenditures for these upgrades. Each part of the country will experience different expenditures per km to maintain its road network, depending upon the percentage of paved roads, climate and the terrain. As can be seen from the breakdown of costs per province/territory given in Table 4.5.1, the distribution of these characteristics has an effect on overall expenditures.

Table 4.5.1: Highway Expenditures in Canada (paved, surface treated and gravel) Level by Province/Territory for all Jurisdictions

Province/Territory	**Expenditures per Road Km ($) (1993)**	**Expenditures per Vehicle ($) (1993)**	**Percentage Paved Roads (1995)**
Alberta	8,000	690	23.1
British Columbia	23,000	550	60.4
Manitoba	5,000	500	12.8
New Brunswick	15,000	620	33.1
Newfoundland	13,000	530	74.8
Nova Scotia	12,000	490	62.5
Ontario	22,000	580	43.2
Prince Edward Island	13,000	650	73.2
Quebec	22,000	710	77.8
Saskatchewan	2,000	530	9.7
Territories	14,000		5
Canada	**13,000**	**610**	**35.3**

Road Infrastructure Expenditures, Fuel Taxes and Road Related Revenues in Canada
http://www.tc.gc.ca/pol/en/report/Highway_Infrastructure_Expenditures/Chapter2.htm
Transportation Association of Canada (TAC), "Transportation in Canada: A Statistical Overview", 1995
"Canada's Roadway Infrastructure: Selected Facts and Figures", 1990
"Highways in Canada 1991 Report"
Road and Transportation Association of Canada, Roadway Infrastructure Study, 1987 (updated 1999)

The territories have a large number of unpaved roads compared to other parts of the country but there are high road expenditures per km in spite of this. The Prairie Provinces, Manitoba, Saskatchewan and Alberta, have low expenditures for roads and lower percentages of paved roads than much of the rest of the country.

4.5.1.2: Bridges

Bridges are designed to carry roadways over obstacles of various sorts such as water, railways, other roadways and rough terrain. Bridges, compared to other structures, are exposed to the most adverse environments of loading and climatic change. The climatic loads that must be considered in bridge design include water loads, ice loads, scour, stream instability, temperature effects, wind effects, frost effects, groundwater effects and soil properties. All of these factors contribute to the cost of bridge construction. Bridges over water, railways and other roadways must take clearances into account. Watercraft of various sorts must be able to pass underneath bridges over waterways; tall vehicles must be able to pass underneath bridges over roadways and trains must be able to pass underneath highway bridges over railways.

Bridges fall into a number of types based on materials and purpose. Bridges may be composed of wood, steel, concrete or combinations thereof. Bridges, and their associated capital costs, have been increasing in their complexity and size. The capital cost associated with bridge construction is derived from the costs associated with the superstructure and the substructure. The substructure accounts for 40% of the total cost and the superstructure accounts for approximately 60% of the total cost. Bridge design, and subsequent construction costs, is assessed on the basis of permanent and transitory loads. The permanent load is composed of the dead load (the bridge itself) plus earth and hydrostatic pressure (if applicable). Secondary prestress effects are also part of permanent loads. The live load (traffic, etc.) plus strains and deformations (temperature-associated concrete shrink) plus the wind load on the structure and live load plus the load due to foundation deformation constitute transitory loads. Wind velocity varies with the elevation above ground and the upstream roughness of the terrain. Earthquakes, stream flow, ice pressure, ice accretion and collision load are considered to be exceptional loads.

Loads that are climatic in nature relate to temperature (both minimum and maximum as they relate to coefficients of expansion, heat of hydration during construction), incident solar radiation, wind (extreme events, gusts, horizontal drag, vertical drag, effects on live loads) and ice (accretion, moving ice, static ice). Different parts of a bridge are affected differently by loads/pressures of various sorts. The superstructure of a bridge is composed of a deck, which includes expansion joints and/or bearing and drainage. The substructure is composed of supports and bank protection.

In general, bridges are currently built to a minimum lifespan of 50 years. The current Ontario bridge design code is used as a reference throughout most of the country and is directed toward a 50-year minimum. The reference climate data for the entire country is given in the OHBDC and so these standards are applicable across the country. The new Canadian standards, which will replace the 1991 OHBDC, will raise this minimum to 75 years, mostly based on changes in materials *(David Lai, MTO, personal communication*). In order to combat bridge deterioration, improvements such as silica fume concrete are being used. While climate change has an effect on bridges, the increased costs due to climate will likely disappear with the new standards, which incorporate more expensive materials such as stainless steel rebar. Stainless steel rebar is used to combat corrosion, particularly salt-induced corrosion and the bridge deterioration that accompanies the use of de-icing salts. Salt has a major impact on bridge lifespan and replacement. Bridges in saltwater deteriorate faster and de-icing salt from roads corrodes the structure. Increased salt usage would cause more rapid bridge deterioration and more frequent replacement of decks. When bridges must be replaced, it is often due to the deterioration of the bridge deck. Bridge decks usually deteriorate first. Bridge replacement may only require a new deck if support structure is still sound and pressure tests indicate that it will still carry the required weight.

Water bodies exert three direct effects on bridges, and consequently on bridge capital costs. These include hydrostatic pressure, physical wear and tear from water flow and clearances. Climate change, in the form of water level changes, will affect clearances for watercraft underneath bridges. Inland lakes and rivers will be affected differently from oceans. Inland lake levels, such as those in the Great Lakes system, are predicted to drop due to climate change. Both precipitation and temperature will change and the result may be a net loss of water into these systems. Lake Ontario is predicted to drop by 0.6metres and St.Lawrence River is predicted to drop by one metre at Montreal. The flow from Lake Ontario is expected to drop by as much as 25%. A strong steady easterly or northeasterly wind during the fall when the river is low will cause problems in Lake St.Lawrence and the water level could easily drop by 20-25 cm. Water fluctuation levels due to wind action, creating waves, are a concern in Lakes Ontario, St.Lawrence, St.Francis and St.Louis but water levels are not expected to be higher throughout the system. *(St.Lawrence-Lake Ontario Plan of Study Team, 1999, http://www.ijc.org/boards/islrbc/pos/studiese.html).* Water level drops will affect such structures as the Welland Canal where the canal may not be able to accommodate the draft of large ships but there will be a net benefit to ship clearances. The Navigable Waterways Protection Act requires a clearance of two metres above normal minimum water levels for a kayak. The Holland River, in Ontario, requires a 5.5 m clearance for its bridges *(Barry Putz, Coast Guard, personal communication).* Clearances are specific to the types of watercraft that normally use the waterway. Major waterways require greater clearances. The clearance under the bridges over the Great Lakes is normally 35.5 metres above the minimum water level for Lake Erie level (maximum given as 173.5m) *(Captain Sony, Seaway Commission)*. A drop in the water level for the Great Lakes will result in improved clearances and, possibly, a decrease in costs for new construction of bridges.

Ocean bridges, on the other hand, will probably experience increased costs of construction, as they must be built higher. Sea level is expected to rise 15-95 centimetres by the year 2100 using the temperature projections from models utilizing greenhouse gas emission with sulphate aerosol effects *(Warrick, R.A.et al, 1996).* When bridge height is increased, the causeway leading to the bridge from the road must be built higher as well. Much of the cost of building bridges higher will be in the increased amount of fill that is required to elevate the bridge structure.

Water also exerts hydrostatic pressure on the submerged portion of the bridge structure *(Ontario Highway Bridge Design Code, 1991)*. Hydrostatic pressure changes will occur with sea level changes. Precipitation changes will increase or decrease the water flow past a bridge, which will increase or decrease erosion on bridge substructures. Particles and debris in water and acidity will act on the concrete and scour both the bridge substructure and the surrounding bank materials. Scour is worst during flood conditions and will cause structural failure in three possible ways. Lateral failure may be caused by bank erosion, bottom scour may undermine the bridge piers and the bridge piers themselves may wear away. Most bridge failures are due to scour.

Temperature can also affect bridge structures as sheer cold temperatures stress metal bridge structures. Metal does not respond well to extreme cold; metal and concrete do not respond well to extremes in temperature variation. Thermal expansion/contraction only have an effect on a bridge when the bridge is completely restrained from moving. Overall, seasonal changes in temperature will cause larger movements than daily temperature changes. The lowest daily temperature is just before sunrise and the highest temperature is in mid-afternoon. The top of a bridge sustains more variation in temperature than sides or bottom and integral abutment bridges, which use few or no expansion joints, sustain more temperature effects. Integral abutment bridges are popular in northern climates as de-icing salts used on roads tend corrode expansion joints and increase maintenance costs.

Bridges are not the same temperature throughout the structure. Bridges do not expand/contract uniformly; the bridge deck usually heats up more than the supporting structure. The temperature difference between the top of the bridge and the interior of the bridge may be approximately 5°C in the summer and 3°C in the winter down to one metre depth. The central portion of deep concrete structures is affected by long term variations in mean daily temperature but not diurnal heating cycles. Incident solar radiation has an effect on bridge temperature. The asphalt increases solar radiation effects on bridges but provides insulation. Radiation and re-radiation will affect bridge superstructure temperature (sunny days and overcast days). Temperature changes within a bridge superstructure are a function of shade temperature and the intensity of incident solar radiation. The bridge may actually re-radiate during cold weather. Expansion joints and bearings are utilized in the design of bridges to accommodate thermal expansion and contraction. A temperature drop of 25°C is normally accommodated in the design of expansion joints and bearings; most bridge construction will not be affected by a 5°C increase in temperature but there may be localized problems with bridges as climate change will not be uniform. Complications may arise from the increased use of integral abutment bridges. These bridges span 100 metres or more without utilizing expansion joints. This avoids the cost of replacing expansion joints (which cost approximately $50,000 per joint to replace). It does, however, place this particular type of bridge in a more vulnerable position with regard to climate change, as the temperature maxima are likely to increase. There is less allowance in the structure of the bridge for thermal expansion as the concrete itself is assumed to absorb this stress.

Temperature deformations can occur in bridges due to the non-uniform heating from top to bottom. Temperature deformations are a function of climate and materials. An increase in temperature will have less effect on concrete than on steel. The Ontario Highway Bridge Design Code (1991) divides bridges into three types of bridge superstructure. Type A is composed of steel beam, box/truss systems with steel decks and truss systems above the deck. Type B is composed of steel beam, box, and deck truss systems with concrete decks. Type C is composed of concrete systems with concrete decks. Climate change will affect each type differently. The difference in temperature tolerances for the three types of bridges is illustrated in Table 4.5.2.

Table 4.5.2: Bridge Type and Temperature Design Standards (OHBDC)

Bridge Type	Minimum Temperature	Maximum Temperature
A	15°C below minimum daily	25°C above maximum daily
B	20°C below minimum daily	20° C above maximum daily
C	10°C below minimum daily	5° C above maximum daily

Ontario Highway Bridge Design Code, 1991

Bridge construction may be affected by temperature; bridges must be constructed in cold climates with protection, and concrete releases heat (heat of hydration) when it hardens and sets. The heat of hydration normally dissipates over a few days depending upon the size of the concrete member.

Wind may or may not have an impact on bridge design and costs, depending upon how strong the wind force is in an area. In Newfoundland, wind load is factored into the design of bridges at double the load of the rest of the country. In bridge design, wind is normally gauged on a 50 year return period for bridge structures, luminare support structures less than 16 m in height and overhead signs according to the Ontario code. Wind is normally gauged on a 25-year return period for luminare and traffic signal support structures l6 m or less in height and barriers. Wind is normally gauged on a 10-year return period for roadside sign structures. Topography factors into wind pressure by funneling. A 20% increase may occur in these locales. Wind load can be broken down into horizontal and vertical load for the bridge structure and horizontal load for the vehicles, as wind will also affect the traffic on the bridge. Horizontal wind drag will also change with the presence of traffic signals, trusses, signs and luminares. Both gust and exposure coefficients for wind are calculated in bridge design. Most bridge construction is calculated on similar coefficients with similar costs for wind effects; cabled bridges, however, are very susceptible to wind effects. Wind tunnels may have to be used to simulate conditions for bridge design where wind load may be severe. Wind effects on bridges are more critical for larger span bridges, as there is more exposed surface area. The lateral load for a wind speed of 100 km/hr is 0.0024 MPa. Doubling the wind load on a large, cabled bridge may increase the cost of the bridge by 5-10% depending upon what other loads must be taken into consideration. Wind is also a factor on the "live load"; consequently high traffic bridges are affected more than low traffic bridges. Increases in traffic will pose a problem if wind speeds also increase and the bridge may have to be reinforced. The wind loads on different bridge components are given in Table 4.5.3.

Table 4.5.3: Differences in Wind Effects on Bridge Components

Structural Component	**Windward Load (pounds/square foot)**	**Leeward Load (pounds/square foot)**
Trusses, columns, arches	50 psf	25 psf
Beams	50 psf	-
Large flat surfaces (decks)	40 psf	-

(Ontario Highway Bridge Design Code, 1991)

Climate will have an effect on the cost of bridge construction in terms of the strength of bridge piers, should the temperatures fall and more ice form. According to Christopher R. Adams, *(http://www.esig.ucar.edu/socasp/weather1/adams.html)*, ice jams threaten bridges and can close major highways. There are two types of impact from ice, ice accretion on the superstructure and ice pressure on substructure. Ice accretion, which is expressed as the unit weight of ice, can exert a force of 9.8 KN/cubic metres on a structure. Ice accretion is a function of temperature plus precipitation plus wind speed. The bridge structure itself seldom sustains an impact from ice accretion as it is already designed for much greater forces. Other structures on the bridge, such as the luminaries, must be designed for ice accretion. There will be a cost imposed if these structures must be upgraded. There are currently four ice zones in Canada; most of the ice accretion problems are in the eastern part of the country *(Ontario Highway Bridge Design Code, 1991)*.

Ice pressure is also a consideration in bridge construction and may add to the costs. While scour is the leading cause of bridge failure, there have been bridge failures due to ice jams. The Upper Steel Arch Bridge constructed over the Niagara River, between the United States and Canada, failed in 1938 and was washed downriver after an ice jam caused structural damage to the bridge abutments and hinge supports of the arch *Bridges over Niagara, http://www.iaw.com/~falls/bridges.html)*. When bridge piers are situated in water, they must be sufficiently sturdy to sustain the effects of ice, if ice normally forms in the area. Ice thickens rapidly in the cold and is insulated by snow. Ice is weaker than steel or concrete but can still do damage. Damage to bridge piers may be caused by moving sheets (ice floes), static ice or ice jams. Static ice creates pressure by expansion during freezing. Ice jams result in the spring when unequal thawing occurs. The size of the bridge piers is directly related to the ice strength and thickness. Ice force and strength is determined by its thickness and the pattern of breakup. Climate change that produces more or less ice will have an impact on the cost of bridge design. The ice loads imposed by different types of moving ice are given in Table 4.5.4.

Table 4.5.4 Ice Loads Imposed by Moving Ice

Ice Type	**Ice Breakup**	**Ice Pressure**
Disintegrated	At melting temperatures	400 kPa
Intact	At melting temperatures	700 kPa
Large Sheets	Internal movement of sheet	1100 kPa
All	Below melting temperatures	1500 kPa

Ontario Highway Bridge Design Code, 1991

Ice loads are different for different types of bridges but are only usually applicable to piers of substantial mass and dimensions. Ice problems can be expected for solid shaft piers greater than one metre in thickness where the top of the footing to the centre of ice action is less than three times the shaft thickness. Slender and flexible piers are not suitable. The Confederation Bridge over the Northumberland Strait, between the mainland and Prince Edward Island, is a good example of a bridge that would have to sustain ice impact. Special ice shields are part of the design of this bridge and have added to the cost of construction. Ice, in the form of permafrost in soil, also may have a stabilizing effect on the substructure of both roads and bridges. When climate changes, bridges may be destabilized by the loss of strength in the supporting soil if the temperature increases.

Water, in the form of precipitation and humidity changes due to climate change, may have some minor effects on the capital costs of bridges. High humidity and fog will facilitate concrete breakdown, especially when coupled with increased concentrations of oxides of sulphur, nitrogen or carbon in the air (acidity). The high humidity and fog coupled with the acidic compounds in the air will also facilitate the corrosion of steel.. Wet-dry cycles will facilitate concrete breakdown and the corrosion of steel, especially where acidic compounds may be present. Keeping concrete dry is critical to preserving it. *(Theodor, N.C. and Al-Bazi, G. MTO, 1997).* Carbon dioxide will diffuse into concrete and react in the presence of water, causing the concrete to become less alkaline. If its pH drops below 9-10, the passivity of concrete breaks down and general corrosion can occur.

4.5.1.3: Ditches and Drains

Ditches and drains are associated with the storm water management system for the highway. Ditches and drains are necessary to carry off water that does not infiltrate hard surfaces, such as roads and rooftops. Roads and roofs are usually sloped to carry off rainfall. Drainage systems are usually put in place with road construction. An improper/inappropriate drainage system installation may result in washouts and road destruction and flooding *(Ontario Ministry of Transportation* *http://www.mto.gov.on.ca/english/engineering/drainage/section9.htm)*. Ditches and drains are designed to carry off water that normally flows through an area plus the storm water that results from single events. The components of storm water management include stream channels, storm sewers, roadside ditches, drains, catchment basins and detention facilities. The storm water management system must be considered in conjunction with culverts and bridges, dams and dikes. The hydrologic/hydraulic analysis to determine the design of receiving drainage systems should include calculations of peak flows, water surface elevations and flow velocities at different reference points and for different frequencies for the area that is to be drained.

Roadways must be designed with adequate drainage systems or rainwater will collect and form puddles or undercut the subsurface of the road. There must be sufficient size in culverts that storm water will not erode the embankments around the drain and cause failure of a roadway above it. The design of the storm water management system must include consideration for flow rates, channel erosion, roadway surface flooding, the potential for scour, identification of catchment inputs, selection of precipitation data, culvert analysis, bridge analysis, flow in open channels, flow in storm sewers, flow in the storm water management system and detention facilities. Bank stabilization and grading are also an important component of drainage management. Drainage systems for roadways may also be part of larger water management systems, particularly in flood-prone areas where all of the components of the drainage system must be able to handle large volumes of water in the event of a flood.

Climate directly affects the capital costs of ditches and drains in terms of the size of culverts that are installed; culvert sizes are determined by return periods for extreme events and by the amount of runoff that is normally expected. Larger ditches, drains and culverts increase the cost of the roadway. The calculations that may be used to design storm events and dictate the design of a storm water management system require the type and duration of precipitation, the rainfall records and station and the input parameters. The parameters to be calculated include peak flows, water surface elevations, flow velocities and runoff volumes. The calculations related to precipitation may include specifications for frequencies of precipitation events (low flow, 2 year events, 5 year events, 10 year events, 25 year events, 50 year events, 100 year events, regulatory storm levels). The highway drainage systems must be designed such that the flow of water along the highway is kept within reasonable limits during major storms. In Ontario, the guidelines state that the crown of the freeway should not become submerged, the depth of flow at the crown of an arterial road should not exceed 0.15 metres and the depth of flow at the gutter should not exceed 0.4 metres.

The calculations that determine flow rates translate into culvert sizes, ditch depths and detention facility capacity changes if there is a change in precipitation. Increased precipitation, increased extreme precipitation events and the increase in runoff that accompanies this increased precipitation will result in the need for larger culverts, deeper ditches and larger storm water detention facilities. Road slopes may have to be increased in order to carry off increased amounts of water more rapidly. Decreased precipitation, a decrease in extreme precipitation events and less runoff will result in overcapacity in existing storm water management facilities. Full storm water management computation requires culvert analysis, bridge analysis, flow in open channels, assessment of channel erosion (including roadside ditches), flow in storm sewers, roadway surface flooding, flow in storm water management detention facilities and scour potential to be calculated.

In developing a storm water management system, the before and after development peak flow depths and velocities must be calculated for design flow frequency and regulatory storm flow (e.g. 1 in 100 year event). The post-development peak flow rate must be less than the design flow capacity. The freeboard requirements (for the highway roadside ditches only) are satisfied if the post-development depth of flow is less than the allowable depth of flow and the post-development flow velocity does not cause erosion or scour. The post-development headwater levels, storage volumes and emergency spillway depths are all subject to similar criteria. Detention facilities are usually designed to specifications in terms of surface area and depth. There are specific configurations for inlet and outlets, flow splitters and emergency spillway locations, types and capacities. Emergency spillways should be designed to pass the regulatory flood without failure, under blocked outlet conditions. A change in the type, amount and/or distribution of precipitation for an area may result in a complete change in all of the specifications for a given area.

Climate factors into the costs of construction of ditches and drains, and provision may have to be made for water management during the construction phase. Construction timing, construction phasing, stabilization requirements, siltation fencing locations, access/mud mat locations, catch-basin controls, rock check dam locations, siltation basins, topsoil stockpile storage locations, inspection and maintenance may have to be altered depending upon the rainfall and flows during construction.

4.5.2: Operating Costs

Operating costs are those costs associated with maintaining the use of the road, bridge or storm water management system. Operating costs may also involve activities such as collecting tolls for roads and bridges and the raising and lowering of lift bridges. These costs are not likely to be affected by changes in climate. Operating costs that will be affected by climate change can be broken down into the maintenance costs associated with roads, bridges, storm water management systems and winter control costs. Winter control costs, where they exist, are often reported separately from other road system costs. Winter control is often a very high proportion of the operating costs for a roadway; it is often in the best interests of good fiscal management to track these expenditures separately. Operating costs may be reported as capital costs when the magnitude of the cost of repairs becomes large. Often, at this point, a decision must be made whether to repair or replace. An analysis of the expected lifespan of the structure, whether it is a road, bridge or drainage system component may be made in order to determine if repairs will extend the life of the structure enough to justify the expenditure. If repair is no longer cost-effective, replacement will be undertaken.

4.5.2.1: Roads

The operating costs for roads are predominantly maintenance costs although there may be features such as tollbooths that are not directly involved in road maintenance and are included in the operating costs for the road. Maintenance of the roadway for asphalt and concrete roads usually involves hardtop or concrete patch and washout repair, cleaning, flushing and sweeping, sign repair or replacement, marking and painting. For gravel roads, the road must be patched, washouts repaired and resurfaced. Chemicals for dust control, such as calcium chloride, are often applied. Shoulders on roads, signs, curbs and sidewalks must be repaired or replaced. Often replacement of curbs is done at the same time as road replacement or resurfacing. Vegetation control is also part of road maintenance. Vegetation control involves tree-trimming, brush clearing, mowing and spraying.

Operating costs for roads include maintenance costs for structures and features that allow safe use of the roadway and that will prolong its lifespan. When maintenance costs are reduced, safety may be compromised and the longevity of the roadway may be reduced, resulting in the need for greater capital expenditures. The environment and human activities will cause deterioration of a road over time; expenditures on operations reduce the need for costly replacements later. There is a point in time where a roadway must be replaced; it is no longer cost-effective to continue to repair it. Often this point is coincident with the need to upgrade the road for increased traffic or to accommodate new materials or new structural elements in the design. Roads may be patched over top of patches but the road surface becomes progressively bumpier and traffic flow will eventually be impeded.

New materials that are being utilized in road construction may alleviate some of the need for road repair. Much of the repair of roads is related to the formation of potholes. The formation of potholes is related to the capacity of the road surface to withstand the expansion and contraction of the road surface itself and water that may seep into the pavement. The incorporation of materials such as crushed rubber tires improves the ability of the road to withstand expansion and contraction. The need for road repair may diminish in the future and operating costs may subsequently drop with these improvements.

4.5.2.2: Bridges

Bridge maintenance activities involve repairs to the bridge deck, repairs to culverts, repairs to guard rails, repairs to support structures (structural steel costs $1.50-$2.00 per lb $US 1995), washing, which is often done with road cleaning, repairs to wing walls and bank stabilization (especially bridges over water), repairs to the lift mechanisms if present and repairs to bridge drainage systems. Bridge maintenance may also involve sealing. Keeping water out is the key to the durability of concrete and steel in bridges. Concrete and steel are subject to attack by salts and sulphates. Concrete and steel are subject to attack by sulphates from rain (acid rain) and groundwater. This may necessitate the replacement of one type of cement with a sulphate-resistant type. Freeze-thaw cycles are very hard on concrete and dense, well-compacted cement must often be used where freeze-thaw cycles are a problem. Alkali-silica reactions are an internal reaction in the concrete that causes swelling and cracking. High alumina cement conversion in conjunction with high humidity will very rarely cause a reaction. Salt crystallization in concrete will result from the movement of salts by capillary action and rise of salt-bearing water. De-icing salts causes salt scaling on horizontal slabs.

Bridge maintenance is intended to minimize effects of traffic load, environmental strain and de-icing chemicals. The environmental strain on bridges results in deterioration due to a number of factors. These factors include creep, shrinkage, humidity, moisture, swelling and variation in vehicular load such that expansion devices may not behave properly. Climate affects bridge maintenance in terms of the amount and the type of maintenance. Climate can also affect the amount of maintenance on bank stabilization structures. Wetter soils will slump. Banks may destabilize from water–freeze thaw, wave action, slumping from heavy rains and wave action. Waves and salt water will affect support structures. Freeze-thaw, wet-dry, salt, high temperatures and low temperatures will affect surface concrete and cause it to spall and crack which will cause rebar to be susceptible to corrosion. Exposed rebar corrodes more easily and the bridge will lose its strength and structure if the rebar is damaged. Damaged rebar leads to bridge deterioration and replacement. Bridge drainage systems may also be clogged by debris, causing poor drainage on the deck. The bridge substructure may be damaged by ice, both static and moving, and may need to be repaired.

Bridge decks, especially the expansion joints, are particularly susceptible to corrosion from de-icing salts that are applied to the roadway on the bridge. The substructure is less susceptible to the effects of de-icing chemicals. The roadway on a bridge often "ices up" sooner and more than the road itself. More de-icing salts may be applied to bridges as a consequence. Salt has the greatest effects on the metal components of a bridge. The metal components of a bridge include the expansion joints; lift mechanisms, bridge drainage systems and guardrails. Salt can also cause or enhance concrete spalling. Concrete spalling results in the ultimate deterioration of the concrete and a loss of strength in the structure. Concrete spalling also exposes the reinforcing materials in the concrete. The reinforcing materials, or rebar, are susceptible to corrosion unless non-metallic, galvanized or stainless steel materials are utilized. The new standards for bridge design for Canada (CHBDC) will utilize corrosion-resistant materials in the construction of new bridges. Other de-icing chemicals are available such as acetate compounds that do not corrode metal to the same degree as the chlorides (salts). Bridges that are constructed largely of steel, such as the large suspension bridges forming the Thousand Islands Bridge from Gananoque, Ontario to New York, utilize acetates instead of chloride salts. The cost, however, is much higher. Sodium magnesium calcium acetate costs approximately $2000 Canadian per metric tonne, whereas sodium chloride (road salt) costs $65 Canadian per metric tonne.

Bridges may be constructed from aluminium and iron, concrete, steel, stone or wood. Aluminium and iron are denser than concrete, which is denser than stone or wood. Both concrete and steel are subject to corrosion; concrete will spall and the steel reinforcing mesh within the concrete will corrode if exposed. Wood tends to decay. Many of the wooden bridges in the country have been replaced with concrete and steel structures as they became unusable. Covered wooden bridges still exist in eastern parts of Canada, through Quebec and the Maritimes. The primary purpose of a covered bridge was to shed snow and stop the decay of the bridge deck but covered bridges are usually kept as historic sites and tourist attractions. Most highway and railway bridges in service in Canada are composed of concrete and/or steel. Railway bridges were often metal truss bridges as these bridges were designed for more weight. Railway bridges do not usually require de-icing salt to maintain their safe utilization by trains; the weight of the train is usually sufficient to clear any ice. Railway bridges are not subject to the same deterioration from de-icing salts as steel highway bridges. Highway bridges may be waterproofed to reduce maintenance costs and compounds such as urea and the acetate compounds may be used to reduce corrosion.

Maintenance practices on bridges must deal with corrosion and fretting fatigue. Fretting fatigue is caused by two metal surfaces continuously subjected to small repetitive sliding motions. An increase in contact pressure results in a decrease in the fretting life if pressure is high enough to prevent sliding movements. A corrosive environment decreases fretting life. Bearings and expansion joints are subject to both fretting fatigue and road salt corrosion. High hardness, higher strength steels are more susceptible to fretting fatigue than lower strength structural steels. Corrosion problems with bridges began with the introduction of salt in the 1960s and the damage from de-icing salts began to show up in the 1970s. There are more problems with deterioration in modern bridges than older bridges because modern bridges are longer and have more expansion joints. Deterioration in bridges may occur as a result of the daily cycles of expansion during the day and contraction at night. Concrete and steel bridges also expand in the summer and contract in the winter. In order to minimize these effects, bridge maintenance is often performed annually. Bridge preventative maintenance involves cleaning all exposed surfaces, drains, bearings and seats. Minor repairs are also done as part of preventative maintenance. Bridge inspection is also often performed periodically to determine the overall condition of the bridge. There are a number of factors that determine the amount of bridge maintenance. The total bridge deck area is a major determinant of bridge operation and maintenance costs, as is the age of the bridge stock on average. Climate factors that may influence the maintenance costs include the average number of freeze-thaw cycles per year (number of days during which the minimum and maximum temperature recorded are above and below the freezing point. The amount of de-icing road salt that is applied per year is also a factor. The traffic intensity, which can be described as the total amount of vehicle-km/ street area, is also a factor. Another factor in bridge maintenance costs is the presence of bridges whose construction predates improved concrete composition.

4.5.2.3: Ditches and Drains

Operations costs for ditches and drains include such activities as the cleaning and clearing of the drainage system, repairs to culverts and digging of ditches. The drainage system must remain clear and operate at its design capacity in order to be useful and serve its function properly. The storm water management system is a means of extending the lifespan of the road and keeping it safe. Culverts and drains may become clogged and not function if debris accumulates. Storm water detention areas may accumulate silt and will not function at capacity. Ditch and drain maintenance also involves vegetation control. Vegetation can overgrow and interfere with the functioning of the drainage system. Grass mowing and brush control in some types of ditches is important to maintain flow. Vegetation control also prevents the trapping and accumulation of debris. Vegetation growth is affected by climate. Increases and decreases in temperature and precipitation will affect vegetation growth and the amount of mowing that must be done. Heavy rainfalls wash debris, including soil materials and tree limbs, into the storm water management system. Complete clogging of the system will occur if these materials are not periodically removed. The silt that is washed into the storm water management system through erosion caused by heavy rainfall will also accumulate in storm water detention areas and may have to be periodically removed.

4.5.2.4: Winter Control

Winter control includes such activities as road patrol, sanding, salting, plowing and snow removal, culvert thawing and the installation of snow fencing. The amount and type of winter control varies by municipality. Some municipalities, such as the City of

Vaughn, offer clearing of sidewalks and windrows as part of their snow removal services. This extra service will substantially inflate winter control costs. Some municipalities do not provide as much side street clearing as other municipalities and their winter control costs are therefore much lower than their climate would normally reflect. Winter control is particularly affected by changes in temperature and precipitation resulting in more or less snow and ice. Wind may be a confounding factor in winter control. Some of the costs of winter control may be exacerbated by the design of roadways. More frequent snowfalls may increase the costs of snow clearing, sanding and salting if the snowfalls are sufficiently heavy. Greater amounts of falling snow or an accumulation of snow with no thawing in between snowfalls may necessitate the removal and stockpiling of snow, which is very expensive.

Wind causes snow to blow, decreasing visibility for snowplow operators and accumulating in drifts. Blowing snow can therefore increase removal costs. Fluffy snow begins to move when the wind speed approaches 20 km/hr and hard snow may resist movement up to 85 km/hr wind speeds. Snow usually ceases to blow when the wind speed falls below 24 km/hr. Most snow transport is within one metre of the road surface. If the blowing and drifting of snow is severe on highways, it may be necessary to install snow fencing and incur the additional costs associated with this activity *(Tabler, R. 1994).*

Greater evaporation may also result from blowing snow than stable snow, resulting in less accumulation of snow over the winter and less need for costly snow removal. Plowing costs may increase, but removal costs may decrease. Blowing snow may also complicate snow removal, however, and necessitate more frequent snow removal as snow blows back into plowed areas. Blowing snow also slows snow removal operations as visibility becomes poor and plows must reduce their speed. Higher relative humidity results in less snow evaporation and more accumulated snow. Areas with high relative humidity are also often subject to snowstorms. This phenomenon is known as a "lake effect" and causes snowstorms in the Buffalo, US area. Climate change in the areas that are particularly subject to lake effects may result in much higher changes in winter control costs than climate change in areas that are not subject to these effects.

Lower temperatures result in less snow evaporation; the evaporation rate for snow doubles with every 10°C rise in temperature *(Tabler,R.., 1994)*. Lower temperatures also affect culvert thawing, as culverts become more prone to freezing. If culverts are not thawed, drainage may be blocked and water will accumulate. Lower temperatures will result in more ice formation on roadways and increase the amount of sand and/or salt that must be applied to maintain safety levels on the road. Lower temperatures, in conjunction with precipitation, will increase winter control costs; higher temperatures when precipitation occurs will have the reverse effect on winter control costs.

4.5.3: Summary

Capital costs and operating costs for roads, bridges and storm water management systems are affected by climate in a number of ways. Depending upon the manner in which climate changes, costs may be increased or decreased. The primary effects of climate on capital costs and operating costs for these structures are as follows:

4.5.3.1: Roads Capital Costs

The major climate-related capital costs for roads include:

- Decrease (increase) in permafrost that decreases (increases) the cost of road building

- Decrease (increase) in rate of permafrost thawing that decreases (increases) the frequency of road replacement
- Increase in temperatures that decrease the winter/ice road season, necessitating construction of all weather roads
- Decrease (increase) in temperatures that requires an increase (decrease) in the depth of the roadbed and more (less) fill to protect against frost heave
- Less (more) precipitation that causes an increase (decrease) in the stability of the roadbed, requiring less (more) depth of underlay
- Decrease (increase) in frequency of avalanche conditions necessitating the construction of fewer (more) snow sheds and tunnels

4.5.3.2: Roads Operating Costs

The major climate-related operating costs for roads include:

- Less (more) snow that decreases (increases) the cost of snow plowing, sanding and salting
- Less (more) frequent heavy snowfalls that decrease (increase) the cost of snow removal
- Fewer (more) freeze-thaw cycles that decrease (increase) the number of potholes
- Shorter (longer) periods of cold temperatures that decrease (increase) the amount of frost heave in the roadbed, creating less surface cracking

4.5.3.3: Bridges Capital Costs

The major climate-related capital costs for bridges include:

- Decreased (increased) temperatures that result in ice cap formation (reduction) and produce lower (higher) water levels that require lower (higher) bridges

- Decreased (increased) temperatures that result in more (less) ice formation and require larger (smaller) bridge piers to guard against sea and lake ice damage
- Decreased (increased) precipitation that results in less (more) runoff and scour and requires smaller (larger) substructure
- Increased wind velocity that results in the need for stronger super and substructure
- Decreased wind velocity that results in the need for less strength in the substructure
- Increases in temperatures (above 0°C) with precipitation that result in less use of de-icing salts and longer bridge life span with less frequent bridge replacement
- Increases in temperature (above -10°C) with precipitation that result in greater use of de-icing salts and shorter bridge life span with more frequent bridge replacement
- Decreases in temperatures (below 0°C) with precipitation that result in greater use of de-icing salts and a shorter bridge life span with more frequent bridge replacement
- Decreases in temperatures (below -10°C) with precipitation that result in less use of de-icing salts and a longer bridge life span with less frequent bridge replacement

4.5.3.4: Bridges Operating Costs

The major climate-related operating costs for bridges include:

- Increases in temperatures (above 0°C) with precipitation that result in less use of de-icing salts and less bridge repair

- Increases in temperature (above -10°C) with precipitation that result in greater use of de-icing salts and more bridge repair
- Decreases in temperatures (below 0°C) with precipitation that result in greater use of de-icing salts and more bridge repair
- Decreases in temperatures (below -10°C) with precipitation that result in less use of de-icing salts and less bridge repair
- Increases in seasonal temperature range that increase concrete spalling and result in more patching
- Decreases in seasonal temperature range that decrease concrete spalling and result in less patching

4.5.3.5: Storm Water Management System Capital Costs

The major climate-related capital costs for storm water management systems include:

- Less (more) frequent heavy precipitation events resulting in decreased (increased) costs for smaller (larger) culverts, shallower (deeper) drains, smaller (larger) storm water detention facilities, decreased (increased) grading of side slopes to increase (decrease) the slope on ditches

4.5.3.6: Storm Water Management Operating Costs

The major climate-related operating costs for storm water management systems include:

- Lighter (heavier) overall precipitation resulting in decreased (increased) costs of drain cleaning, ditch clearing and storm water detention facility dredging

- Less (more) frequent heavy precipitation events that cause flooding and washouts of culverts and necessitate replacement or repair of various components of the storm water management system

4.6: The Costs of Adaptation

The costs of adaptation to climate change may be broken into capital costs and operating costs for roads, bridges and storm water management systems.

4.6.1: Capital Costs

Capital costs associated with climate change adaptation include the additional costs imposed on road reconstruction and new construction, bridge reconstruction and new construction and storm water management reconstruction and new construction. While reconstruction may be included in operating costs for many levels of government, large reconstruction costs are usually included in capital expenditures. There are many options open to governments in the maintenance of a road system in terms of the amount of repair that is performed on a road, bridge or storm water management system. Roads may be patched indefinitely but the road becomes progressively more difficult to travel on and speeds must be reduced. Bridges may be patched almost indefinitely but the costs of repair often must be assessed with respect to the ability of the bridge to sustain the “live load” or traffic. Drainage systems may be temporarily repaired year after year but there is a cost to the road system in so doing. There is less flexibility in the reconstruction versus repair of these storm water management systems as these systems are often the weak points in maintaining the highway system. A poorly maintained drainage system will result in much higher costs for its associated road system.

4.6.1.1: Roads

The impact of climate change on the capital cost of roads can be broken into general effects on all roads plus a few special, high-impact cases. All roads will sustain some impact of changes in temperature, particularly changes in freeze-thaw cycles, changes in the depth of frost (frost heave) and the potential destruction of the road system due to culvert washouts. Temporary roads in the north, also known as “ice roads” or “winter roads” will sustain a particularly high impact from warming. These roads will not be useable if the temperature warms substantially. These roads may have to be replaced with more permanent structures at a very high cost. Roads on permafrost will also be very susceptible to changes in temperature. The loss of permafrost destabilizes the roadbed and results in the need for major road reconstruction, often over very large areas. Road building costs are higher for the roads on permafrost in the Northwest Territories. Roads on permafrost cost approximately $500,000 per km to build; roads on non-permafrost cost approximately $350,000 per km to build. Roads on permafrost are constructed differently and must be constantly monitored for the loss of the integrity of the roadbed *(Larry Purcka, Northwest Territories Transportation, personal communication)*. The loss of permafrost means that new road construction will be less expensive throughout the discontinuous permafrost zone but the existing road system will sustain heavy impact as the permafrost slowly disappears from the roadbed.

4.6.1.1.1: All Roads

The capital costs for roads will be affected by the need for greater expenditure when a road is built. Capital expenditures for roads will sustain climate change impact from the need for greater amounts of fill to produce a more stable roadbed where the frost line may extend further into the soil profile. Capital expenditures for roads will also sustain more climate change impact where the stability of the roadbed may be affected by increases and decreases in the amount of precipitation and changes in the depth of frost.

Ice lenses tend to form at the frost line and the roadbed must be sufficiently well drained that moisture does not collect at the normal, expected frost depth. Excess moisture at the frost line will freeze and expand. Ice lenses also draw moisture from the surrounding soil. A concentration gradient is set up through the soil profile as water is withdrawn from the soil matrix, resulting in the movement of water within the soil profile toward the developing ice lens. The resulting ice lenses are large and cause heaving of the road surface in the winter while they are forming and slumping in the spring when they melt and dissipate. The road surface cracks and is eroded by the passing traffic when this happens. Many parts of the country restrict individual truck weights on the road network in the spring to prevent or minimize the damage that frost heave causes. Much of the heavier weight truck traffic moves over the road system through the winter when the sub grade is frozen and able to withstand heavier loads.

4.6.1.1.2: Winter/Ice Roads

Ice/winter roads are temporary roads that are functional in the winter only. They are created from a mixture of soil, snow and/or ice and may be created on the frozen surface of lakes and rivers. Winter roads may be roads that are not passable in the warmer weather due to high moisture content in the soils. Winter roads often involve ice crossings over rivers and lakes. The government of the Northwest Territories often utilizes temporary bridges on its major winter roads to ensure safe passage of vehicles *(Larry Purcka, Northwest Territories government, personal communication)*.

The Ontario government recently spent $2.7 million (1999) for the construction and maintenance of over 2700 km of ice/winter roads linking the northern part of the province. In the Northwest Territories, all weather roads service only a portion of the communities. Most communities are linked, one way or another, by ice/winter roads.

The town of Fort Chipewyan, which is land-locked at the northern boundary of Alberta, is only accessible from the south by a temporary winter road running north from Fort McMurray. All freight must otherwise move by air. Most heavy equipment, construction materials, fuel and heavy goods move into the remote communities during the winter over this system of roads. It is estimated that approximately 10-15% of the total annual flow of goods in the Mackenzie Valley (Northwest Territories / Yukon) moves over winter roads *(EPA, 1998)*. Table 4.6.1 shows a summary of the quantity and distribution of winter/ice roads in Canada.

Table 4.6.1: Summary of Quantity and Distribution of Winter/Ice Roads in Canada

Province	**Winter/Ice Roads (publicly maintained)** [1]	**Total Km (approximate)**
Alberta	0 provincial but two major roads maintained by municipality of Wood Buffalo through Fort Chipewyan (285 km) and to the Saskatchewan border (100 km), one road federally maintained from Fort Chipewyan to Fort Smith (228 km) [2]	650
British Columbia	0 [3]	
Manitoba	1000 km provincial, 600 km municipal [4]	1,600
New Brunswick	0	
Newfoundland	0 [5]	
Nova Scotia	0	
Ontario	2700 km provincial and municipal (8 km maintained by Moosonee) [6]	2,700
Prince Edward Island	0	
Quebec	~3000 (1305 provincial)[7]	3,000
Saskatchewan	~500 (381 km maintained by province - four major ice roads – Athabasca (180 km), Stoney Rapids-Fond du Lac (160 km), Wollaston Lake crossing (36 km) and Riverhurst crossing (5 km))[8]	500
Northwest Territories	1400 km provincially maintained [9]	1,400
Nunavut	0 [10]	
Yukon	0 provincial, very few municipal (1 km ice bridge maintained by the municipality of Dawson City) [11]	10
Total Km		9,860

[1] *There are also additional winter roads that have been constructed and maintained by the private sector which are publicly funded; there is also a large number of private winter roads developed and maintained by the mining and forest industries*

[2] *Bill Kenny, Alberta Infrastructure, personal communication; Municipality of Wood Buffalo; Wood Buffalo Park*
[3] *Dave Moore, British Columbia Ministry of Transportation and Highways, personal communication*
[4] *"Ice Road Blitz", Transport Canada publication ISSN0710-0914 TP 2711 E*
[5] *Gerry Goss, Newfoundland Works, Services and Transportation, personal communication*
[6] *"Bear Country", in-flight magazine of Bearskin airlines; Town of Moosonee*
[7] *estimate based on Ontario figures, provincial figure derived from http://www.mtq.gouv.qc.ca/regions (routes d'access aux resources)*
[8] *estimate based on Manitoba figures, provincial figure from http://www.highways.gov.sk.ca/travellers_information/ice_roads.htm; Saskatchewan Highways and Transportation, Prince Albert office*
[9] *Larry Purcka, Northwest Territories Transportation, personal communication*
[10] *Doug Sitlin, Nunavut Community and Transportation, personal communication*
[11] *Bernie Cross, Yukon Community and Transportation Services, personal communication*

The yearly costs for building and maintaining ice roads are quite variable, normally ranging from $2,000 to $5,000 per km *(Gary McClelland, Saskatchewan Highways and Transportation; Bear Country; Jennifer Tallman, Abitibi Consolidated Iroquois Falls)*. Maintenance costs for the two main provincial ice roads for Saskatchewan average only slightly less than the initial opening costs (Table 4.6.2). The province of Saskatchewan is currently building a 180 km winter road from Points North Landing to Black Lake at a cost of $8 million to supply the communities in the Lake Athabasca area *(Saskatchewan Highways and Transportation http://www.inac.gc.ca/nr/prs/s-d1997/1-9730.html)* resulting in an initial cost of $44,000 per km. This would be expected to drop in subsequent years. The costs for winter/ice roads are summarized in Table 4.6.2.

Table 4.6.2: Opening and Maintenance Costs for Winter/Ice Roads

Road	**Initial Opening**	**Maintenance**	**Distance (km)**	**Normal Duration for Use**
Hwy 905 Stony Rapids to Fond du Lac	$55,000 ($1,719/km/yr)	$40,000 ($1250/km/yr)	32	8-12 weeks (8 clearings)
Hwy 905 Wollaston Lake Landing to Wollaston Lake settlement	$73,000 ($1,431/km/yr)	$50,000 ($980/km/yr)	51	8-12 weeks (10 clearings)

All weather roads are considerably more expensive to build and maintain. In northern Ontario, construction of an all-weather road will cost at least $85,000 per km plus bridges. An average bridge for an all weather road in Ontario will cost between $65,000 and $150,000 per bridge *(Jennifer Tallman, Abitibi Consolidated Iroquois Falls)*. An all-weather replacement for the winter road at Grandmother's Bay in northern Saskatchewan cost the Saskatchewan provincial government $1.45 million dollars for 11.7 km of road ($124,000 per km) in 1997 *(Saskatchewan Executive Council* (*http://www.gov.sk.ca/newsrel/1995/04/11-167.html*)*.* Construction of an all weather road where no road previously existed is more expensive than replacement of an existing road. The "Route du Nord", a gravel all weather road from Chibougamou to Nemiscau in Quebec, cost the Quebec provincial government approximately $350,000 per km in 1999 to build. (*http://www.gov.sk.ca/newsrel/1995/04/11-167.html*)*.*

All weather roads require maintenance in addition to the capital expenditure. At present, British Columbia spends approximately $4,000 per lane-km in road maintenance *(BC Ministry of Transportation and Highways Annual Report 1999-2000, pg17)*. All weather gravel roads must be graded, potholes patched and culverts replaced. The replacement of an ice/winter road with an all weather road does not mean that the cost of ice/winter road construction and maintenance will be completely forgone. Large capital expenditures and the continuation of maintenance costs will accompany the construction of all weather roads to replace the ice/winter roads. The replacement of an ice/winter road with an all weather road will not necessarily follow the same route. According to Parks Canada staff in Wood Buffalo Park, the ice road between Fort McMurray and Fort

Chipewyan will likely follow another route. This is often done to minimize bridge construction and its associated high costs.

Climate change will affect the winter/ice roads in two ways. The season may be shortened such that these roads are no longer a viable means of transportation for the affected communities in the north. S.C. Lonergan, et al *(1993)* identified shortening of the ice road season as a major climate change impact for the north. The permafrost underlying these roads (and many all weather roads) in the northerly parts of Canada is receding. Every year more of the permafrost disappears in some areas. Winter roads in all permafrost zones (no permafrost, discontinuous permafrost and continuous permafrost) would be affected by anything that causes a temperature rise and shortens the length of the ice road season. All roads may be affected by permafrost changes.

The current ice road season lasts for approximately 90 days in northern Ontario *(Ministry of Northern Development and Mines, 1999)* and approximately 70 days for the 300 km Ekati mine road northeast of Yellowknife in the Northwest Territories *(Transwest Mining Systems Inc.1998).* In Saskatchewan, the ice roads are open 8-12 weeks of the year (56-84 days) *(Gary McClennan, Saskatchewan Highways and Transportation, personal communication).* Conditions for ice road haulage are very specific, as evidenced by the tables developed by Saskatchewan Highways and Transportation (see Tables in Appendix 4.6.1). A 50% loss of ice depth will result in more than a 50% reduction in load for both types of ice. It may no longer be possible to move either the volume or the type of freight (such as heavy mine equipment) that currently moves over these roads during the winter/ice road season. *(Saskatchewan Highways and Transportation, http://www.highways.gov.sk.ca/travellers_information/ice_roads.htm).*

Publicly funded winter/ice roads exist primarily in the Northwest Territories and northern Alberta, Saskatchewan, Manitoba, Ontario and Quebec. The Yukon has a publicly funded ice crossing in Dawson City and other isolated ice crossings are also found across the country. Ice roads over lakes and rivers are often utilized where ferry service must be discontinued in the winter. There are international ice crossings between the United States and Canada used by snowmobile enthusiasts between Drummond Island, Michigan to St.Joseph Island (18 km) and Thessalon (29 km) in Ontario *(Woodmoor, http://www.sault.com/woodmoor/news/bridge.html)*. Winter/ice roads are found in CGCM1 grid boxes 183-189, 218-226, 253-263, 270-272, 295-301, 305-309, 335-343, 371-379 and 411-412. The Greenhouse Gas Only Simulation (GG1), the mean monthly winter temperatures (November to April) within these grid boxes, are given in Appendix 4.6.2 for the years 1961-1990, 2010-2039, 2040-2069 and 2070-2099. A summary of the mean winter temperatures for the years 1961-1990, 2010-2039, 2040-2069 and 2070-2099 is given in Table 4.6.3.

Table 4.6.3: Mean Winter Temperatures 1961-1990, 2010-2039, 2040-2069, 2070-2099

GRID BOX NUMBER	PRIMARY PROVINCE/ TERRITORY	MEAN TEMP 1961-1990	MEAN TEMP 2010-2039	MEAN TEMP 2040-2069	MEAN TEMP 2070-2099
183	YK	-21.33	-17.49	-14.67	-10.51
184	YK	-20.63	-16.57	-13.20	-8.90
185	NT	-21.37	-17.23	-13.98	-9.61
186	NT	-22.92	-19.19	-16.22	-12.14
187	NT	-22.29	-19.06	-15.89	-12.03
188	NT	-21.60	-18.72	-15.69	-11.95
189	NT	-21.59	-18.92	-16.07	-12.30
218	YK	-15.38	-12.17	-10.21	-7.02
219	YK	-17.61	-13.82	-11.83	-8.75
220	YK	-14.84	-11.42	-9.03	-6.32
221	NT	-14.98	-11.84	-9.32	-6.82
222	NT	-14.44	-11.66	-8.95	-6.59

223	NT	-14.08	-11.70	-8.93	-6.65
224	NT	-14.20	-11.94	-9.12	-6.51
225	NT	-14.46	-11.85	-8.91	-5.71
226	NT	-19.50	-16.60	-13.82	-9.63
253	YK	-9.04	-6.46	-3.85	-0.49
254	YK	-7.84	-5.45	-3.15	-0.88
255	YK	-8.49	-6.23	-3.96	-1.86
256	YK	-8.91	-6.74	-4.58	-2.54
257	YK/NT	-8.62	-6.51	-4.46	-2.39
258	NT	-8.28	-6.09	-4.01	-1.98
259	NT	-8.19	-6.43	-4.16	-1.94
260	NT	-8.39	-6.61	-4.51	-2.01
261	NT	-8.90	-6.79	-4.59	-1.90
262	NT	-10.85	-8.41	-6.34	-3.25
263	NT	-15.35	-12.44	-9.97	-6.25
270	PQ	-7.62	-1.15	1.38	3.56
271	PQ	-16.95	-12.13	-8.80	-3.94
272	PQ	-5.55	-0.63	1.64	3.76
295	AB	-4.37	-2.44	-0.16	1.27
296	AB	-5.17	-3.20	-1.08	0.77
297	SK	-6.10	-4.14	-2.00	-0.12
298	SK	-8.41	-6.15	-4.09	-1.87
299	SK/MB	-10.42	-7.90	-5.76	-3.31
300	MB	-11.65	-8.89	-6.43	-3.80
301	MB	-15.52	-12.11	-9.28	-6.09
305	PQ	-6.36	-0.83	2.14	4.18
306	PQ	-13.72	-10.11	-6.93	-2.99
307	PQ	-12.02	-8.70	-5.98	-2.71
308	PQ	-11.03	-8.35	-5.85	-2.73
309	PQ	-10.93	-9.13	-6.81	-3.21
335	MB	-6.96	-4.57	-2.46	-0.01
336	MB/ON	-7.63	-5.00	-2.96	-0.21
337	ON	-11.46	-8.07	-5.71	-1.85
338	ON	-11.51	-8.26	-5.87	-1.95
339	ON	-11.21	-8.45	-5.89	-2.25
340	PQ	-7.76	-5.46	-3.14	-0.58
341	PQ	-8.74	-6.60	-4.48	-2.18
342	PQ	-9.62	-7.41	-5.51	-3.30
343	PQ	-9.20	-6.91	-5.13	-2.97
371	ON	-4.48	-2.10	-0.17	2.29
372	ON	-5.10	-2.81	-0.92	1.69
373	ON	-4.99	-2.81	-0.85	1.79
374	ON	-4.61	-2.60	-0.61	1.93
375	ON/PQ	-4.28	-2.60	-0.75	1.58
376	PQ	-4.51	-2.96	-1.38	0.67

377	PQ	-5.02	-3.36	-1.90	0.12
378	PQ	-4.64	-2.77	-1.19	0.71
379	PQ	0.29	1.93	3.26	4.72
411	PQ	-1.28	0.37	1.94	3.94
412	PQ	-0.92	0.61	2.11	3.98
Grid Boxes Above –4^0 C		3 (4.84%)	16 (25.81%)	23 (37.10%)	44 (70.97%)
Rate of Change			+20.97%	+11.29%	+33.87%

At the present time, the southernmost major ice roads are located in grid boxes 262 (Fond du Lac, SK), 295 (Wood Buffalo, AB), 298 and 299 (Stony Rapids and Points North, SK and Brochet, MB) and those grid boxes along the shoreline of James Bay and Hudson Bay. Moosonee straddles grid boxes 374 and 375. There may be winter road construction in parts of grid boxes 379, 411 and 412 but this has not been confirmed. The mean winter temperature (November, December, January, February, March and April) averages below –4.28^0 Celsius for all other areas where ice roads are known to exist and to be utilized every winter for at least an eight to 12 week period. Riverhurst, Saskatchewan, which is in grid box 368, has a temporary ice crossing over Lake Diefenbaker on Highway 42 but this crossing is not officially open every year, as conditions do not allow for the formation of sufficient ice thickness. If the temperatures are sufficiently cold at Christmas, the ice crossing will usually open in mid-February. This crossing is often open only until the last week in March and must be closed at this time as cracking of the ice begins to occur.

The mean winter temperature for the grid box containing Riverhurst is –1.91^0. If mean winter temperatures rise above –4^0 C, the length of the ice road season may drop substantially, construction of ice roads may not be feasible every year and the larger transport vehicles may not be able to travel over these roads any longer. It requires 100 cm of white ice to support a 30,000 kg vehicle. By 2099, the percentage of grid boxes where ice roads are currently being utilized will drop by close to 70%. A breakdown of the winter/ice road conditions in 1961-1990, 2010-2039, 2040-2069 and 2070-2099 is given in Tables 4.6.4, 4.6.5 and 4.6.6. Table 4.6.4 contains those grid boxes where a complete loss of winter/ice roads will likely occur. Table 4.6.5 contains those grid boxes where the winter/ice road season may be substantially shortened and Table 4.6.6 contains those grid boxes where the winter/ice road season is unaffected.

Table 4.6.4: Grid Boxes With Potentially Complete Loss of Winter/Ice Roads (mean winter temperatures higher than –2^0 C)

GRID BOX NUMBER	PRIMARY PROVINCE/ TERRITORY	MEAN TEMP 1961-1990	MEAN TEMP 2010-2039	MEAN TEMP 2040-2069	MEAN TEMP 2070-2099
253	YK	-9.04	-6.46	-3.85	-0.49
254	YK	-7.84	-5.45	-3.15	-0.88
255	YK	-8.49	-6.23	-3.96	-1.86
258	NT	-8.28	-6.09	-4.01	-1.98
259	NT	-8.19	-6.43	-4.16	-1.94
261	NT	-8.90	-6.79	-4.59	-1.90
270	PQ	-7.62	-1.15	1.38	3.56
272	PQ	-5.55	-0.63	1.64	3.76
295	AB	-4.37	-2.44	-0.16	1.27
296	AB	-5.17	-3.20	-1.08	0.77
297	SK	-6.10	-4.14	-2.00	-0.12
298	SK	-8.41	-6.15	-4.09	-1.87
305	PQ	-6.36	-0.83	2.14	4.18
335	MB	-6.96	-4.57	-2.46	-0.01
336	MB/ON	-7.63	-5.00	-2.96	-0.21
337	ON	-11.46	-8.07	-5.71	-1.85
338	ON	-11.51	-8.26	-5.87	-1.95
340	PQ	-7.76	-5.46	-3.14	-0.58
371	ON	-4.48	-2.10	-0.17	2.29
372	ON	-5.10	-2.81	-0.92	1.69
373	ON	-4.99	-2.81	-0.85	1.79
374	ON	-4.61	-2.60	-0.61	1.93
375	ON/PQ	-4.28	-2.60	-0.75	1.58
376	PQ	-4.51	-2.96	-1.38	0.67
377	PQ	-5.02	-3.36	-1.90	0.12

378	PQ	-4.64	-2.77	-1.19	0.71
379	PQ	0.29	1.93	3.26	4.72
411	PQ	-1.28	0.37	1.94	3.94
412	PQ	-0.92	0.61	2.11	3.98

Table 4.6.5: Grid Boxes With Shortening of Winter/Ice Road Season (mean winter temperatures between –2^0 C and –4^0 C)

GRID BOX NUMBER	PRIMARY PROVINCE/ TERRITORY	MEAN TEMP 1961-1990	MEAN TEMP 2010-2039	MEAN TEMP 2040-2069	MEAN TEMP 2070-2099
256	YK	-8.91	-6.74	-4.58	-2.54
257	YK/NT	-8.62	-6.51	-4.46	-2.39
260	NT	-8.39	-6.61	-4.51	-2.01
262	NT	-10.85	-8.41	-6.34	-3.25
271	PQ	-16.95	-12.13	-8.80	-3.94
299	SK/MB	-10.42	-7.90	-5.76	-3.31
300	MB	-11.65	-8.89	-6.43	-3.80
306	PQ	-13.72	-10.11	-6.93	-2.99
307	PQ	-12.02	-8.70	-5.98	-2.71
308	PQ	-11.03	-8.35	-5.85	-2.73
309	PQ	-10.93	-9.13	-6.81	-3.21
339	ON	-11.21	-8.45	-5.89	-2.25
341	PQ	-8.74	-6.60	-4.48	-2.18
342	PQ	-9.62	-7.41	-5.51	-3.30
343	PQ	-9.20	-6.91	-5.13	-2.97

Table 4.6.6: Grid Boxes With Little/No Impact on Winter/Ice Roads (mean winter temperatures remain below –4^0 C)

GRID BOX NUMBER	PRIMARY PROVINCE/ TERRITORY	MEAN TEMP 1961-1990	MEAN TEMP 2010-2039	MEAN TEMP 2040-2069	MEAN TEMP 2070-2099
183	YK	-21.33	-17.49	-14.67	-10.51
184	YK	-20.63	-16.57	-13.20	-8.90
185	NT	-21.37	-17.23	-13.98	-9.61
186	NT	-22.92	-19.19	-16.22	-12.14
187	NT	-22.29	-19.06	-15.89	-12.03
188	NT	-21.60	-18.72	-15.69	-11.95
189	NT	-21.59	-18.92	-16.07	-12.30
218	YK	-15.38	-12.17	-10.21	-7.02
219	YK	-17.61	-13.82	-11.83	-8.75
220	YK	-14.84	-11.42	-9.03	-6.32
221	NT	-14.98	-11.84	-9.32	-6.82
222	NT	-14.44	-11.66	-8.95	-6.59
223	NT	-14.08	-11.70	-8.93	-6.65

224	NT	-14.20	-11.94	-9.12	-6.51
225	NT	-14.46	-11.85	-8.91	-5.71
226	NT	-19.50	-16.60	-13.82	-9.63
263	NT	-15.35	-12.44	-9.97	-6.25
301	MB	-15.52	-12.11	-9.28	-6.09

It can be seen from these tables that the major ice roads at Fond du Lac, Wollaston, Stony Rapids, Points North, Brochet and Wood Buffalo will be open less or not at all. The winter roads connecting communities around James Bay and Hudson Bay, including the Moosonee area, will probably not be passable. The winter roads and ice crossings in the far north, through the Yukon, Northwest Territories and northern Quebec will likely still be in use, although there may be greater load restrictions and a shorter season. Table 4.6.7 contains a breakdown of the impact of climate change by province for those grid boxes containing winter/ice roads.

Table 4.6.7: Provincial Temperature Scenarios for Grid Boxes within Winter/Ice Road Zone by 2100

Province	#Grid Boxes Containing Winter/Ice Roads Total	#Grid Boxes $< -4^0$ C (winter/ice roads unaffected)	#Grid Boxes $> -4^0$ C and $< -2^0$ C (more road restrictions)	#Grid Boxes $> -2^0$ C (complete road replacement)
Alberta	2	0	0	2 (100%)
British Columbia	0			
Manitoba	5	1 (20%)	2 (40%)	2 (40%)
New Brunswick	0			
Newfoundland	0			
Nova Scotia	0			
Ontario	9	0	1 (11%)	8 (89%)
Prince Edward Island	0			
Quebec	19	0	8 (42%)	11 (58%)
Saskatchewan	3	0	1 (33%)	2 (67%)
Northwest Territories	18	12 (67%)	3 (16.5%)	3 (16.5%)
Nunavut	0			
Yukon	10	5 (50%)	2 (20%)	3 (30%)

If, by the year 2100, all of the winter/ice roads that will no longer be in use are replaced with all weather roads and 50% of the winter/ice roads that have restrictions placed on them are replaced with all weather roads, the number of kilometres of roads that will require replacement are as shown in Table 4.6.8.

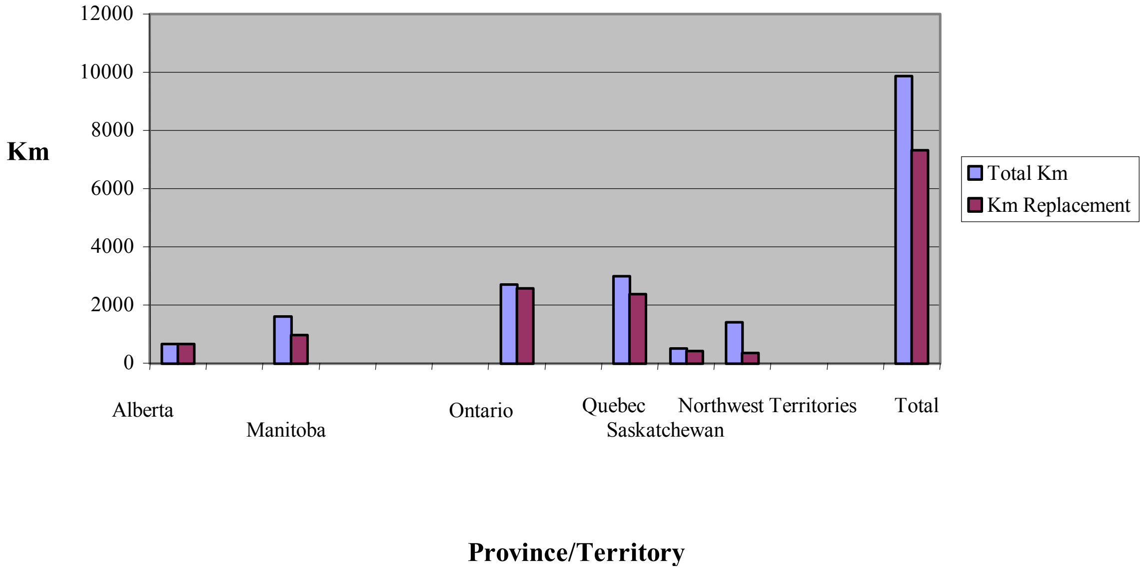
Table 4.6.8: Provincial Replacement Scenarios for Grid Boxes within Winter/Ice Road Zone by 2100

Province	**Total km (approximate)**	**%Replacement by Year 2100**	**Km Replacement by 2100**	**$Replacement by 2100***
Alberta	650	100%	650	80,600,000
British Columbia				
Manitoba	1,600	40%+20%	960	119,040,000
New Brunswick				
Newfoundland				
Nova Scotia				
Ontario	2,700	89% +6%	2565	318,060,000
Prince Edward Island				
Quebec	3,000	58% +21%	2370	293,880,000
Saskatchewan	500	67%+17%	420	52,080,000
Northwest Territories	1,400	17% +8%	350	43,400,000
Nunavut				
Yukon	10	30% +10%	4	496,000**
Total	9,860	(74%)	7,319	907,556,000

** This figure is based on a minimum replacement cost of $124,000 per km of road ($1997) for the Grandmother's Bay winter road in Saskatchewan. This may be much higher in some areas depending upon the terrain.*
*** This figure may be deceptively low as the ice roads in the Yukon are river crossings and would require bridge construction for replacement*

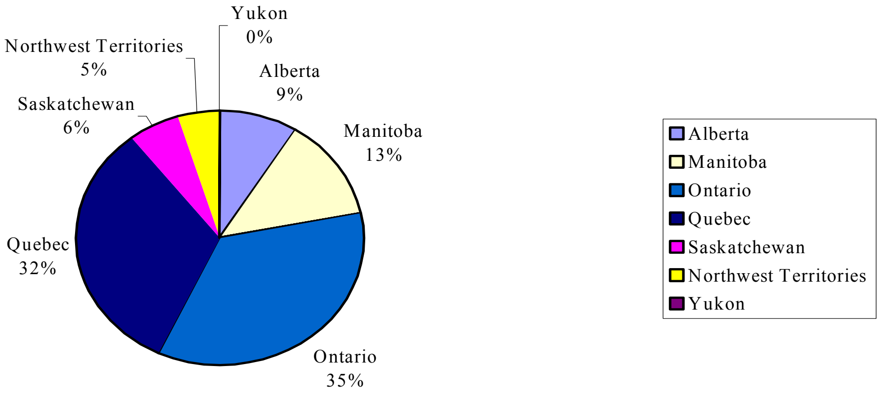
The cost of winter road replacement is in addition to the capital expenditures that the federal, provincial, regional or municipal governments would normally incur during this time. A break down by province is given below (Figure 4.6.1 and Figure 4.6.2). These costs include expenditures by all levels of government within any give province. As can be seen from these charts and Table 4.6.10 above, the bulk of the costs for winter/ice road replacement will be incurred by Ontario and Quebec. The winter/ice roads within these provinces are provincially or municipally maintained.

Figure 4.6.1: Winter/Ice Road Replacement (km) by the Year 2100



Ontario and Quebec will bear most of the cost of winter/ice road replacement, followed by Manitoba, Alberta, Saskatchewan, the Northwest Territories and the Yukon (Figure 4.6.1 and Figure 4.6.2). Although there are a large number of kilometres of winter roads and ice crossings in the Northwest Territories, it is not expected that conditions will become mild enough to necessitate complete replacement of these roads in the next 100 years.

Figure 4.6.2: Proportion of Winter /Ice Road Replacement Costs by Province by the Year 2100



The adaptation costs for all levels of government for winter/ice road replacement are summarized in Table 4.6.9.

Table 4.6.9: Climate Change Adaptation Costs for Winter/Ice Road Replacement by Province (Year 2100)

Province	**Canadian Dollars**
Alberta	$80,600,000
Manitoba	$119,040,000
Ontario	$318,060,000
Quebec	$293,880,000
Saskatchewan	$52,080,000
Northwest Territories	$43,400,000
Yukon	$496,000
Total	**$907,556,000**

4.6.1.1.3: Roads on Permafrost

The discontinuous permafrost zone in Canada covers areas from northern British Columbia and Alberta, northern and central Saskatchewan and Manitoba, northern Ontario and Quebec, all of Labrador, most of the Yukon and Northwest Territories and substantial portions of Nunavut. The continuous permafrost zone is limited to only a small portion of the country *(Geologic Survey Canada http://sts.gsc.nrcan.gc.ca/permafrost/pfmapheg2.jpg)*. The discontinuous permafrost zone is characterized by mean annual temperatures of -2°C near the surface of the ground. North of this isotherm, where mean annual temperatures are colder, the discontinuous permafrost becomes continuous permafrost. Technically speaking, permafrost is ground that remains below 0°C for two summers and an intervening winter. In practical terms, however, permafrost may be thought of as frozen ground, because it is ice in the ground that creates most of the challenges associated with these areas *(Geologic Survey Canada permafrosthttp://sts.gsc.nrcan.gc.ca/permafrost/distribution.htm)*.

Particularly affected by permafrost changes are those communities in the discontinuous permafrost zone, where even the slight temperature increases of the last few years have caused the permafrost underlying the highways to melt and the roads to crack and slump. According to Alan Hanna of AGRA Earth and Environmental Limited *(Mackenzie Basin Impact Study (MBIS) Final Report: Summary of Results 1997)*, the discontinuous permafrost zone is most likely to feel the effects of climate change while the continuous permafrost zone would be less affected. The cross-section of permafrost depths through the Northwest Territories would appear to bear this out *(Geologic Survey Canada http://sts.gsc.nrcan.gc.ca/permafrost/pfmacval.jpg)*. The effects of warming and loss of permafrost are already being felt in Yellowknife where 90 km of all weather roads are currently being replaced at a cost of $840,000 per km. In this area, the permafrost is already 35 cm thinner than when these roads were constructed. The permafrost disappears first from under the shoulders and edges of the road, causing cracking down the middle of the roadway. A central core of permafrost may remain in the middle of the road. This core may rotate with the changes in temperature through the year and cause further road damage. In addition, road shoulders may fail and the drainage system for the road may be compromised when the permafrost disappears. The loss of permafrost in the middle of a ditch between two drains will result in a settling of the ground and pooling of water. Water draining from the road surface no longer flows through the storm water management system and tends to collect, causing local flooding of the road *(Larry Purcka, Northwest Territories Transportation, personal communication)*.

The communities, such as Inuvik, which have deep continuous permafrost will not likely undergo as much change, or change as quickly as those in the more southerly parts of the north where the permafrost is discontinuous. Geologic Survey Canada has also identified the discontinuous permafrost zone as the most susceptible to the impacts of climate change. The ground temperature is generally higher in the discontinuous permafrost zone and resides within 1-2 °C of melting. This general hypothesis may vary with differences in the expected temperature change for the north, especially along the boundary between these two zones.

General circulation models predict that, for a doubling of atmospheric concentrations of carbon dioxide due to anthropogenic sources, mean annual air temperatures may rise up to several degrees over much of the Arctic. In the discontinuous permafrost region, permafrost is predicted to disappear with global warming. Where ground ice contents are high, this permafrost degradation will have associated physical impacts. Of greatest concern are soils with the potential for instability upon thaw (thaw settlement, creep or slope failure). Such instabilities may have implications for the landscape, ecosystems, and infrastructure. Roads and possibly bridge substructures and storm water management systems will be affected. Permafrost does not respond immediately to climate change and these effects may be slow to appear. There are layers of permafrost beneath the Beaufort Sea that were generated during the last ice age. These layers of permafrost are slowly disappearing but the response to climate change is slow and variable. The lag time between changes in surface temperature and loss of permafrost may be thousands of years in the continuous permafrost zone and but only years in the discontinuous permafrost zone. The effects of climate change will be felt more rapidly in the discontinuous zone *(Geologic Survey Canada http://sts.gsc.nrcan.gc.ca/permafrost/climate.htm).*

Environment Canada data on temperature departures from normal for January to December 1998 indicate that the effects of El Niño in 1998 were felt more intensely in the western Canadian Arctic (Yukon and Northwest Territories). Permafrost melting is predicted to be more intense here than in Nunavut. The northwestern part of the country may feel the effects of global warming more quickly than the rest of Canada. Site specific one-dimensional transient modelling has also been undertaken at a few select sites in the Mackenzie River valley, to assess the magnitude of ground temperature change, the rate of increase in thaw depth, and the associated thaw settlement. A pilot project has recently been initiated to develop an approach to assess the impact of climate change on permafrost in northern communities and the sensitivity of infrastructure to the associated ground temperature warming, active layer increase or permafrost degradation. The predicted thaw depths for the north show an increase in maximum annual thaw depth over 50 years. In all simulations, the rate of change in thaw depth is very slow in the first

10 to 20 years of the simulations *(Geologic Survey Canada http://sts.gsc.nrcan.gc.ca/permafrost/climate.htm)*. The most intense effects of global warming on permafrost melting may not appear for 100 years. During the period of time that the depth of thawing increases, there will also be more turbation as more of the soil profile alternately freezes and thaws. The land surface may slump, creep and fail and there may be considerable heaving as well. All of these effects are deleterious to the longevity of infrastructure, including roads.

The discontinuous permafrost exists across the northern part of Canada and throughout the Rocky Mountains. The CICS grid boxes that would be affected by changes in the discontinuous permafrost zone include 218-227, 253-265, 291-302, 306-309, 328-330 (mountains), 335-346 and 364-366 (mountains). Table 4.6.10 illustrates the mean annual temperature changes within the grid boxes for the Greenhouse Gas Only Simulation (GG1).

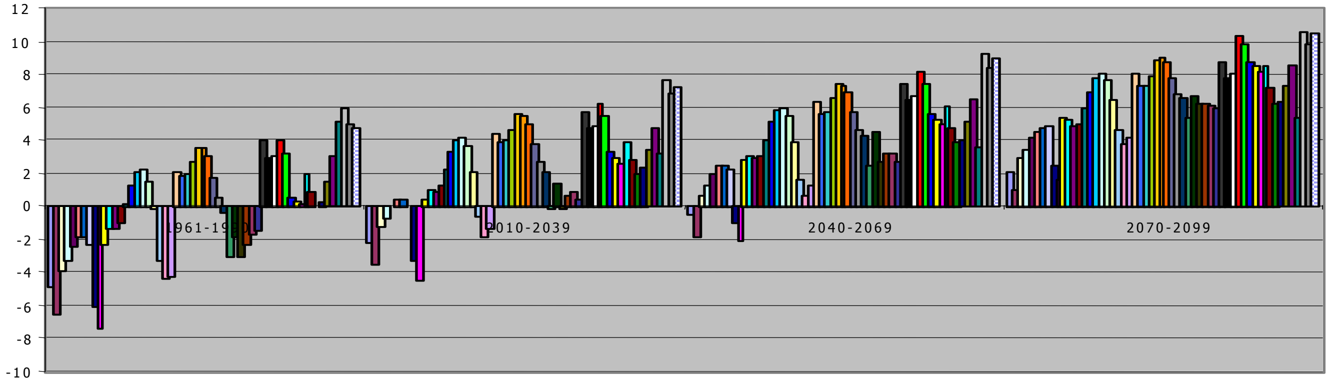
Table 4.6.10: Temperature Changes in the Grid Boxes Within the Discontinuous Permafrost Zone (all values in °C)

Grid Box Number	1961-1990	Change 2010	2010-2039	Change 2040	2040-2069	Change 2070	2070-2099
218	**-4.75803**	2.60308	**-2.15495**	4.32352	**-0.43451**	6.89643	**2.1384**
219	**-6.47419**	2.96929	**-3.5049**	4.7316	**-1.74259**	7.48426	**1.01007**
220	**-3.85008**	2.63939	**-1.21069**	4.47633	**0.62625**	6.78115	**2.93107**
221	**-3.22804**	2.53496	**-0.69308**	4.45854	**1.2305**	6.66553	**3.43749**
222	**-2.37267**	2.37225	**-0.00042**	4.3815	**2.00883**	6.50282	**4.13015**
223	**-1.8253**	2.20805	**0.38275**	4.2444	**2.4191**	6.33283	**4.50753**
224	**-1.79691**	2.17483	**0.37792**	4.25449	**2.45758**	6.54128	**4.74437**
225	**-2.28823**	2.35323	**0.065**	4.51711	**2.22888**	7.12372	**4.83549**
226	**-5.95391**	2.75238	**-3.20153**	5.03212	**-0.92179**	8.37889	**2.42498**
227	**-7.31428**	2.93184	**-4.38244**	5.34391	**-1.97037**	8.88998	**1.5757**
253	**-2.29835**	2.70286	**0.40451**	5.07413	**2.77578**	7.70682	**5.40847**
254	**-1.25854**	2.2741	**1.01556**	4.35476	**3.09622**	6.4647	**5.20616**
255	**-1.31192**	2.17352	**0.8616**	4.18689	**2.87497**	6.1948	**4.88288**
256	**-0.88779**	2.07606	**1.188268**	3.98629	**3.098498**	5.91409	**5.026298**
257	**0.121021**	2.06137	**2.182391**	3.85267	**3.973691**	5.78194	**5.902961**

258	**1.23651**	2.10888	**3.34539**	3.88539	**5.1219**	5.72699	**6.9635**
259	**2.08911**	1.91002	**3.99913**	3.75505	**5.84416**	5.63123	**7.72034**
260	**2.19443**	2.00246	**4.19689**	3.76333	**5.95776**	5.76077	**7.9552**
261	**1.53337**	2.06604	**3.59941**	3.93186	**5.46523**	6.16486	**7.69823**
262	**-0.06651**	2.19782	**2.13131**	4.00833	**3.94182**	6.51214	**6.44563**
263	**-3.25155**	2.73464	**-0.51691**	4.89739	**1.64584**	7.86377	**4.61222**
264	**-4.29261**	2.52691	**-1.7657**	4.97	**0.67739**	8.04282	**3.75021**
265	**-4.16611**	2.86827	**-1.29784**	5.42879	**1.26268**	8.32841	**4.1623**
291	**2.04512**	2.39623	**4.44135**	4.25972	**6.30484**	5.97971	**8.02483**
292	**1.90156**	1.98595	**3.88751**	3.73781	**5.63937**	5.34038	**7.24194**
293	**1.98851**	1.99006	**3.97857**	3.7443	**5.73281**	5.25424	**7.24275**
294	**2.70034**	1.95916	**4.6595**	3.81215	**6.51249**	5.23844	**7.93878**
295	**3.5808**	1.9752	**5.556**	3.87754	**7.45834**	5.31999	**8.90079**
296	**3.53358**	1.99292	**5.5265**	3.79404	**7.32762**	5.44817	**8.98175**
297	**3.07311**	1.95743	**5.03054**	3.81507	**6.88818**	5.60388	**8.67699**
298	**1.71824**	2.08089	**3.79913**	3.94439	**5.66263**	5.99282	**7.71106**
299	**0.457235**	2.24388	**2.701115**	4.15984	**4.617075**	6.39239	**6.849625**
300	**-0.30681**	2.40098	**2.094166**	4.53503	**4.228216**	6.91756	**6.610746**
301	**-2.95962**	2.90026	**-0.05936**	5.43142	**2.4718**	8.3372	**5.37758**
302	**-1.78651**	3.19454	**1.40803**	6.23871	**4.4522**	8.41354	**6.62703**
306	**-3.0403**	2.97337	**-0.06693**	5.78546	**2.74516**	9.25002	**6.20972**
307	**-2.26471**	2.8544	**0.58969**	5.43913	**3.17442**	8.403	**6.13829**
308	**-1.61564**	2.44515	**0.82951**	4.82278	**3.20714**	7.68248	**6.06684**
309	**-1.3683**	1.80845	**0.44015**	4.0978	**2.7295**	7.34237	**5.97407**
328mtn	**4.01212**	1.75312	**5.76524**	3.37616	**7.38828**	4.7584	**8.77052**
329mtn	**2.88529**	1.83104	**4.71633**	3.57185	**6.45714**	4.89795	**7.78324**
330mtn	**3.04976**	1.84895	**4.89871**	3.66138	**6.71114**	4.9557	**8.00546**
335	**3.98093**	2.2063	**6.18723**	4.13661	**8.11754**	6.29717	**10.2781**
336	**3.16507**	2.27107	**5.43614**	4.21588	**7.38095**	6.61627	**9.78134**
337	**0.512843**	2.72395	**3.236793**	5.0583	**5.571143**	8.21406	**8.726903**
338	**0.24634**	2.65999	**2.90633**	5.01571	**5.26205**	8.21377	**8.46011**
339	**0.134648**	2.40139	**2.536038**	4.80809	**4.942738**	7.96449	**8.099138**
340	**1.96443**	1.99372	**3.95815**	4.10736	**6.07179**	6.5541	**8.51853**
341	**0.853407**	1.9229	**2.776307**	3.92891	**4.782317**	6.29861	**7.152017**
342	**0.040081**	1.974	**2.014081**	3.85521	**3.895291**	6.18855	**6.228631**
343	**0.241397**	2.037	**2.278397**	3.81693	**4.058327**	6.07276	**6.314157**
344	**1.52392**	1.90735	**3.43127**	3.57405	**5.09797**	5.70373	**7.22765**
345	**3.05225**	1.67527	**4.72752**	3.40411	**6.45636**	5.49082	**8.54307**
346	**5.15712**	-2.00079	**3.15633**	-1.60085	**3.55627**	0.14008	**5.2972**
364	**5.97684**	1.71551	**7.69235**	3.2052	**9.18204**	4.60176	**10.5786**
365	**4.97214**	1.84267	**6.81481**	3.43886	**8.411**	4.87902	**9.85116**
366	**4.78767**	2.39501	**7.18268**	4.24665	**9.03432**	5.64363	**10.4313**

If the temperatures in degrees Celsius for the grid boxes within the discontinuous permafrost zone are plotted over time, the warming trend in this zone can clearly be seen (Figure 4.6.3).

Figure 4.6.3: Temperature Distribution (°C) for Grid Boxes Within Discontinuous Permafrost Zone



Each grid box is represented by a different colour in Figure 4.6.2. It can be easily seen that the mean annual temperature increases over the four scenarios (1961-1990 base, 2010-2039, 2040-2069, 2070-2099). Mean annual temperatures of 1-2°C characterize the discontinuous permafrost zone. Table 4.6.11 summarizes the changes that are projected to take place for the 57 grid boxes within this zone with reference to permafrost stability.

Table 4.6.11 Temperature Changes Within Grid Boxes Located Within Discontinuous Permafrost Zone

Scenario	**Number of Grid Boxes with Mean Annual Temperature Below 2 °C**	**Grid Boxes with Mean Annual Temperature Below 2 °C as a Percentage of the Total Grid Boxes**	**Percent Change in Number of Grid Boxes Between Scenarios**
1961-1990	40	70%	
2010-2039	23	40%	30%
2040-2069	9	16%	24%
2070-2099	2	4%	12%

As can be seen from this table, 70% of the grid boxes that are completely or partially within the discontinuous permafrost zone have mean annual temperatures below 2 °C for the 1961-1990 base. According to the CGCM1-GG1 model, by 2010-2039, that percentage will have dropped to 40%. By 2040-2069, that percentage will have further decreased to 16%. The mean annual temperature for the grid boxes affected by the discontinuous zone will have risen to the point that only 4% of these areas will have temperatures below 2 °C by 2070-2099. Virtually all permafrost will have disappeared from 96% of this area. The remaining 4% of the grid boxes have projected mean annual temperatures of 1-1.5°C, which suggests that the permafrost may disappear from these areas as well. While an analysis of the amount of change between different scenarios suggests that the loss of permafrost may be progressively less with each temporally advancing scenario (30% to 24% to 12%), it must be remembered that the permafrost will come into equilibrium with the ambient temperature at a slower rate than temperature is changing. Mineral and organic soil act as insulators and slow the rate of permafrost melting.

4.6.1.2: Bridges

The adaptation costs associated with Canada's bridge infrastructure are expected to be low for two reasons. First, in North America, a significant percentage of the existing bridge infrastructure has deteriorated and is in need of repair or replacement *(Newhook et al, 1997)*. As a result, most bridges will require repair regardless of climate change. Second, the national standard for bridge design (CAN/CSA-S6-88) is in the process of being replaced with a more rigorous code. The new code will require bridges to be designed to last for 75 years (25 years longer than the present code). Many bridges, especially in British Columbia, are currently being retrofitted to be able to withstand earthquakes. As the stresses from an earthquake far exceed any building stress that could result from climate change and the new bridge code utilizes improved materials in construction, most new bridges will be more than adequately prepared to survive the influences of climate change. While changes in humidity and temperature have an effect on concrete and steel, much of the effects of climate change will be absorbed in the cost of upgrading existing structures to the new standards.

In the United Kingdom in 1990, 30% of bridges were in good condition, 50% of bridges were in fair condition and 20% of bridges were in poor condition. An estimate of repair on this bridge condition profile was approximately £10 million, to be spent on 200 bridges over 10 years. Bridges in good condition require an average expenditure of one quarter of the expenditures on bridges in fair condition. Bridges in fair condition require an average expenditure of one quarter to one fifth of the expenditures on bridges that are in poor condition. If bridges are allowed to deteriorate, the expenditures escalate enormously. It is a geometric, rather than an arithmetic progression in terms of costs versus condition for bridges. The deterioration of Canada's infrastructure will necessitate expenditures on bridges that will likely overshadow any climate change adaptation costs. Typical bridge replacement costs in the United States and Canada are $500,000 to $625,000 (Cdn); typical bridge replacement costs in the UK are double this amount.

The effects on capital expenditures for bridges can be subdivided into effects on inland versus coastal bridges. The increased effects of scour will be sustained as a maintenance cost. There may be additional costs on bridges with respect to vessel impacts. This will affect all bridges over water.

4.6.1.2.1: Inland Bridges

Inland bridges are not expected to sustain the impact that coastal bridges are expected to sustain. The impact of climate change in the form of increased loads is small compared to such factors as earthquake susceptibility. As stated earlier, provincial bridges in British Columbia are currently in the process of being retrofitted to withstand seismic activity. The increased strength and durability imposed by earthquake susceptibility retrofitting far exceeds any cost imposed by climate changes. Most bridges are over designed; there is sufficient strength in the structure to compensate for additional wind force, for example. Increasing the wind force by 100%, which is in excess of predicted levels, will only increase bridge construction costs by 5-10% and only on very large bridges *(Madar Bahkt, personal communication)*. Most bridges do not have enough exposed surface area to be affected by wind force. Increased scour due to increased water flow may have an effect on bridges over water and the addition of gabions or riprap to stabilize the substructure may be necessary.

4.6.1.2.2: Coastal Bridges

One of the primary impacts of global warming is sea level rise. In Canada, all provinces and territories have coastal areas except Alberta and Saskatchewan. One province, Prince Edward Island, is completely surrounded by ocean. The impact on bridges from sea level rise is twofold. Firstly, the substructure of the bridge will be more exposed to salt water and, therefore, more subject to the deleterious effects of chloride ions. The superstructure may be subject to increased salt spray, causing damage. Both concrete and steel are subject to breakdown by salt action. Concrete spalling and the corrosion of steel bridge structures result in a shortening of the longevity of the bridge. Increased spalling and corrosion can be alleviated by increased maintenance (cleaning, painting and repair). Concrete bridges are maintained by washing, patching broken concrete, replacing corroded expansion joints and drains and the use of electrical techniques to "pull" the chloride ions from the concrete. When a bridge must be rehabilitated, it is usually the superstructure that has deteriorated first, not the substructure. Bridge failure is not usually due to the deterioration of the structure of the bridge. More often, bridge failure is due to scour; the flow of water around the base of the structure tends to remove materials from the base and the bridge collapses. Although there are salt-water effects, the deterioration of bridges is not usually linked to a salt-water environment. Engineers do not consider a salt-water environment to be as major a source of bridge deterioration as road de-icing salts for state and provincial bridges. There may also be minor changes in the amount of deterioration due to changes in the amount of salt-laden fog in the coastal areas.

Secondly, the superstructure of the bridge may be too low to allow the passage of vessels underneath. Raising a bridge usually entails the removal of all, or part, of the bridge deck. This is a major expense, and may be close to the replacement cost for the entire bridge. In 1958-1959, the Jacques Cartier Bridge over the St.Lawrence River in Montreal, Quebec was raised from 12.2 metres to 36.5 metres above the water to accommodate ships passing through the newly constructed St. Lawrence Seaway. This "bridge raising" was only performed on the section of bridge between piers 9 and 10 and took 16 months. Thirty jacks with a capacity of 362.87 to 544.3 tons were employed to raise the bridge to its present level. Temporary bridges were also part of the cost; traffic was not disrupted *(Jacques Cartier and Champlain Bridges Incorporated http://www.pjcci.ca/English/jacques-cartier/construction.htm)*. The expense of raising a bridge is the cost of deck replacement plus the installation of jacks between the substructure and the superstructure. For the Jacques Cartier Bridge, this cost was $6,698,750 in 1959 for only a small section. It was possible to raise this particular bridge but, in most cases, the bridge will have to be replaced rather than raised. While there may be some effect from increased salt spray and increased exposure of the bridge to salt water, the major cost associated with increased sea level is the raising of the bridge to accommodate ship passage.

Most of the coastal bridges that will be affected by sea level rise are along the east coast of the country and were built over the Atlantic Ocean or the St. Lawrence River. The lower portion of the St.Lawrence River will be affected by sea level changes and the portion of the river affected by tidal influences may increase. Currently, the brackish water zone (where salt and fresh water mix) extends between La Pocatière and Île d'Orléans. Tidal effects may be felt as far south as Trois-Rivières. The topography of the west coast of Canada does not lend itself to the construction of coastal roads; hence there are few roads that span inlets from the Pacific Ocean. The coastline of the Arctic Ocean is sparsely populated and does not have many bridges. There are no major coastal roads running the length of the Arctic Ocean. A summary of the number of coastal bridges in the country in given in Table 4.6.12.

Table 4.6.12: Number of Coastal Bridges in Canada

Province	**Coastal Bridges (publicly maintained)** [1]	**Total Number**
Alberta	0 (no sea coast)	
British Columbia	5[2]	5
Manitoba	0[3]	
New Brunswick	700 (mostly provincial) including causeways[4]	700
Newfoundland	30 (provincial) 10 (municipal) [5]	40
Nova Scotia	1800 (provincial) very few municipal [6]	1,800
Ontario	0[7]	
Prince Edward Island	300 (provincial) [8]	300

Quebec	330 (provincial and municipal)[9]	330
Saskatchewan	0 (no sea coast)	
Northwest Territories	0[10]	
Nunavut	10[11]	10
Yukon	0[12]	
Total		3,185

[1] *Bridges maintained by the federal, provincial, regional and local governments*
[2] *Bill Szeto, BC Ministry of Transportation and Highways*
[3] *Manitoba Highways and Transportation; Town of Churchill*
[4] *Neil Gilbert, New Brunswick Department of Transportation (25% of total bridges)*
[5] *Peter Lester, Newfoundland Works, Services and Transportation*
[6] *Tom Gouthro, Nova Scotia Transportation and Public Works (50% of total bridges)*
[7] *Town of Moosonee*
[8] *Ken Hoy, Prince Edward Island Transportation and Public Works (25% of total bridges)*
[9] *based on 10% of total number of bridges in regions of Quebec with coastal areas*
http://www.mtq.gouv.qc.ca/regions
[10] *Larry Purka, Northwest Territories Transportation*
[11] *Doug Sitlin, Nunavut Community and Transportation*
[12] *Bernie Cross, Yukon Community and Transportation Services*

The total number of bridges in Canada that potentially need to be adapted to a rise in sea level is approximately 3,185. While it may be possible to utilize jacks or remove the deck and increase the height of the substructure, this may not always be feasible. The process is very individual, depending on the bridge design. Bridge replacement is more costly than bridge jacking but there may not be an alternative. The substructure of many bridges may not be able to withstand the additional weight, and improvements are often in order if any bridgework is required. Bridge replacement is likely the most viable alternative for bridges affected by sea level rise. Ocean-going vessels are increasing in size and decreasing in maneuverability, and will be expected to navigate into ports and under bridges with less clearance. The present clearances are not, therefore, excessive. In order to maintain the present portfolio of bridge infrastructure, approximately 3,185 coastal bridges will require replacement. There may be additional causeways that may have to be replaced, but this information was not readily available.

The replacement cost of bridges is unknown, as the new standard for bridge construction will be in effect shortly. One study in the United States estimates that $90 billion should be allocated to replace approximately 200,000 bridges *(Dunker and Rabbat 1993)*. If we take the total cost and divide it by the total number of bridges we get the average cost of $450,000 US per bridge for bridge replacement. At the present exchange rate of 1.5, this gives a cost of $670,000 Canadian. Estimates from Newfoundland and Manitoba on the average bridge replacement cost, at the provincial level, are currently $500,000 and $625,000 ($1.5 billion divided by 8,200 bridges) respectively. The average cost is therefore approximately $600,000 for a bridge. This appears to be consistent with the replacement of a variety of bridge sizes. The total cost to replace 3185 coastal bridges affected by climate change at an average cost of $600,000 would therefore be $1,911,000,000 (see Table 4.6.13).

Table 4.6.13: Coastal Bridge Replacement by Province

Province	**Total Number**	**Replacement Costs ($)**
Alberta		
British Columbia	5	3,000,000
Manitoba		
New Brunswick	700	420,000,000
Newfoundland	40	24,000,000
Nova Scotia	1,800	1,080,000,000
Ontario		
Prince Edward Island	300	180,000,000
Quebec	330	198,000,000
Saskatchewan		
Northwest Territories		
Nunavut	10	6,000,000
Yukon		
Total	**3,185**	**1,911,000,000**

Most of the costs of bridge replacement due to sea level rise will be borne by the Atlantic Provinces (Figure 4.6.3 and Figure 4.6.4). Nova Scotia is most vulnerable to the rise in sea level caused by climate change; over half the costs of bridge replacement will fall on this province. Other east coast provinces are much less susceptible.

Figure 4.6.3: Coastal Bridge Replacement by Province by the Year 2100

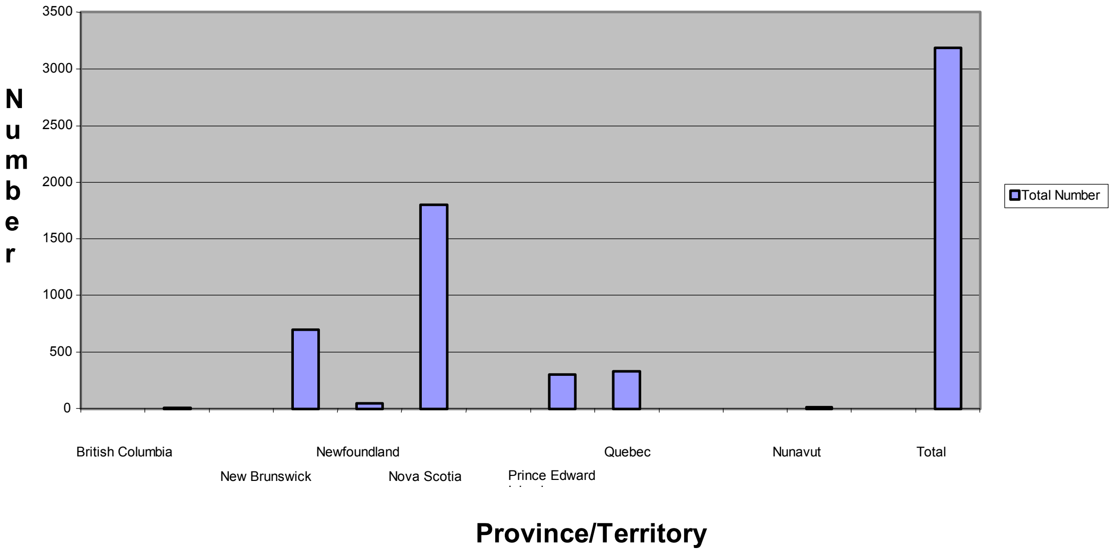
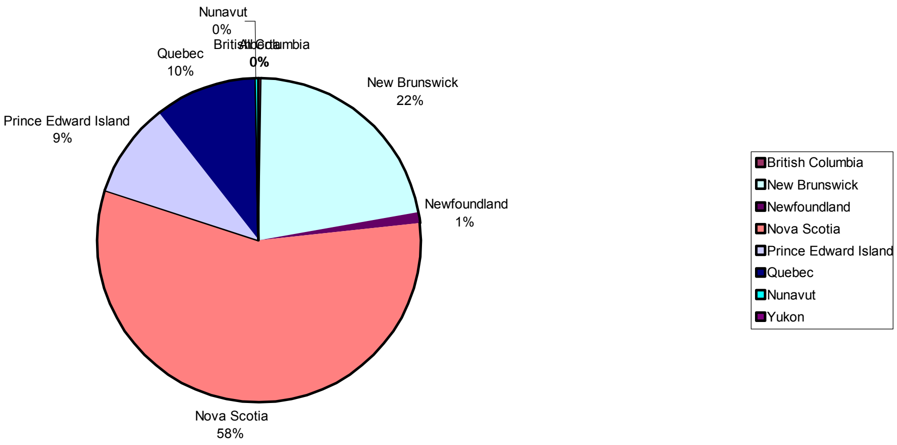


Figure 4.6.4: Proportion of Coastal Bridge Replacement Costs by Province



A summary of coastal bridge replacement costs for all levels of government is given by province in Table 4.6.14.

Table 4.6.14: Coastal Bridge Replacement by Province (Year 2100)

Province	Total Number	Replacement Costs ($)
British Columbia	5	3,000,000
New Brunswick	700	420,000,000
Newfoundland	40	24,000,000
Nova Scotia	1,800	1,080,000,000
Prince Edward Island	300	180,000,000
Quebec	330	198,000,000
Nunavut	10	6,000,000
Total	**3,185**	**1,911,000,000**

4.6.1.2.3: Bridges Over Water

All bridges over water are built to certain specifications regarding the impact of vessels on the structures themselves. There must be sufficient strength to withstand a ship hitting the piers of the bridge. While these incidents are fairly rare, they often have severe consequences for the bridge structure and lives are often lost when the bridge breaks apart. According to the report by the American Association of State Highway Transportation Officials (*1991)*, ship-bridge collisions are likely to increase. Many bridges are not currently designed to accommodate modern ships, which may exceed 800 feet in length and 100 feet in width. The bridge spans are often too narrow. If this is coupled with poor visibility, which often accompanies dense rainfall and high winds, ship-bridge collisions tend to increase in frequency. A bridge substructure that incorporates narrow spans on the bridge will increase the likelihood of collision under adverse hydraulic or wind conditions. In 1985, the St.Louis Bridge across the St.Lawrence near Valleyfield, Quebec was partially destroyed by a freighter that rammed one of the side spans of the lift bridge, temporarily closing the St.Lawrence Seaway. There are bridges in the United States that have been hit multiple times in the last 30 years. There are also indications that ship-bridge collisions are increasing. Between 1960 and 1970, there were 0.5 ship-bridge collisions per year. Between 1971 and 1982, there were 1.5 ship-bridge collisions per year. An increase in precipitation and wind speed with climate change will likely produce a greater number of ship-bridge collisions per year, with catastrophic life and property loss over the next 100 years.

4.6.1.3: Ditches and drains

The impact of climate change on capital costs for ditches and drains is expected to be large. The expenditures on ditches and drains are small, however, compared to the capital expenditures on roads and bridges and the overall costs are likely to be low for most of the country. The ability of the storm water management system to handle large flow volumes determines, at least to some degree, the longevity of the road system. The road surface is only expected to last 15-25 years but this is deceptive. An inadequate storm water management system will not only wash out, resulting in the loss of the culverts and destruction of the ditches and drains in the process, but the road over top of, and adjacent to, the culvert will also disappear. Larger storm water management facilities may sustain greater adaptation costs, especially if dams or dikes are involved.

4.6.2: Operating Costs

The impact of climate change on operating costs can be broken down into the impact on roads, bridges, ditches and drains (storm water management systems) and winter control. Winter control often includes operating costs that may be associated with bridges, roads and storm water management systems but municipalities do not separate these different aspects. Winter control is often separated from other operating costs, as it is a major portion of the budget of municipal, provincial and the federal government in many parts of the country. From our point of view, it was fortunate that this separation occurred. Winter control costs are severely affected by changes in climate. The climate variables involved in winter control costs are different from the climate variables that will affect summer maintenance on the road network and its associated components.

4.6.2.1: Roads

The impact of climate change on road operating costs is expected to fall mainly on road repair and primarily on paved roads. In order to maintain the integrity of the road surface and provide for safe movement of a car over the surface, roads must be patched regularly. Pothole formation occurs when the road surface freezes and thaws, causing cracking and erosion of the road surface. The road surface is also affected by frost heave in the more northerly parts of the country. Freeze-thaw cycles result when the temperature of the roadway moves above and below 0°C; these conditions are not a result of a severe climate. According to the Transportation Association of Canada (*https://mediant.magma.ca/tacatc/resource/viewDocuments.cfm?ID=16&member=REG*), there are indications that improvements in tolerance of high temperature rutting and low temperature cracking can be achieved through the use of different materials such as recycled tire rubber in asphalt pavements. While some improvements in the tolerance of pavement to freeze-thaw cycles can be expected, freeze-thaw cycles are critical to the amount of maintenance and the longevity of the pavement. An approximation of the number of freeze-thaw cycles across central and southern Canada is given in Table 4.6.14.

Table 4.6.14: Approximate Number of Freeze-Thaw Cycles in Heavily Populated Areas of Canada

Grid Box Number	1961-1990	Location
327	30	Central BC
328	63	Central BC
330	45	Central AB
331	30	Central AB
332	25	Central SK
333	36	Central SK

334	31	Central SK/MB
363	1	Southern BC
364	52	Southern BC
365	54	Southern BC
367	39	Southern AB/SK
368	42	Southern SK
369	46	Southern SK/MB
370	34	Southern SK
371	37	Northern ON
409	38	Northern/Central ON
410	36	Central ON
411	37	Eastern ON, Southwestern PQ
412	31	Southern PQ
413	59	NB, NS
414	55	NB, NS, PEI
417	0	Southern NF
444	41	Central ON
445	37	Southern ON
446	54	Southern ON

Some of the highest numbers of freeze-thaw cycles are found in the Atlantic Provinces (except southern Newfoundland), southern Ontario and parts of the interior of British Columbia. The southern part of British Columbia along the Pacific coast has few, if any, freeze-thaw cycles. The temperature is simply too high in this area throughout the winter. The Prairie Provinces do not appear to have as many freeze-thaw cycles. Although the climate is characterized by severe winters in this area, temperatures do not tend to hover near freezing. The advent of winter is characterized by a rapid progression from temperatures above freezing to temperatures below freezing. The Prairie springs are characterized by a rapid progression of temperatures below freezing to temperatures above freezing. There is little fluctuation over the late fall, winter and early spring. The effects of freeze-thaw cycles would be expected to be most severe in Alberta, Saskatchewan and Manitoba.

Roads in the colder, more extreme parts of the country would be expected to sustain more damage due to frost heave, where the duration of the winter and not the freeze-thaw cycles may factor more into the road maintenance costs.

4.6.2.2: Bridges

The changes in operating costs for bridges with climate change will arise from two sources, changes in scour for bridges that are over water and changes in deterioration due to changes in salt application. There may also be some changes in bridge deterioration due to changes in ground water salinity changes and changes in vegetation growth. It is not expected than any other climate factors will have a major impact on the maintenance costs for bridges. There may be small changes in the amount of concrete spalling due to changes in diurnal temperature ranges, but bridges are built to compensate for large variations in temperature. The daily temperature fluctuations have much less effect on a bridge than the seasonal fluctuations. Unless there is a large increase in the amount of temperature difference between the winter and the summer, there will be little effect on bridges. According to Phil Jarrett (*Environment Canada, personal communication)*, the climate is not getting warmer; rather, the climate is getting less cold.

The impact of climate change on bridge repair and maintenance will arise from changes in the speed and volume of water that flows past the substructure. Lower water flow will result in less scour effect for bridge substructures (*Madar Bahkt, personal communication*). The bridges over the Great Lakes and the St.Lawrence Seaway Bridges will likely be a cost saving on the substructure due to reduced maintenance and reduced bridge failure. In areas that will sustain heavier rainfall, the bridge substructure may be more subject to failure and more maintenance will be performed in the form of gabions and riprap.

Cost changes due to climate change impact will also result from changes in salt application. Salt is a major cause of the deterioration of bridges and salt application is related to temperature and precipitation. Salt is not needed above freezing and is not effective below -10°C. Salt will spall the concrete and corrode the steel in the bridge. Current bridge maintenance procedures, such as cathode extraction of chloride ions, may become more or less necessary depending upon the amount of salt that is applied to the bridge. Integral abutment bridges have been introduced in the last few years. These bridges lack the steel expansion joints in the middle of the bridge, thus rendering them less susceptible to the effects of salt and expensive bridge rehabilitation. A single expansion joint replacement may cost as much as $50,000 Canadian (*Ralph Sholtz, Regional Municipality of Niagara, personal communication)*. The use of this new type of design, which allows for the use of expansion joints only every 100 to 150 metres of bridge span results in more thermal expansion stress for the bridge structure but less impact from salt use.

4.6.2.2.1: Salt Application on Bridges

Scour is the greatest cause of bridge failure but salt is the major cause of bridge deterioration. Unfortunately bridges tend to "ice up" more than road surfaces and more de-icing chemicals are necessary to ensure that bridges are safe for both vehicles and foot traffic. There are a number of de-icing chemicals used to melt ice on bridge surface. Sodium chloride and calcium chloride are usually used to remove ice from road and bridge surfaces. Acetates, such as calcium magnesium acetate, may be used in place of the chloride compounds but the cost is considerably higher. Acetate compounds cost approximately $2,000 per tonne; sodium chloride costs approximately $65 per tonne *(Mittlestaedt, 2001)*. The chloride compounds are the de-icing chemicals of choice, except for large steel bridges, due to the considerable difference in price. The cost of repairing bridges affected by road salt corrosion is accepted as part of the cost of maintaining safe traveling conditions on the bridge. In spite of the lower costs of the chloride compounds, de-icing chemicals are one of the major costs of road maintenance, according to the Ontario Ministry of Transportation. At $65 per tonne the costs of road salt exceed $300 million per year in Canada. A warmer climate will reduce these costs in the areas of the country where salt is currently used for de-icing. For bridges such as the Thousand Islands Bridge at Gananoque, Ontario, climatic warming will reduce the direct costs of de-icing and winter control dramatically. This bridge complex is composed of two large steel suspension bridges and two smaller bridges. The maintenance costs exceed $2 million annually for these bridges. Acetate compounds are used on these bridges and the costs of winter control are high as a result.

Road salt corrodes steel bridges, any exposed steel rebar in concrete bridges, guard rails, expansion joints in concrete bridges plus lighting fixtures associated with bridges. Corrosion from road salt will also spall concrete, exposing the steel rebar to salt damage. Some improvements have been made in salt-induced deterioration of concrete bridges by changes in the type of concrete that is used, and by using epoxy-coated rebar, which is salt-resistant. In the new Canada Highway Bridge Design Code, stainless steel rebar is recommended, which will provide greater protection against bridge deterioration. Some additional longevity in bridges has been provided by the development of cathode rehabilitation. This technique will draw the chloride ions from the concrete and may add 10 years to the lifespan of the bridge. It should be pointed out, however, that most of the bridges in Canada pre-date the development of stainless steel rebar and improved concrete. There have been a few problems with the integrity of the concrete as a result of the use of cathode rehabilitation. Road salt will likely continue to be a major cause of bridge deterioration. Toronto alone uses 130,000 tonnes of road salt yearly. The largest users of road salt include Toronto, Ottawa, Halifax and Quebec City; these cities lie within a climatic zone where the temperature range in winter permits the melting of snow using de-icing chemicals. Vancouver uses some salt, but the temperatures are usually too warm for ice formation *(Mittlestaedt, 2001).* Other cities, such as Edmonton, Calgary, Regina, Saskatoon and Winnipeg, are too cold, rendering salt ineffective for much of the winter. A reduction or increase in the use of road salt as a result of climate change will make a difference to the operating costs associated with bridges.

4.6.2.3: Ditches and Drains

The impact of climate change on the costs associated with maintaining ditches and drains and the storm water management system are expected to be very small. Maintenance of ditches and drains is a very small component of operating costs and these procedures are often performed at the same time as the regular road inspection and maintenance. There are indications that changes in the amount of mowing may be necessary *(Palutiko et al, 1997, pg135)*. It is also possible that there may be changes in the amount of material that passes through the drains and culverts, resulting in an increased or decreased need to flush and clean the storm water management system. Culvert thawing involves ditches and drains maintenance but is usually included as part of winter control budgets.

4.6.2.4: Winter Control

The impact of climate change on the costs associated with winter control is substantial. Winter control may be as much as 50% of a municipal road operations budget, depending on the amount of service that the municipality provides. Some cities clear streets, sidewalks and windrows. The winter control budget for these cities constitutes a large portion of the funds allocated to roads operations expenditures. Other cities have no winter control budget. Temperatures rarely reach freezing and snow and ice formation is consequently not a problem. Winter control costs are therefore related to both the level of service and the winter conditions. It is reasonable to assume that the winter control costs will vary to a large degree with the amount of snowfall. This relationship is somewhat complicated by the distribution of snowfall; it is possible to have a few large snowfalls during the winter that result in very high winter control costs. It is also possible to have low winter control costs if the snow is evenly distributed as frequent, very light snowfalls throughout the winter season. Large snowfalls are particularly expensive for the municipalities, as cities and towns often do not have the space to store excess snow. Provincial ministries of transportation often utilize right-of-ways for snow storage and are able to handle heavy snowfalls more easily.

The costs of winter control vary considerably across the country, which is not unreasonable considering the variability in climate and the level of services provided for a vast geographic area. Based on our questionnaire response, costs of winter control may range from 0 to nearly 50 % of the roads operating expenditures for an individual municipality. As operating expenses comprise a substantial portion of the roads operating expenditures, the effect of increases or decreases in such costs as a result of regional climate change could be substantial. The relationship between winter control costs can be expected to vary with location, with the level of service provided by the municipality and with the ability of the individual municipality to levy taxes to pay for these services. Winter control will vary considerably with geography; the City of Victoria in southern coastal British Columbia has no winter control budget but the City of Yellowknife in the Northwest Territories could not reasonably be expected to have no winter control expenditures.

We have initially speculated that there is a linear relationship between winter control expenditure and total snowfall, per km of roadway, ignoring differences in the level of service between municipalities. This may be an oversimplification, as we are not capturing differences in costs associated with different types of roadways. Paved roads usually accommodate more traffic and have higher plowing, sanding and salting costs than gravel roads. Highways with higher superelevation (8% versus 6%) must be salted and sanded more frequently for safety reasons. Paved roadways may also be multi-lane and the kilometres of road may not reflect the actual amount of road surface. Gravel roads are usually narrower and require less plowing. Winter control for gravel roads does not usually include salting. The amount of snowfall is not the only parameter involved in winter control costs; the distribution of snowfall is critical to the need for snow removal. Costs depend on the snow pack and accumulation and not just on simple snowfall. In general, however, municipalities that have more snowfall on their roadways should incur higher costs, *ceteris paribus*. This should logically be reflected in empirical analysis of real world data.

A general relationship of the following structure was examined:

$$\mathbf{WC_i = \alpha_0 + \beta_1 Sn_1 + \beta_2 D_{2i} + \beta_3 D_{3i} + \ldots + \beta_n D_{ni} + u_i}$$

WC - winter control expenditure per km of roadway (1996, 1997 or 1998 dollars)
n - total annual snowfall, in centimetres, based on Canadian Climate Normals
D - dummy variables that are introduced to take into account location factors that influence costs
α - constant
β - slope (rate)

u - residuals (error)

In order to undertake the above analysis we would normally require a fairly rich data set, with reliable information on actual winter control operating expenses and measures of the size of the infrastructure characteristic in question, including the number of kilometres of roadway, the type of road surface and the level of service for which the municipality is responsible. Unfortunately, we did not have so rich a data set to work with. We began with a sample of 98 municipalities. The numbers of kilometres of roads was available for only 26. In the case of 10 of these 26, there seemed to be glaring inconsistencies as to the size of expenditures in relation to the number of kilometres of roadways. We were therefore forced to drop these municipalities from our sample. That left us with 16 municipalities for which the data seemed reasonable.

We then plotted a scatter diagram of winter control expenditure per km of roadway against total snowfall per annum in centimetres. As expected, there was a simple linear relationship between winter control expenditure and total snowfall. We did note, however, that the data from the City of Yellowknife appeared to be an "outlier." What we seemed to have was a group of municipalities that probably face similar economic conditions and input cost structures with one exception. Unfortunately, we are unable to carry out the analysis outlined above using dummy variables to capture the locational differences, as there were not enough data points. We were forced to drop the anomalous observation on the assumption that the municipalities included in the analysis are fairly homogeneous from the standpoint of the sorts of input costs they face. We were then left with 15 data points, displayed in Figure 4.6.5 and noted in Table 4.6.15.

Figure 4.6.5: Winter Control Expenditure Versus Annual Snowfall (per km of road)

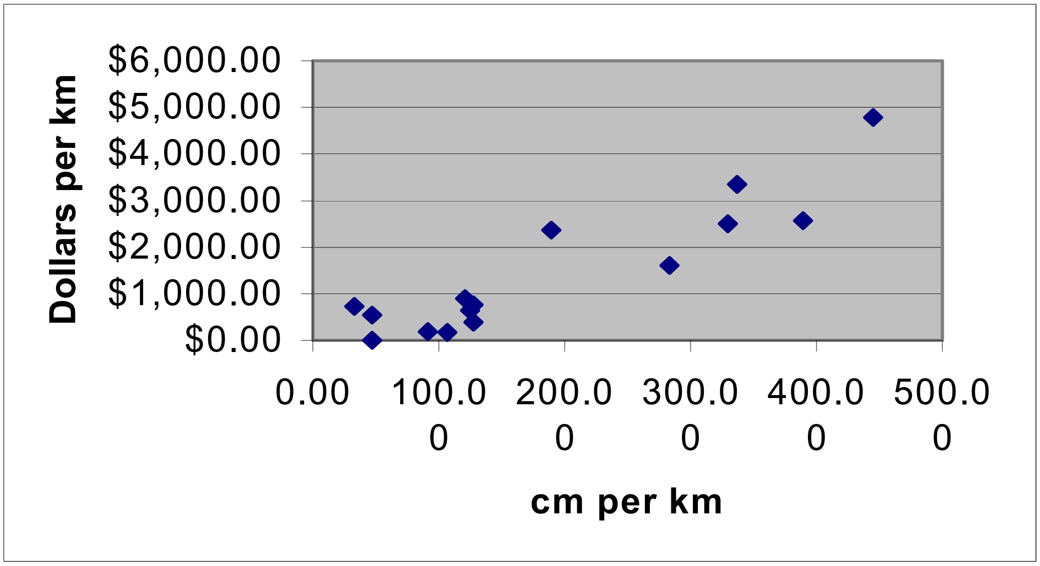


Table 4.6.15 Winter Control Costs – Selected Municipalities

Municipality	Population (1996)	Operations-Winter Control-fraction	Operations-Winter Control-actual	Operations Budget-Total	Kilometres of Roads	Winter Control Expenditure per Kilometre	Snowfall in cm
Terrace	12779	0.17	$334,019.53	$1,941,974.00	130.00	$2,569.38	389.00
Quesnel	8468	0.12	$205,492.08	$1,712,434.00	87.00	$2,361.98	189.40
Morinville	6226	0.34	$34,346.80	$101,020.00	45.29	$758.37	127.20
Spruce Grove	14271	0.28	$46,639.60	$166,570.00	117.50	$396.93	127.20
Red Deer	60075	0.20	$237,963.60	$1,189,818.00	366.00	$650.17	125.10
Vermilion	3744	0.50	$662,295.50	$1,324,591.00	3806.00	$174.01	106.70
Esquimalt	16151	0.02	$25,105.95	$1,394,775.00	47.00	$534.17	46.90
Comox	11069	0.02	$12,954.32	$647,716.00	67.00	$193.35	91.40
Port Alberni	18468	0.06	$183,128.45	$3,157,387.00	206.00	$888.97	120.50
Victoria	73504	0.00	$0.00	$13,665,813.00	259.00	$0.00	46.90
Richmond	1422	0.03	$434,561.61	$14,485,387.00	593.00	$732.82	32.80
Revelstoke	8047	0.28	$472,743.04	$1,688,368.00	99.00	$4,775.18	445.30
Pont-Rouge	4676	0.45	$314,665.11	$695,700.00	94.15	$3,342.17	337.00
Digby	2199	0.35	$49,247.80	$140,708.00	30.60	$1,609.41	283.30
Kentville	5551	0.27	$118,709.01	$439,663.00	47.40	$2,504.41	329.50

We can take the information from this figure and table and undertake the simpler analysis following the general model:

$$\mathbf{WC_i = \alpha_0 + \beta_1 Sn_1 + u_i}$$

WC - winter control expenditure per km of roadway (1996, 1997 or 1998 dollars)
Sn - total annual snowfall, in centimetres, based on Canadian Climate Normals
α - constant
β - slope (rate)
u - residuals (error)

It should be noted that any conclusions drawn are applicable to municipalities similar to those in the data set, from the standpoint of input costs.

The fitted model is expressed as follows:

$$\mathbf{\hat{W}C_i = -326.7809 + 9.4321Sn_1}$$

265.4963	1.1676
t=(-1.23)	08

These results from the regression equation indicate that a one-centimetre increase in total annual snowfall leads to a $9 per km increase in winter control costs. Indeed as this is averaged data, it might be sensible to take the 95 percent upper confidence limit of the estimate, which is $11.95. That is, we are 95 % confident that one-centimetre of snowfall leads to $12 per km increase in winter control costs. The coefficient estimate on the intercept term is not statistically different from zero, which agrees with our intuition that cities that have no snowfall incur no winter control costs.

In order to extrapolate this relationship and produce an indication of costs resulting from a change in climatic conditions, it is necessary to utilize the climate scenario projections provided by CGCM1 GG1. Unfortunately, the information provided by CGCM1 is spatially and temporally averaged and does not provide exact information on changing snowfall patterns at a coarse or fine (local) level. Information on snowfall can only be projected from CGCM1 GG1 on the basis of monthly precipitation that falls when the mean temperature is below 0°C. Projected global average warming will be accompanied by significant regional variations in warming and shifts in precipitation belts. Climate models generally predict greater warming than the global average at middle to high latitudes, including Canada, and a greater warming in winter than in summer at middle to high latitudes. More winter precipitation at mid latitudes is predicted but there are wide differences on changes in summer precipitation.

A simulation of the present day distribution of precipitation, cloudiness, soil moisture and ice and snow amounts is a necessary but not sufficient condition for reliable simulation of regional changes in adaptation costs. Many important processes, such as cloud development, precipitation and land surface hydrological changes, occur at scales finer than the grid resolution of climate models and therefore cannot be adequately represented. The information that is currently available allows only a rough estimation of the impact of climate change.

At present, global climate models seem to indicate that:

1. In general, winters will be 3-5°C warmer in the south and 10-15°C warmer in the Arctic; summers will be warmer by 2°C in the south and 3°C in the Arctic.
2. Storm tracks would be displaced northward increasing Arctic precipitation; snow seasons would be shorter in the Arctic but snow totals and spring runoff might be greater.

There are two approaches to calculating winter control costs. We can think in terms of climate change analysis as trading climates. For example, by 2030 enhanced greenhouse warming is expected to give Toronto the climate of Pittsburgh in the 1980s, Sudbury that of Cleveland, Winnipeg that of Minneapolis, Charlottetown that of Boston, Edmonton that of Cheyenne, Wyoming and Vancouver that of San Francisco. Consequently, by 2030 we might reasonably expect municipalities in southern British Columbia to have little or no annual snowfall, those in southern Alberta to have about 20 percent less total snowfall, and those in the southern Maritimes to have about two-thirds less snowfall. Based on these rough generalizations, figures for expected expenditures for winter control were calculated using the above regression equation. The results are displayed in Table 4.6.16.

Table 4.6.16: Projected Cost Changes for Winter Control to 2030

Municipality	Snowfall in cm	Expected Snowfall 2030	Expected Expenditure 2030 per km	Fitted Value	Difference
Terrace	389.00	310.00	$2,597.17	$3,342.31	-$745.14
Quesnel	189.40	150.00	$1,088.03	$1,459.66	-$371.62
Morinville	127.20	100.00	$616.43	$872.98	-$256.55
Spruce Grove	127.20	100.00	$616.43	$872.98	-$256.55
Red Deer	125.10	100.00	$616.43	$853.17	-$236.75
Vermilion	106.70	85.00	$474.95	$679.62	-$204.68
Esquimalt	46.90	0.00	-$326.78	$115.58	-$442.37
Comox	91.40	0.00	-$326.78	$535.31	-$862.09
Port Alberni	120.50	100.00	$616.43	$809.79	-$193.36
Victoria	46.90	0.00	-$326.78	$115.58	-$442.37
Richmond	32.80	0.00	-$326.78	-$17.41	-$309.37
Revelstoke	445.30	350.00	$2,974.45	$3,873.33	-$898.88
Pont-Rouge	337.00	100.00	$616.43	$2,851.84	-$2,235.41
Digby	283.30	100.00	$616.43	$2,345.33	-$1,728.90
Kentville	329.50	100.00	$616.43	$2,781.10	-$2,164.67

On the basis of intuition, these results seem reasonable. The cost projections for winter control given above are consistent with other information about global warming. Global warming should result in cost savings for winter control, provided the magnitude of the temperature increase overshadows the increase in precipitation resulting from the acceleration of the hydrologic cycle. The above calculations based on the estimated regression suggest that for the municipalities given in Table 4.6.16, the expenditure on winter control can be expected to go down. Global warming should lead to a reduction in snowfall for most of Canada. Projected changes in winter temperatures and snowfall are given in the tables in Appendices 4.6.2 and 4.6.3. However, as to how these projections could be used to simulate future costs of adaptation remains a subject for future research.

4.6.3: Directions for Future Research

In this report we have concentrated on the adaptation costs for roads in the following categories:

1. For northern Canada we have looked at the adaptation costs involved in converting winter/ice roads to all weather roads (a capital cost). We have also looked at the capital costs for roads in dealing with the loss of permafrost.
2. For the coastal areas of Canada we have looked the capital costs for bridge replacement.
3. For road maintenance we have looked at winter control costs and road repair costs.

Based on our preliminary research, there are still a number of areas that need to be addressed in so far as climate adaptation costs are concerned.

4.6.3.1: Roads

Road capital and maintenance costs need to be addressed in greater detail. One could purchase digital road data from Natural Resources Canada's Centre for Topographic Information as a series of CD ROMs (*http://maps.nrcan.gc.ca/*). This digital road information, which is available as a series of 1:50,000 maps, is called the Updated Roads Network (URN) and is available for sections of the country. The data are available as ArcView shape files, which are compatible with our GIS. At the present time, only a small portion of the country has been completed. The cost per CD ROM is approximately $300 and the coverage is fairly detailed. The Niagara Peninsula, for example, is covered by five CD ROMs (five topographic sheets), which would cost $1500. This is only a small portion of the country (12 small census subdivisions). While the detail in the urban areas may not be sufficient for climate change adaptation analysis, these maps may be useful for the less populated areas of the country.

Many of the costs associated with climate change adaptation have been evaluated without consideration for the type of road, although we know that the activities associated with paved roads and other types of roads are different. Our data have shown that about 50% of all roads in Canada are gravel roads. It would be appropriate to determine whether there are differences in costs associated with the different types of roads. We expect that gravel roads would be situated largely in northern communities or in southern rural communities. The impact of climate change adaptation for roads across the country may be quite different on this basis alone.

The impact of changes in avalanches may result in greater or lesser costs for road construction and maintenance. At present, snow sheds and tunnels are used to deflect snow from the roadway, thus avoiding both the maintenance costs of clearing large amounts of snow and the possibility of vehicles being buried and lives lost. More or fewer avalanches may result from the changes in climate parameters producing specific snow and temperature conditions. This may increase or decrease the need to put protective structures on roads in the mountainous areas where avalanches are common.

Permafrost monitoring has been ongoing for many years in the Arctic, particularly in the discontinuous permafrost zone. A more detailed examination of the impact of permafrost loss on the interaction between permafrost and roads is warranted. The results of a recent conference in Whitehorse (March, 2001) have underlined the magnitude of the changes. The impact of climate change for roads, in terms of both permafrost and winter/ice roads, is expected to be large.

4.6.3.2: Bridges

Bridge information is also available as part of the URN digital data. As in roads, the data may be too coarse for analysis of the urban areas but these data may be suitable for analyzing the rural and northern areas. In addition, it was discovered that the definition of a bridge was quite variable from one province to the next. In Alberta, a bridge was any structure spanning over 1.8 m; in Newfoundland, a bridge was any structure spanning over 6 m. The data were collected without considering the differences in definition; consequently the tallies for different parts of the country may be over or under estimated.

Changes in bridge construction and replacement as a result of ship-bridge collisions induced by climate change should be examined. Changes in visibility resulting from climate change plus water level rise or fall may have an impact on the number of times that ships hit bridges over a year. Increased ship-bridge collisions increase the number of bridge replacements and may require that the bridge designs be changed in the future. Larger bridge spans may be required to avoid collisions and stronger piers may have to be built to withstand the collision with a ship. Ship-bridge collisions often result in both loss of life and heavy property damage.

The effect of road salt on winter control costs and on bridge maintenance have yet to be determined. The use of road salt is determined by a temperature minimum and maximum; the use of road salt is not a simple relationship with temperature. Precipitation also factors heavily into the use of de-icing chemicals. Temperatures below 0°C do not result in increased use of road salt if there is no precipitation. The application of de-icing chemicals involves a direct cost, as part of winter control costs, and an indirect cost, as part of bridge repair, rehabilitation and replacement.

4.6.3.3: Storm Water Management Systems

At present, we have no handle on the costs of adaptation for storm water management systems. Larger amounts of precipitation would be expected to result in increased costs for larger culverts, deeper ditches and larger storm water detention ponds. Large water management structures, such as dams, must also be taken into consideration. These structures are identified by the URN digital database and further analysis may be considered for these structures using a digital database. The costs of failure for the current storm water management systems must also be considered. Although the cost of a larger culvert is small, the cost of installing a larger culvert is large; sections of road must be removed, the new culvert installed and the road replaced after. This must be weighed against the probability of any particular section of road washing out due to insufficient culvert size.

4.6.4: Summary

1. There may be changes in the number of freeze-thaw cycles. A change in freeze-thaw cycles is more likely to occur in the heartland with fewer cycles on the west coast. An overall increase of approximately 5°C is expected to occur, accompanied by an increase of approximately 10% in precipitation.
2. The distribution of roads and bridges between the provincial and local governments is quite variable across the country. In Ontario, the regional government assumes much of the responsibilities for road, bridge and storm water management system construction that would otherwise be handled by the province. Other provinces, such as British Columbia, also have a two-tier local government system. Both the municipal and regional levels of government handle roads.

3. About two-thirds of all roads in Canada are under municipal jurisdiction, about a quarter are under provincial and the rest are under Federal jurisdictions.
4. Roadways are fairly consistent in their design standards as well. Most provinces use the Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Roads. There are also guides specific to each province, which often exist to accommodate special considerations for climate within the province.
5. About 50 percent of all roads in Canada are gravel roads; about a third are paved roads.
6. The standards for bridge design are fairly consistent across the country, with the Canadian Standards Association guide, CAN/CSA-S6-88, used in most provinces.
7. Storm water management system guidelines are very diverse across the country. In most provinces, the design of the drainage system and the level of protection provided for the associated road depend upon the type of road. Major highways have more protection against flooding than local roads.
8. A single bridge estimate, which is usually performed before any work is undertaken, may cost $15,000.
9. Climate affects both capital and operating expenditures. Climate and other environmental factors constitute one component of the deterioration of roads, bridges and storm water management systems; the impact of human activities is the other.
10. The road system in British Columbia, particularly the bridges, is already over-designed for climate factors, as considerations for seismic activity must be taken into account already. In the Northwest Territories, considerations for the

behaviour of permafrost add almost 50% to the cost of road building per km. A road built on permafrost costs approximately $500,000 per km to construct; a road on non-permafrost costs approximately $350,000 per km to construct in the Northwest Territories.

11. Freeze-thaw cycles and frost heave (temperature effects on soil moisture) require specific depths of well-drained materials below the road surface to prevent the deleterious effects of these climatic effects on the roadbed.
12. The highway expenditures in Canada vary across the country. The lowest expenditures per kilometre of road are found in the Prairie Provinces and the Atlantic Provinces. British Columbia, Ontario and Quebec have the highest expenditures per kilometre. These provinces also have high percentages of paved roads. The percentage of paved roads varies from a low of 5% in the territories (Yukon, Northwest Territories and Nunavut) to a high of 78% in Quebec. The Prairie Provinces generally have a low percentage of paved roads. The provincial expenditures per vehicle do not vary as much as the expenditures per kilometre of road. Some of the differences in provincial road expenditures may be due to higher traffic volumes and the increased wear and tear on the road. This is not the only explanation for the differences.
13. Bridges, compared to other structures, are exposed to the most adverse environments of loading and climatic change. The climatic loads that must be considered in bridge design include water loads, ice loads, scour, stream instability, temperature effects, wind effects, frost effects, groundwater effects

and soil properties. All of these factors contribute to the cost of bridge construction.

14. About 75 percent of bridges in Canada are old and will require replacing anyway. When they are replaced using the new higher standards, these bridges will be over-dimensioned and will not need any further adaptation to climate change. Therefore the climate change adaptations costs will be near zero for bridges.
15. Coastal bridges will need to be replaced due to sea level rises, as it is cheaper to replace than to raise bridges. The average cost of a bridge is $600 000. The total cost of replacing over 3000 bridges is estimated to about be $2 billion.
16. There are about 10 000 km of ice roads; most of these are in Ontario and Quebec. Therefore these two provinces will incur the highest adaptation costs for ice roads.
17. All weather roads are considerably more expensive to build and maintain. In northern Ontario, construction of an all-weather road will cost at least $85,000 per km plus bridges. An average bridge for an all weather road in Ontario will cost between $65,000 and $150,000 per bridge.
18. If, by the year 2100, all of the winter/ice roads that will no longer be in use are replaced with all weather roads, and 50% of the winter/ice roads that have restrictions placed on them are replaced with all weather roads, the number of kilometres of roads that will require replacement will be about 10,000 km, costing $908 million.

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Appendix 4.6.1:
Standards for Ice Road Use – White Ice

WHITE ICE - Layers of the ice may have formed from melting snow or slush and is white to opaque in appearance. Normally associated with river crossings.

Thickness in centimetres	Equivalent inches	Load-pounds	Load - kg
15	6	1,482	673
20	8	2,635	1,196
25	10	4,117	1,868
30	12	5,929	2,690
35	14	8,070	3,662
40	16	10,540	4,782
45	18	13,340	6,053
50	20	16,469	7,473
55	22	19,927	9,042
60	24	23,715	10,760
65	26	27,832	12,629
70	28	32,279	14,646
75	30	37,055	16,813
80	31	42,160	19,130
85	33	47,595	21,596
90	35	53,359	24,211
95	37	59,452	26,976
100	39	65,875	29,890
105	41	72,627	32,954
110	43	79,709	36,167
115	45	87,120	39,530
120	47	94,860	43,042
125	49	102,930	46,703
130	51	111,329	50,514

(http://www.highways.gov.sk.ca/travellers_information/ice_roads.htm)

Standards for Ice Road Use – Blue Ice

BLUE ICE - relatively clear type of ice, no snow/slush frozen in layers in the ice; usually found on lakes, but not on river crossings. Colour may range from clear to almost black.

Thickness in centimetres	Equivalent inches	Load in Pounds	Load in Kilograms
15	6	2,964	1,345
20	8	5,270	2,391
25	10	8,234	3,736
30	12	11,858	5,380
35	14	16,139	7,323
40	16	21,080	9,565
45	18	26,679	12,105
50	20	32,938	14,945
55	22	39,854	18,083
60	24	47,430	21,521
65	26	55,664	25,257
70	28	64,558	29,292
75	30	74,110	33,626
80	31	84,320	38,259
85	33	95,190	43,191
90	35	106,718	48,422
95	37	118,905	53,951
100	39	131,750	59,780
105	41	145,255	65,907
110	43	159,418	72,334

115	45	174,240	79,059
120	47	189,720	86,083
125	49	205,860	93,406
130	51	222,658	101,028

Appendix 4.6.2:
Winter Temperatures 1961-1990 (Baseline)

GRID BOX NUMBER	**1961-1990 NOV**	**1961-1990 DEC**	**1961-1990 \JAN**	**1961-1990 FEB**	**1961-1990 MAR**	**1961-1990 APR**	**MEAN TEMP 1961-1990**
183	-15.09	-21.11	-26.27	-28.12	-22.98	-14.40	**-21.33**
184	-14.99	-21.65	-27.39	-28.16	-20.75	-10.85	**-20.63**
185	-16.46	-22.55	-28.19	-28.92	-21.27	-10.84	**-21.37**
186	-17.00	-22.52	-27.85	-29.70	-24.84	-15.64	**-22.92**
187	-16.70	-22.16	-26.77	-28.16	-24.41	-15.56	**-22.29**
188	-16.72	-21.80	-25.65	-26.77	-23.43	-15.19	**-21.60**
189	-16.91	-22.07	-25.31	-26.84	-23.19	-15.20	**-21.59**
218	-11.15	-18.81	-21.53	-21.08	-13.41	-6.31	**-15.38**
219	-11.24	-19.27	-22.91	-23.93	-18.21	-10.11	**-17.61**
220	-6.97	-18.91	-22.76	-21.33	-13.41	-5.63	**-14.84**
221	-7.17	-19.51	-23.52	-21.82	-13.37	-4.49	**-14.98**
222	-6.66	-19.35	-23.46	-21.44	-12.57	-3.18	**-14.44**
223	-7.68	-19.04	-22.78	-20.57	-11.85	-2.57	**-14.08**
224	-8.26	-19.65	-22.72	-20.03	-11.76	-2.81	**-14.20**
225	-5.19	-20.06	-23.13	-20.82	-13.06	-4.47	**-14.46**
226	-9.64	-21.62	-25.77	-26.14	-21.89	-11.96	**-19.50**
253	-3.61	-10.09	-11.68	-13.30	-10.03	-5.51	**-9.04**
254	-1.70	-9.37	-11.55	-12.01	-8.37	-4.07	**-7.84**
255	-1.56	-10.21	-12.97	-13.02	-9.00	-4.15	**-8.49**
256	-1.40	-10.89	-14.38	-13.80	-9.25	-3.73	**-8.91**
257	-0.78	-10.12	-15.62	-13.99	-8.98	-2.26	**-8.62**
258	-0.33	-9.69	-16.40	-14.01	-8.19	-1.04	**-8.28**
259	-0.30	-11.08	-17.05	-14.00	-6.74	0.03	**-8.19**
260	-0.78	-12.02	-17.09	-14.24	-6.41	0.18	**-8.39**
261	-0.25	-11.18	-17.72	-15.27	-7.87	-1.13	**-8.90**
262	-0.95	-13.58	-19.19	-17.39	-10.42	-3.57	**-10.85**
263	-4.43	-17.89	-21.58	-21.99	-16.65	-9.56	**-15.35**
270	0.15	-2.09	-6.24	-13.28	-13.98	-10.28	**-7.62**
271	-2.68	-15.34	-22.30	-24.83	-22.52	-14.06	**-16.95**
272	2.14	-1.01	-4.09	-9.42	-11.68	-9.27	**-5.55**
295	0.85	-2.49	-10.18	-10.02	-4.47	0.07	**-4.37**
296	0.67	-5.04	-11.76	-10.78	-4.65	0.57	**-5.17**
297	0.63	-4.51	-13.83	-12.46	-5.95	-0.45	**-6.10**
298	0.12	-8.35	-17.16	-15.05	-8.36	-1.64	**-8.41**
299	-0.44	-11.97	-19.46	-17.24	-10.26	-3.11	**-10.42**
300	-0.99	-14.45	-20.24	-18.22	-11.60	-4.38	**-11.65**
301	-1.55	-16.57	-22.66	-23.59	-18.78	-9.97	**-15.52**
305	3.50	-0.85	-4.85	-13.27	-13.89	-8.79	**-6.36**
306	-0.05	-12.46	-19.13	-21.48	-18.57	-10.65	**-13.72**

307	-0.51	-11.71	-16.52	-18.06	-15.79	-9.55	**-12.02**
308	-0.19	-10.92	-15.70	-16.84	-14.09	-8.44	**-11.03**
309	0.40	-9.64	-16.55	-17.87	-14.01	-7.89	**-10.93**
335	0.18	-9.76	-15.21	-12.80	-5.45	1.29	**-6.96**
336	0.35	-9.08	-15.15	-13.32	-7.59	-0.97	**-7.63**
337	0.67	-10.00	-18.52	-18.79	-15.05	-7.09	**-11.46**
338	0.82	-9.99	-17.66	-19.15	-15.36	-7.73	**-11.51**
339	1.07	-8.91	-17.38	-19.06	-15.31	-7.68	**-11.21**
340	0.92	-5.38	-13.61	-14.06	-10.43	-3.98	**-7.76**
341	0.39	-7.23	-14.55	-15.04	-11.12	-4.87	**-8.74**
342	-0.35	-8.81	-15.49	-15.93	-11.68	-5.42	**-9.62**
343	0.05	-8.05	-14.97	-15.52	-11.27	-5.44	**-9.20**
371	1.35	-5.52	-11.25	-9.74	-3.98	2.26	**-4.48**
372	1.32	-4.91	-11.93	-10.39	-4.91	0.22	**-5.10**
373	1.48	-3.70	-11.56	-10.73	-5.51	0.06	**-4.99**
374	1.69	-2.95	-10.55	-10.61	-5.73	0.48	**-4.61**
375	1.70	-1.70	-9.51	-10.23	-5.99	0.04	**-4.28**
376	1.36	-1.31	-9.04	-10.39	-6.72	-0.98	**-4.51**
377	1.08	-1.89	-9.62	-10.79	-7.30	-1.60	**-5.02**
378	1.47	-1.24	-9.03	-10.22	-7.08	-1.73	**-4.64**
379	6.00	2.66	-0.65	-2.53	-2.90	-0.84	**0.29**
411	2.58	0.37	-2.98	-6.60	-2.71	1.64	**-1.28**
412	2.73	0.58	-2.12	-5.74	-2.38	1.39	**-0.92**

Winter Temperatures 2010-2039

GRID BOX NUMBER	**2010-2039 NOV**	**2010-2039 DEC**	**2010-2039 JAN**	**2010-2039 FEB**	**2010-2039 MAR**	**2010-2039 APR**	**MEAN TEMP 2010-2039**
183	-12.50	-18.84	-22.53	-22.63	-18.34	-10.09	**-17.49**
184	-11.39	-19.74	-23.00	-22.17	-15.91	-7.20	**-16.57**
185	-12.96	-20.86	-24.22	-22.79	-15.90	-6.68	**-17.23**
186	-13.77	-20.94	-25.06	-24.31	-19.47	-11.57	**-19.19**
187	-13.87	-20.23	-24.87	-24.35	-19.24	-11.77	**-19.06**
188	-13.85	-19.52	-23.59	-23.94	-19.14	-12.26	**-18.72**
189	-14.30	-19.21	-23.33	-24.19	-19.62	-12.91	**-18.92**
218	-8.24	-16.07	-18.37	-16.49	-9.71	-4.16	**-12.17**
219	-7.75	-16.49	-19.05	-18.34	-13.78	-7.50	**-13.82**
220	-4.39	-16.15	-19.16	-15.99	-9.50	-3.36	**-11.42**
221	-5.35	-17.12	-19.93	-16.78	-9.59	-2.28	**-11.84**
222	-4.33	-17.38	-20.60	-17.08	-9.20	-1.40	**-11.66**
223	-5.59	-17.08	-20.80	-17.01	-8.93	-0.80	**-11.70**
224	-6.19	-17.20	-20.85	-17.27	-9.10	-1.06	**-11.94**
225	-2.32	-16.30	-21.32	-18.28	-10.32	-2.56	**-11.85**
226	-5.64	-18.04	-23.18	-23.56	-18.58	-10.59	**-16.60**

253	-1.04	-6.97	-9.66	-9.81	-7.27	-4.01	**-6.46**
254	-0.04	-6.07	-9.66	-8.80	-5.68	-2.42	**-5.45**
255	-0.27	-7.24	-11.32	-9.89	-6.28	-2.38	**-6.23**
256	-0.20	-8.04	-12.81	-10.90	-6.70	-1.81	**-6.74**
257	0.22	-7.10	-13.75	-11.32	-6.52	-0.59	**-6.51**
258	0.54	-6.25	-14.27	-11.26	-5.58	0.30	**-6.09**
259	-0.21	-9.09	-15.23	-11.58	-4.32	1.85	**-6.43**
260	-0.29	-9.85	-15.12	-11.83	-4.47	1.93	**-6.61**
261	0.85	-6.80	-15.81	-13.19	-5.78	-0.03	**-6.79**
262	0.59	-7.80	-17.48	-15.40	-8.52	-1.86	**-8.41**
263	-1.23	-13.56	-19.57	-19.72	-13.47	-7.09	**-12.44**
270	2.31	0.61	-0.90	-2.46	-3.51	-2.96	**-1.15**
271	0.31	-10.46	-16.91	-19.85	-15.40	-10.49	**-12.13**
272	4.05	1.08	-0.90	-2.08	-3.06	-2.86	**-0.63**
295	1.54	-0.53	-7.01	-7.31	-2.43	1.10	**-2.44**
296	1.51	-2.15	-9.16	-8.30	-2.78	1.69	**-3.20**
297	1.31	-1.16	-10.79	-10.40	-4.09	0.29	**-4.14**
298	0.97	-3.31	-14.39	-13.18	-6.56	-0.45	**-6.15**
299	0.72	-6.13	-16.95	-15.04	-8.37	-1.62	**-7.90**
300	0.60	-8.47	-17.87	-15.52	-9.38	-2.70	**-8.89**
301	0.61	-10.59	-19.67	-19.67	-14.95	-8.40	**-12.11**
305	5.60	1.43	-0.69	-2.85	-4.86	-3.60	**-0.83**
306	1.22	-6.90	-16.04	-17.25	-13.38	-8.34	**-10.11**
307	0.66	-7.16	-14.07	-14.13	-10.54	-7.00	**-8.70**
308	0.66	-6.95	-13.75	-13.66	-10.00	-6.38	**-8.35**
309	0.90	-5.84	-14.77	-15.78	-12.17	-7.14	**-9.13**
335	1.90	-5.54	-12.57	-10.12	-3.68	2.58	**-4.57**
336	1.86	-4.40	-12.49	-10.45	-4.99	0.45	**-5.00**
337	2.14	-3.78	-15.29	-15.06	-11.37	-5.09	**-8.07**
338	2.36	-4.05	-14.97	-15.00	-11.90	-6.02	**-8.26**
339	2.34	-3.69	-15.40	-15.08	-12.32	-6.55	**-8.45**
340	1.90	-1.82	-11.45	-10.86	-7.85	-2.66	**-5.46**
341	1.21	-3.90	-12.39	-12.06	-8.51	-3.91	**-6.60**
342	0.53	-5.92	-12.86	-12.95	-8.80	-4.49	**-7.41**
343	0.79	-4.67	-12.36	-12.63	-8.39	-4.20	**-6.91**
371	3.21	-2.44	-8.36	-7.34	-1.86	4.22	**-2.10**
372	2.88	-2.07	-8.46	-8.19	-2.90	1.86	**-2.81**
373	3.08	-0.69	-8.12	-8.47	-3.47	0.80	**-2.81**
374	3.19	-0.07	-7.96	-8.34	-3.67	1.25	**-2.60**
375	3.00	0.16	-6.88	-8.31	-4.19	0.62	**-2.60**
376	2.43	0.07	-6.43	-8.47	-5.00	-0.33	**-2.96**
377	2.10	-0.47	-7.05	-8.79	-5.32	-0.63	**-3.36**
378	2.60	0.21	-6.17	-8.27	-4.64	-0.35	**-2.77**
379	7.33	3.97	0.74	-0.66	-0.59	0.79	**1.93**
411	4.16	0.98	-1.04	-3.61	-1.36	3.10	**0.37**

412	4.29	1.18	-0.67	-3.05	-1.05	2.95	**0.61**

Winter Temperatures 2040-2069

GRID BOX NUMBER	2040-2069 NOV	2040-2069 DEC	2040-2069 JAN	2040-2069 FEB	2040-2069 MAR	2040-2069 APR	MEAN TEMP 2040-2069
183	-6.87	-16.64	-19.14	-20.25	-15.69	-9.45	**-14.67**
184	-5.30	-17.00	-19.54	-19.54	-12.66	-5.16	**-13.20**
185	-7.84	-17.92	-20.32	-19.91	-13.12	-4.76	**-13.98**
186	-8.95	-17.98	-20.53	-21.30	-17.86	-10.67	**-16.22**
187	-8.60	-17.49	-19.96	-20.90	-17.75	-10.61	**-15.89**
188	-8.83	-17.19	-19.66	-20.49	-17.49	-10.50	**-15.69**
189	-9.48	-17.77	-20.01	-20.72	-17.69	-10.77	**-16.07**
218	-5.46	-14.49	-16.25	-14.18	-7.73	-3.13	**-10.21**
219	-4.37	-14.44	-16.70	-16.39	-11.99	-7.08	**-11.83**
220	-1.08	-12.80	-16.12	-13.97	-7.80	-2.42	**-9.03**
221	-1.11	-13.74	-16.82	-14.47	-7.92	-1.84	**-9.32**
222	-0.58	-13.13	-17.04	-14.54	-7.30	-1.09	**-8.95**
223	-1.89	-13.58	-16.83	-14.08	-6.67	-0.53	**-8.93**
224	-2.80	-13.59	-16.84	-14.18	-6.86	-0.45	**-9.12**
225	-0.01	-11.26	-17.42	-15.10	-8.03	-1.62	**-8.91**
226	-2.07	-16.00	-20.00	-19.77	-15.97	-9.12	**-13.82**
253	0.14	-4.19	-6.49	-6.94	-4.96	-0.67	**-3.85**
254	0.55	-2.68	-6.17	-6.17	-3.58	-0.86	**-3.15**
255	0.34	-3.43	-7.97	-7.23	-4.34	-1.13	**-3.96**
256	0.34	-4.18	-9.77	-8.15	-4.78	-0.95	**-4.58**
257	0.58	-3.10	-10.84	-8.60	-4.42	-0.40	**-4.46**
258	0.97	-2.49	-10.93	-8.83	-3.32	0.54	**-4.01**
259	1.10	-5.03	-12.04	-8.96	-2.33	2.27	**-4.16**
260	1.04	-6.82	-12.26	-9.22	-2.46	2.68	**-4.51**
261	1.19	-3.73	-12.00	-10.17	-3.43	0.58	**-4.59**
262	0.79	-4.81	-14.45	-12.50	-6.19	-0.88	**-6.34**
263	-0.23	-11.48	-17.67	-16.25	-10.14	-4.07	**-9.97**
270	4.36	2.64	1.28	0.18	-0.26	0.10	**1.38**
271	1.49	-3.88	-13.21	-15.67	-13.71	-7.80	**-8.80**
272	5.93	3.04	1.14	0.09	-0.35	-0.03	**1.64**
295	2.14	0.72	-1.60	-3.94	-0.71	2.40	**-0.16**
296	2.17	-0.49	-5.07	-5.63	-0.86	3.41	**-1.08**
297	1.89	0.01	-5.89	-7.29	-1.74	1.00	**-2.00**
298	1.37	-1.72	-10.88	-9.96	-3.60	0.22	**-4.09**
299	1.02	-3.23	-14.34	-11.71	-5.74	-0.54	**-5.76**
300	1.02	-4.65	-15.09	-11.95	-6.72	-1.22	**-6.43**
301	1.53	-5.45	-16.68	-16.34	-12.20	-6.56	**-9.28**
305	7.72	3.47	1.45	0.14	-0.24	0.29	**2.14**
306	2.29	-1.44	-11.82	-14.23	-10.74	-5.64	**-6.93**

307	1.54	-2.67	-10.95	-11.43	-8.11	-4.28	**-5.98**
308	1.23	-2.85	-10.57	-11.13	-7.81	-3.97	**-5.85**
309	1.34	-1.93	-11.03	-13.40	-10.39	-5.48	**-6.81**
335	2.45	-3.19	-9.82	-7.00	-1.42	4.20	**-2.46**
336	2.47	-1.54	-9.94	-7.83	-2.73	1.81	**-2.96**
337	2.93	-0.68	-11.93	-13.10	-8.93	-2.57	**-5.71**
338	3.28	-1.05	-12.08	-13.00	-9.02	-3.36	**-5.87**
339	3.38	-0.38	-11.53	-13.03	-9.40	-4.39	**-5.89**
340	2.87	0.08	-7.42	-8.38	-5.29	-0.69	**-3.14**
341	1.86	-1.25	-9.23	-9.60	-6.49	-2.17	**-4.48**
342	1.08	-3.25	-10.38	-10.62	-7.07	-2.81	**-5.51**
343	1.14	-2.21	-9.94	-10.47	-6.82	-2.49	**-5.13**
371	4.12	-0.32	-5.80	-4.59	-0.11	5.71	**-0.17**
372	3.87	-0.02	-6.15	-5.28	-1.18	3.25	**-0.92**
373	4.11	0.34	-5.17	-5.30	-1.55	2.45	**-0.85**
374	4.30	0.57	-4.41	-5.32	-1.68	2.92	**-0.61**
375	4.19	0.58	-3.42	-5.61	-2.22	2.00	**-0.75**
376	3.57	0.43	-3.54	-6.15	-3.25	0.64	**-1.38**
377	2.90	0.20	-4.66	-6.75	-3.61	0.55	**-1.90**
378	3.47	0.69	-3.48	-5.92	-2.87	0.99	**-1.19**
379	8.61	5.15	2.12	0.79	0.74	2.16	**3.26**
411	5.53	1.43	-0.12	-1.14	0.17	5.77	**1.94**
412	5.58	1.63	0.12	-0.91	0.42	5.83	**2.11**

Winter Temperatures 2070-2099

GRID BOX NUMBER	**2070-2099 NOV**	**2070-2099 DEC**	**2070-2099 JAN**	**2070-2099 FEB**	**2070-2099 MAR**	**2070-2099 APR**	**MEAN TEMP 2070-2099**
183	-0.76	-11.74	-16.09	-15.61	-12.36	-6.51	**-10.51**
184	-0.43	-11.68	-16.53	-14.70	-8.64	-1.45	**-8.90**
185	-2.66	-14.06	-16.70	-14.94	-8.63	-0.69	**-9.61**
186	-4.42	-15.32	-16.88	-16.23	-13.79	-6.19	**-12.14**
187	-4.24	-15.32	-16.80	-16.09	-14.01	-5.71	**-12.03**
188	-3.96	-14.55	-16.72	-16.07	-14.31	-6.11	**-11.95**
189	-3.77	-14.30	-17.26	-16.71	-14.66	-7.08	**-12.30**
218	-1.26	-9.88	-12.73	-11.32	-5.57	-1.37	**-7.02**
219	-1.04	-10.36	-13.24	-13.76	-9.24	-4.88	**-8.75**
220	0.07	-7.25	-12.98	-11.42	-5.53	-0.81	**-6.32**
221	-0.10	-9.02	-14.13	-11.87	-5.42	-0.35	**-6.82**
222	0.23	-7.60	-14.98	-12.21	-5.12	0.15	**-6.59**
223	-0.30	-8.81	-15.36	-11.93	-4.35	0.86	**-6.65**
224	-0.38	-8.66	-15.10	-11.69	-4.23	1.01	**-6.51**
225	0.77	-2.97	-14.63	-12.18	-5.27	0.02	**-5.71**
226	0.42	-8.15	-16.31	-16.07	-12.11	-5.58	**-9.63**
253	1.83	-0.53	-2.74	-3.19	-0.77	2.46	**-0.49**

254	1.40	0.05	-2.49	-3.58	-1.16	0.53	**-0.88**
255	0.77	-0.45	-4.31	-5.37	-1.95	0.13	**-1.86**
256	0.64	-1.13	-6.13	-6.50	-2.27	0.12	**-2.54**
257	0.91	-0.35	-6.40	-7.04	-1.96	0.49	**-2.39**
258	1.36	0.22	-6.14	-7.46	-1.55	1.69	**-1.98**
259	1.67	-0.68	-7.97	-7.55	-0.88	3.77	**-1.94**
260	1.79	-1.65	-8.76	-7.20	-0.69	4.44	**-2.01**
261	1.71	0.55	-5.98	-7.61	-1.41	1.36	**-1.90**
262	1.27	-0.18	-8.15	-9.47	-3.32	0.32	**-3.25**
263	0.87	-5.25	-13.13	-12.56	-6.36	-1.09	**-6.25**
270	6.45	4.64	3.37	2.45	2.07	2.36	**3.56**
271	2.59	-0.02	-7.94	-11.16	-5.72	-1.37	**-3.94**
272	7.97	5.01	3.23	2.28	1.87	2.21	**3.76**
295	3.12	1.00	0.48	-1.66	0.31	4.35	**1.27**
296	3.10	0.97	-1.43	-3.53	0.06	5.46	**0.77**
297	2.73	0.85	-0.75	-4.88	-0.54	1.90	**-0.12**
298	2.06	0.55	-4.81	-8.17	-1.82	1.00	**-1.87**
299	1.65	0.02	-8.69	-10.19	-3.16	0.50	**-3.31**
300	1.66	-0.26	-10.20	-10.44	-3.89	0.37	**-3.80**
301	2.42	-0.54	-11.61	-14.01	-9.16	-3.62	**-6.09**
305	9.63	5.29	3.51	2.23	1.90	2.50	**4.18**
306	3.77	0.49	-6.04	-9.59	-5.49	-1.11	**-2.99**
307	2.81	0.08	-6.87	-7.88	-4.28	-0.09	**-2.71**
308	2.36	0.05	-6.79	-7.83	-4.14	-0.05	**-2.73**
309	2.32	0.20	-6.34	-9.19	-5.45	-0.79	**-3.21**
335	4.06	-0.83	-5.81	-5.09	0.32	7.29	**-0.01**
336	3.92	-0.13	-4.75	-5.21	-0.54	5.47	**-0.21**
337	4.40	0.66	-4.02	-9.48	-4.50	1.85	**-1.85**
338	4.85	0.68	-4.52	-9.82	-4.99	2.12	**-1.95**
339	5.03	0.86	-4.66	-10.15	-5.62	1.04	**-2.25**
340	4.55	0.79	-2.43	-5.82	-2.13	1.57	**-0.58**
341	3.42	0.34	-5.53	-7.45	-3.99	0.12	**-2.18**
342	2.36	-0.88	-7.45	-8.47	-4.76	-0.60	**-3.30**
343	2.28	-0.17	-6.79	-8.26	-4.43	-0.45	**-2.97**
371	6.07	0.99	-1.97	-2.71	2.02	9.34	**2.29**
372	5.79	1.15	-1.82	-3.17	0.64	7.58	**1.69**
373	6.08	1.36	-0.90	-2.90	0.28	6.80	**1.79**
374	6.21	1.47	-0.74	-2.66	0.29	7.01	**1.93**
375	5.96	1.40	-0.57	-2.92	-0.26	5.89	**1.58**
376	5.19	1.04	-0.92	-3.81	-1.12	3.65	**0.67**
377	4.45	0.76	-1.56	-4.81	-1.32	3.18	**0.12**
378	4.90	1.15	-0.76	-3.75	-0.80	3.51	**0.71**
379	10.10	6.40	3.53	2.25	2.33	3.73	**4.72**
411	7.36	2.67	0.74	0.40	2.80	9.69	**3.94**
412	7.15	2.72	0.93	0.58	2.96	9.55	**3.98**

Appendix 4.6.3:
Projected Changes in Snowfall for all Grid Boxes to 2100

GRID BOX NUMBER	1961-1990 mm of water	%CHANGE FROM BASE	2010-2039 mm of water	%CHANGE FROM BASE	2040-2069 mm of water	%CHANGE FROM BASE	2070-2099 mm of water
1	293.41	**12.24**	329.32	**-47.04**	155.38	**-88.85**	32.72
2	294.21	**11.41**	327.77	**-35.51**	189.73	**-88.61**	33.52
3	294.66	**11.43**	328.35	**-35.06**	191.35	**-88.33**	34.38
4	294.83	**10.86**	326.83	**-34.54**	192.99	**-88.04**	35.26
5	294.56	**10.54**	325.61	**-33.99**	194.43	**-87.75**	36.10
6	293.96	**10.35**	324.39	**-21.73**	230.09	**-87.48**	36.79
7	338.71	**-4.67**	322.88	**-31.93**	230.56	**-88.97**	37.37
8	337.12	**-4.57**	321.70	**-31.65**	230.44	**-88.80**	37.75
9	334.91	**-4.39**	320.19	**-31.43**	229.64	**-88.68**	37.92
10	332.14	**-3.96**	318.99	**-31.23**	228.42	**-88.60**	37.87
11	328.94	**-3.67**	316.86	**-31.05**	226.80	**-88.56**	37.62
12	325.54	**-3.22**	315.05	**-31.00**	224.63	**-88.58**	37.19
13	322.03	**-2.83**	312.92	**-31.11**	221.84	**-88.62**	36.63
14	318.58	**-2.16**	311.69	**-31.38**	218.62	**-88.71**	35.97
15	315.43	**-1.97**	309.23	**-31.79**	215.14	**-88.83**	35.22
16	312.53	**-1.94**	306.46	**-32.28**	211.66	**-88.96**	34.51
17	309.94	**-1.72**	304.61	**-32.65**	208.74	**-89.06**	33.91
18	307.67	**-1.61**	302.72	**-32.84**	206.63	**-89.14**	33.40
19	306.05	**-1.91**	300.22	**-42.59**	175.71	**-89.23**	32.95
20	285.04	**-6.23**	267.30	**-38.63**	174.92	**-88.58**	32.54
21	285.25	**-6.52**	266.65	**-38.85**	174.42	**-76.66**	66.58
22	285.67	**-16.88**	237.44	**-39.08**	174.03	**-76.73**	66.49
23	286.20	**-17.05**	237.41	**-39.23**	173.93	**-76.79**	66.42
24	286.82	**-16.71**	238.90	**-39.23**	174.29	**-76.84**	66.43
25	287.78	**-16.37**	240.68	**-39.19**	175.00	**-76.90**	66.47
26	289.18	**-16.15**	242.49	**-39.19**	175.86	**-76.98**	66.56
27	290.93	**-16.24**	243.69	**-39.21**	176.86	**-77.03**	66.81
28	292.83	**-16.16**	245.50	**-39.29**	177.79	**-77.10**	67.06
29	294.71	**-16.49**	246.12	**-39.31**	178.85	**-77.14**	67.38
30	296.63	**-16.83**	246.71	**-39.40**	179.75	**-77.21**	67.62
31	298.73	**-17.31**	247.03	**-39.55**	180.58	**-77.31**	67.78
32	301.07	**-17.95**	247.04	**-39.78**	181.29	**-77.46**	67.86
33	303.50	**-18.70**	246.74	**-40.03**	182.02	**-77.69**	67.72
34	305.60	**-19.25**	246.76	**-49.40**	154.64	**-89.70**	31.48
35	307.23	**-19.88**	246.15	**-49.32**	155.70	**-89.97**	30.81
36	397.51	**-4.93**	377.91	**-48.98**	202.80	**-92.32**	30.51
37	398.65	**-4.36**	381.25	**-48.88**	203.81	**-92.37**	30.44
38	399.21	**-3.66**	384.60	**-48.54**	205.45	**-92.43**	30.22
39	400.30	**-3.00**	388.29	**-48.25**	207.17	**-92.46**	30.16

40	401.33	**-2.79**	390.15	**-48.14**	208.13	**-92.41**	30.47
41	400.88	**-2.67**	390.18	**-47.99**	208.50	**-92.17**	31.40
42	398.37	**-2.51**	388.39	**-38.16**	246.34	**-91.84**	32.52
43	394.36	**-15.26**	334.17	**-37.40**	246.88	**-91.57**	33.25
44	389.92	**-0.70**	387.19	**-36.96**	245.81	**-91.40**	33.54
45	386.57	**0.08**	386.87	**-36.88**	244.01	**-91.35**	33.43
46	383.90	**0.37**	385.31	**-36.93**	242.12	**-91.40**	33.00
47	381.30	**0.50**	383.21	**-37.12**	239.76	**-91.48**	32.47
48	378.53	**0.68**	381.12	**-37.70**	235.84	**-81.75**	69.10
49	375.69	**1.07**	379.70	**-38.41**	231.37	**-81.99**	67.64
50	371.26	**1.74**	377.73	**-38.82**	227.14	**-82.12**	66.39
51	366.16	**1.78**	372.67	**-39.11**	222.97	**-82.12**	65.49
52	359.64	**1.52**	365.11	**-38.90**	219.74	**-81.93**	64.97
53	352.61	**1.12**	356.57	**-38.43**	217.09	**-81.61**	64.83
54	346.15	**0.87**	349.16	**-38.15**	214.10	**-81.15**	65.24
55	340.64	**0.58**	342.61	**-38.56**	209.29	**-80.59**	66.12
56	335.39	**0.47**	336.98	**-39.29**	203.62	**-80.08**	66.80
57	329.43	**0.86**	332.28	**-39.76**	198.44	**-79.72**	66.81
58	322.50	**-21.87**	251.98	**-39.67**	194.56	**-79.40**	66.44
59	316.28	**-20.83**	250.39	**-39.27**	192.08	**-79.00**	66.41
60	312.24	**-20.31**	248.81	**-38.47**	192.13	**-78.74**	66.38
61	221.70	**7.77**	238.93	**-26.54**	162.85	**16.00**	257.18
62	224.31	**8.15**	242.59	**-25.42**	167.30	**15.25**	258.51
63	228.25	**8.43**	247.48	**-23.99**	173.50	**14.74**	261.89
64	324.17	**-6.04**	304.61	**-33.49**	215.62	**-62.02**	123.13
65	333.04	**4.90**	349.34	**-32.66**	224.27	**-49.40**	168.51
66	345.18	**4.81**	361.77	**-32.07**	234.49	**-48.84**	176.58
67	360.73	**14.07**	411.47	**-31.81**	245.97	**-48.11**	187.18
68	380.68	**21.37**	462.05	**-31.87**	259.37	**-48.00**	197.96
69	403.68	**12.20**	452.92	**-31.68**	275.79	**-47.90**	210.32
70	349.82	**1.87**	356.36	**-13.63**	302.12	**3.68**	362.70
71	342.60	**-28.34**	245.50	**-49.74**	172.20	**-91.21**	30.13
72	339.52	**-10.83**	302.75	**-51.06**	166.15	**-91.27**	29.65
73	338.88	**-11.04**	301.46	**-39.76**	204.14	**-91.39**	29.17
74	341.78	**-12.37**	299.50	**-38.18**	211.29	**-91.55**	28.88
75	344.43	**-4.46**	329.08	**-36.38**	219.12	**-81.36**	64.21
76	342.17	**-5.97**	321.75	**-34.38**	224.52	**-81.26**	64.14
77	335.10	**8.59**	363.89	**-32.19**	227.24	**-81.03**	63.56
78	330.15	**-3.28**	319.31	**-30.82**	228.41	**-80.74**	63.60
79	333.94	**-5.98**	313.98	**-31.43**	228.99	**-80.87**	63.90
80	341.50	**-9.78**	308.11	**-33.31**	227.74	**-81.57**	62.94
81	346.56	**-11.90**	305.32	**-35.25**	224.40	**-82.39**	61.03
82	347.41	**1.49**	352.59	**-36.56**	220.39	**-83.21**	58.34
83	342.84	**4.33**	357.69	**-37.17**	215.39	**-83.36**	57.06
84	338.51	**6.43**	360.27	**-38.22**	209.15	**-83.10**	57.19

85	336.42	**-3.78**	323.69	**-39.23**	204.45	**-82.96**	57.32
86	339.32	**8.47**	368.06	**-39.93**	203.83	**-74.19**	87.57
87	347.10	**-8.33**	318.19	**-40.16**	207.71	**-74.15**	89.71
88	354.97	**-18.25**	290.18	**-40.04**	212.84	**-65.40**	122.81
89	363.14	**-0.21**	362.40	**-41.13**	213.78	**-64.72**	128.11
90	368.39	**1.30**	373.18	**-42.92**	210.27	**-63.68**	133.81
91	257.17	**-9.17**	233.58	**-2.44**	250.88	**-24.53**	194.07
92	252.75	**-8.95**	230.13	**-2.21**	247.16	**-22.41**	196.12
93	247.26	**-9.19**	224.55	**-2.26**	241.67	**-3.90**	237.63
94	243.21	**-9.74**	219.53	**-2.90**	236.16	**-3.85**	233.84
95	239.08	**-10.12**	214.90	**-3.26**	231.30	**-2.56**	232.95
96	234.40	**-10.02**	210.91	**-3.07**	227.20	**15.60**	270.96
97	230.74	**-10.27**	207.03	**-1.48**	227.31	**16.59**	269.01
98	229.32	**-9.79**	206.87	**0.52**	230.51	**19.00**	272.89
99	229.28	**2.18**	234.27	**2.97**	236.09	**22.20**	280.18
100	279.64	**-14.13**	240.12	**-13.40**	242.18	**2.38**	286.30
101	284.58	**4.45**	297.26	**-1.74**	279.64	**1.39**	288.55
102	290.10	**5.96**	307.40	**-2.65**	282.40	**-0.90**	287.48
103	295.86	**9.07**	322.69	**17.36**	347.21	**-2.35**	288.91
104	366.66	**-5.74**	345.62	**-1.66**	360.58	**-18.18**	300.02
105	384.06	**-1.99**	376.41	**1.14**	388.45	**-14.35**	328.95
106	303.13	**-20.91**	239.74	**-60.19**	120.66	**-100.00**	0.00
107	302.68	**-21.19**	238.54	**-59.28**	123.24	**-100.00**	0.00
108	313.32	**-23.78**	238.83	**-57.70**	132.53	**-100.00**	0.00
109	332.56	**-27.19**	242.13	**-56.70**	144.00	**-100.00**	0.00
110	352.36	**-20.30**	280.83	**-46.42**	188.80	**-100.00**	0.00
111	363.90	**-19.01**	294.74	**-45.21**	199.37	**-100.00**	0.00
112	360.30	**-15.04**	306.10	**-41.64**	210.27	**-100.00**	0.00
113	357.40	**-13.50**	309.14	**-37.71**	222.62	**-91.46**	30.53
114	358.69	**-14.24**	307.61	**-37.69**	223.49	**-92.51**	26.86
115	357.62	**-1.11**	353.65	**-40.44**	212.99	**-82.82**	61.44
116	351.82	**-17.80**	289.20	**-34.91**	229.01	**-83.10**	59.45
117	342.32	**-19.04**	277.15	**-36.15**	218.57	**-82.74**	59.10
118	334.55	**-19.00**	270.98	**-37.98**	207.51	**-82.77**	57.66
119	331.46	**-17.87**	272.23	**-40.13**	198.43	**-81.77**	60.43
120	329.98	**-16.65**	275.04	**-39.92**	198.26	**-100.00**	0.00
121	222.62	**0.43**	223.58	**7.90**	240.21	**-16.41**	186.08
122	342.71	**-18.28**	280.07	**-37.65**	213.70	**-63.56**	124.89
123	358.14	**-19.33**	288.90	**-37.17**	225.02	**-63.83**	129.53
124	380.69	**-18.37**	310.76	**-37.87**	236.51	**-64.15**	136.48
125	420.23	**-33.59**	279.07	**-40.64**	249.46	**-74.32**	107.92
126	324.21	**-9.87**	292.21	**-8.28**	297.38	**-12.96**	282.20
127	324.34	**-9.72**	292.81	**-5.34**	307.00	**4.62**	339.31
128	316.69	**-8.87**	288.60	**-4.29**	303.12	**-11.38**	280.65
129	304.85	**-8.69**	278.35	**-35.50**	196.61	**-13.04**	265.11

130	345.93	**-26.39**	254.63	**-47.50**	181.61	**-72.38**	95.55
131	290.20	**-18.60**	236.21	**-50.02**	145.03	**-100.00**	0.00
132	284.76	**-19.39**	229.53	**-48.63**	146.27	**-100.00**	0.00
133	288.36	**-18.20**	235.88	**-46.45**	154.41	**-100.00**	0.00
134	304.99	**-1.23**	301.24	**5.07**	320.45	**-11.05**	271.27
135	404.08	**-18.33**	329.99	**-11.49**	357.64	**-9.44**	365.95
136	474.53	**-15.54**	400.77	**-14.78**	404.39	**-17.92**	389.50
137	527.89	**-5.82**	497.18	**8.96**	575.18	**-19.41**	425.42
138	471.78	**-2.86**	458.29	**9.10**	514.74	**10.51**	521.37
139	403.10	**3.01**	415.23	**12.21**	452.31	**35.32**	545.49
140	367.38	**7.40**	394.56	**12.54**	413.45	**37.30**	504.40
141	308.62	**-39.88**	185.55	**-65.57**	106.25	**-100.00**	0.00
142	357.58	**-45.80**	193.82	**-68.39**	113.03	**-100.00**	0.00
143	368.74	**-44.14**	205.99	**-67.13**	121.21	**-100.00**	0.00
144	477.58	**-47.35**	251.43	**-73.23**	127.84	**-100.00**	0.00
145	427.23	**-39.36**	259.06	**-59.29**	173.91	**-100.00**	0.00
146	441.99	**-24.16**	335.21	**-59.85**	177.44	**-100.00**	0.00
147	545.36	**-35.57**	351.38	**-58.62**	225.68	**-91.77**	44.91
148	541.17	**-34.97**	351.94	**-59.48**	219.27	**-86.65**	72.25
149	511.72	**-33.46**	340.49	**-58.76**	211.04	**-86.72**	67.96
150	483.64	**-26.16**	357.10	**-58.09**	202.68	**-86.93**	63.21
151	428.38	**-20.79**	339.31	**-52.67**	202.76	**-86.30**	58.70
152	365.03	**-28.54**	260.85	**-56.72**	157.99	**-91.50**	31.01
153	364.26	**-30.17**	254.37	**-49.75**	183.03	**-91.28**	31.76
154	303.23	**-17.55**	250.02	**-28.39**	217.16	**-34.47**	198.69
155	304.97	**-18.49**	248.58	**-16.60**	254.33	**-32.97**	204.43
156	295.79	**-14.57**	252.70	**-27.98**	213.02	**-30.05**	206.89
157	279.76	**-6.75**	260.87	**-22.26**	217.48	**-28.68**	199.52
158	273.88	**-3.24**	265.02	**-16.76**	227.97	**-25.67**	203.57
159	428.97	**-22.92**	330.63	**-42.20**	247.93	**-60.48**	169.53
160	315.08	**-5.53**	297.66	**-14.57**	269.17	**-14.43**	269.61
161	350.22	**-8.07**	321.96	**-14.48**	299.51	**-14.15**	300.68
162	373.96	**-6.44**	349.87	**-13.41**	323.81	**-12.76**	326.24
163	376.34	**-2.74**	366.03	**-14.16**	323.03	**-12.01**	331.12
164	358.16	**-17.81**	294.37	**-14.63**	305.76	**-12.05**	315.00
165	329.79	**-19.23**	266.36	**-16.06**	276.83	**-13.67**	284.71
166	252.78	**-8.55**	231.16	**-38.44**	155.61	**-100.00**	0.00
167	266.84	**-22.48**	206.86	**-59.51**	108.04	**-100.00**	0.00
168	246.53	**-19.49**	198.48	**-56.78**	106.54	**-100.00**	0.00
169	228.18	**-24.10**	173.19	**-48.16**	118.28	**-100.00**	0.00
170	263.72	**-19.85**	211.38	**-42.17**	152.50	**-100.00**	0.00
171	503.42	**-1.81**	494.32	**6.39**	535.58	**-0.54**	500.70
172	732.31	**-1.68**	720.04	**-9.10**	665.68	**-15.05**	622.12
173	679.94	**1.89**	692.80	**5.16**	715.03	**12.50**	764.91
174	550.07	**6.51**	585.87	**9.48**	602.19	**21.81**	670.05

175	461.66	**8.32**	500.08	**13.15**	522.36	**27.83**	590.12
176	301.12	**-36.99**	189.75	**-66.06**	102.20	**-100.00**	0.00
177	296.19	**-10.38**	265.46	**-17.92**	243.13	**-27.89**	213.60
178	319.31	**-15.75**	269.02	**-20.67**	253.31	**-19.41**	257.33
179	346.72	**-19.75**	278.24	**-26.06**	256.35	**-24.98**	260.12
180	365.35	**-5.73**	344.42	**-30.13**	255.25	**-29.39**	257.97
181	361.81	**-3.43**	349.39	**-19.10**	292.69	**-30.02**	253.18
182	344.83	**-0.23**	344.04	**-17.43**	284.71	**-29.66**	242.57
183	321.50	**0.56**	323.30	**-16.04**	269.91	**-28.33**	230.43
184	295.46	**-25.68**	219.59	**-25.58**	219.89	**-24.16**	224.08
185	281.84	**-6.64**	263.12	**-26.86**	206.14	**-26.97**	205.84
186	270.82	**3.41**	280.06	**-25.96**	200.51	**-26.79**	198.28
187	282.52	**0.31**	283.39	**-26.59**	207.41	**-29.65**	198.75
188	312.15	**-4.61**	297.77	**-15.46**	263.87	**-30.78**	216.08
189	339.39	**-3.57**	327.26	**-15.77**	285.86	**-28.90**	241.32
190	342.38	**-18.67**	278.46	**-12.74**	298.77	**-23.59**	261.61
191	361.18	**-25.86**	267.78	**-19.60**	290.38	**-26.06**	267.06
192	329.93	**-26.83**	241.42	**-19.80**	264.60	**-25.31**	246.43
193	306.09	**-28.54**	218.72	**-21.35**	240.74	**-27.72**	221.23
194	201.61	**7.38**	216.50	**13.96**	229.76	**1.00**	203.63
195	274.89	**-16.92**	228.37	**-12.00**	241.89	**-26.64**	201.67
196	318.82	**-20.71**	252.78	**-15.17**	270.45	**-30.99**	220.03
197	405.99	**-31.49**	278.13	**-26.76**	297.33	**-24.80**	305.31
198	421.06	**-31.25**	289.46	**-27.71**	304.39	**-19.56**	338.70
199	408.39	**-11.04**	363.29	**-25.62**	303.75	**-13.36**	353.81
200	686.48	**-30.33**	478.25	**-54.42**	312.93	**-67.85**	220.70
201	337.55	**-22.67**	261.02	**-22.90**	260.26	**-12.10**	296.71
202	209.55	**7.50**	225.27	**12.67**	236.10	**-17.32**	173.25
203	192.78	**3.85**	200.20	**-5.88**	181.44	**6.78**	205.84
204	181.88	**-8.50**	166.41	**-51.30**	88.58	**-100.00**	0.00
205	206.96	**-6.80**	192.89	**-51.54**	100.29	**-100.00**	0.00
206	268.64	**-4.93**	255.39	**-54.28**	122.82	**-100.00**	0.00
207	517.40	**6.06**	548.78	**2.04**	527.98	**-36.82**	326.88
208	746.19	**-5.37**	706.14	**-10.53**	667.63	**0.78**	752.00
209	840.99	**9.88**	924.06	**13.01**	950.42	**27.43**	1071.70
210	874.14	**6.62**	931.99	**10.13**	962.71	**18.91**	1039.47
211	252.48	**-10.09**	227.01	**-46.78**	134.36	**-100.00**	0.00
212	289.96	**-8.68**	264.78	**-1.74**	284.90	**-33.18**	193.76
213	338.59	**-16.73**	281.96	**-13.43**	293.12	**-23.86**	257.81
214	380.16	**-19.68**	305.35	**-17.50**	313.65	**-27.06**	277.29
215	416.38	**-21.11**	328.48	**-19.64**	334.60	**-27.38**	302.38
216	532.11	**-16.58**	443.89	**-31.75**	363.19	**-26.45**	391.36
217	543.34	**-33.88**	359.28	**-30.89**	375.49	**-25.98**	402.19
218	523.28	**-31.84**	356.66	**-30.09**	365.80	**-23.22**	401.76
219	470.00	**-16.47**	392.59	**-11.08**	417.91	**-21.01**	371.25

220	319.48	-3.79	307.38	-1.87	313.52	-22.87	246.42
221	243.36	11.61	271.62	12.66	274.18	9.10	265.51
222	237.54	1.72	241.62	1.45	240.98	-37.28	149.00
223	243.12	-6.71	226.81	-6.41	227.53	-25.67	180.72
224	248.51	-8.10	228.39	-4.79	236.60	-22.35	192.97
225	261.53	-6.93	243.40	-4.43	249.96	-35.31	169.18
226	308.86	0.75	311.17	-14.25	264.85	-26.53	226.93
227	305.27	3.55	316.12	7.20	327.26	-25.21	228.31
228	286.62	4.18	298.60	11.45	319.44	-22.31	222.66
229	270.51	3.54	280.10	6.56	288.24	-23.92	205.81
230	280.00	-0.67	278.13	-2.18	273.89	-32.67	188.52
231	300.31	-1.30	296.41	-7.33	278.29	-36.91	189.45
232	330.60	-7.10	307.13	-9.75	298.37	-35.60	212.90
233	340.52	-7.64	314.49	-5.37	322.23	-30.59	236.36
234	669.75	-40.70	397.18	-64.84	235.49	-79.21	139.21
235	473.76	-23.17	363.98	-48.77	242.69	-69.58	144.10
236	376.63	-6.28	352.98	-7.71	347.61	-15.78	317.21
237	358.91	-12.37	314.50	-11.09	319.11	-38.83	219.55
238	289.98	-4.85	275.91	-19.45	233.57	-32.58	195.49
239	190.95	-6.28	178.95	-45.73	103.62	-100.00	0.00
240	161.59	19.40	192.93	-31.32	110.98	-100.00	0.00
241	180.86	22.55	221.65	-46.76	96.28	-100.00	0.00
242	504.72	-9.43	457.12	-1.75	495.86	-16.56	421.13
243	651.43	29.41	843.01	13.28	737.92	-15.62	549.69
244	995.04	3.62	1031.03	-8.54	910.06	-32.29	673.74
245	1181.33	1.19	1195.40	-9.62	1067.72	-33.67	783.58
246	310.82	-65.88	106.04	-100.00	0.00	-100.00	0.00
247	335.22	10.57	370.65	-25.54	249.60	-37.99	207.87
248	381.33	-7.58	352.42	-2.60	371.42	-36.74	241.25
249	478.80	-9.58	432.92	-9.18	434.86	-39.21	291.06
250	612.59	5.70	647.53	-35.19	397.02	-42.07	354.86
251	765.14	5.02	803.57	-35.04	497.03	-65.81	261.60
252	1064.60	-13.16	924.49	-22.37	826.47	-55.49	473.86
253	1120.71	-13.29	971.71	-27.76	809.64	-41.54	655.15
254	1027.05	-9.40	930.52	-24.55	774.89	-55.08	461.38
255	826.30	-8.73	754.19	-24.38	624.82	-35.41	533.72
256	549.55	-0.87	544.76	-22.23	427.37	-32.30	372.04
257	384.03	-23.87	292.36	-22.31	298.34	-36.52	243.77
258	280.42	-39.34	170.11	-38.99	171.09	-62.52	105.11
259	198.41	-7.84	182.85	-29.16	140.55	-31.83	135.26
260	191.67	-4.67	182.72	-29.24	135.62	-26.33	141.19
261	258.26	-20.04	206.50	-39.72	155.68	-52.77	121.98
262	308.62	-18.95	250.15	-23.04	237.52	-27.91	222.48
263	391.95	-11.68	346.15	-12.02	344.82	-22.34	304.38
264	384.17	8.78	417.89	-10.29	344.66	-24.99	288.16

265	378.20	1.96	385.61	-16.74	314.88	-33.37	251.99
266	356.89	0.71	359.44	-33.70	236.63	-36.08	228.13
267	318.99	-26.02	236.00	-65.11	111.28	-100.00	0.00
268	292.71	-25.92	216.84	-87.12	37.70	-100.00	0.00
269	355.87	-36.37	226.43	-89.26	38.23	-100.00	0.00
270	353.96	-29.67	248.94	-87.83	43.07	-100.00	0.00
271	392.69	-10.57	351.17	-8.39	359.73	-24.80	295.30
272	444.85	-31.56	304.44	-77.18	101.54	-100.00	0.00
273	364.13	-20.58	289.21	-74.04	94.51	-100.00	0.00
274	231.67	-32.74	155.83	-79.31	47.92	-100.00	0.00
275	0.00	0.00	94.15	0.00	0.00	0.00	0.00
276	0.00	0.00	186.89	0.00	217.97	0.00	0.00
277	0.00	0.00	76.50	0.00	0.00	0.00	0.00
278	739.08	5.66	780.89	-13.42	639.93	-24.27	559.70
279	867.77	4.65	908.11	5.70	917.20	-18.25	709.38
280	661.70	-20.17	528.22	-64.00	238.20	-9.04	601.89
281	187.63	-100.00	0.00	-100.00	0.00	-100.00	0.00
282	292.45	-100.00	0.00	-100.00	0.00	-100.00	0.00
283	229.48	-100.00	0.00	-100.00	0.00	-100.00	0.00
284	438.52	-51.71	211.75	-100.00	0.00	-100.00	0.00
285	0.00	0.00	0.00	0.00	0.00	0.00	0.00
286	0.00	0.00	0.00	0.00	0.00	0.00	0.00
287	0.00	0.00	0.00	0.00	0.00	0.00	0.00
288	0.00	0.00	0.00	0.00	0.00	0.00	0.00
289	0.00	0.00	0.00	0.00	0.00	0.00	0.00
290	838.33	-44.97	461.35	-100.00	0.00	-100.00	0.00
291	1047.20	-43.50	591.66	-58.98	429.55	-100.00	0.00
292	730.33	-1.14	722.00	-39.95	438.54	-83.64	119.51
293	440.81	-11.44	390.37	-12.22	386.96	-46.02	237.95
294	300.23	-13.70	259.11	-40.41	178.91	-61.43	115.80
295	188.50	7.41	202.46	-27.45	136.75	-75.52	46.14
296	177.02	6.38	188.32	4.86	185.63	-45.67	96.18
297	218.37	-12.98	190.02	-38.35	134.63	-34.45	143.14
298	236.16	-3.11	228.82	-14.95	200.85	-38.26	145.81
299	300.40	-20.57	238.61	-8.42	275.11	-51.50	145.68
300	293.77	-20.62	233.19	-11.23	260.77	-32.25	199.03
301	353.96	-11.68	312.61	-32.31	239.58	-27.46	256.78
302	366.59	-35.87	235.08	-64.13	131.50	-100.00	0.00
303	431.32	-49.26	218.87	-81.05	81.75	-100.00	0.00
304	437.94	-45.60	238.24	-91.25	38.34	-100.00	0.00
305	397.52	-31.07	274.02	-87.70	48.90	-100.00	0.00
306	443.46	-11.22	393.71	-23.71	338.33	-39.53	268.17
307	507.16	-10.88	451.98	-25.88	375.92	-39.41	307.31
308	504.75	-11.37	447.37	-27.35	366.69	-39.78	303.95
309	417.98	4.65	437.43	-17.64	344.26	-32.04	284.05

310	118.24	**116.60**	256.10	**69.50**	200.41	**-100.00**	0.00
311	0.00	**0.00**	223.58	**0.00**	244.59	**0.00**	182.73
312	0.00	**0.00**	247.77	**0.00**	197.74	**0.00**	0.00
313	0.00	**0.00**	183.82	**0.00**	111.50	**0.00**	0.00
314	0.00	**0.00**	0.00	**0.00**	204.18	**0.00**	199.87
315	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
316	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
317	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
318	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
319	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
320	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
321	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
322	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
323	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
324	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
325	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
326	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
327	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
328	707.80	**-38.66**	434.14	**-100.00**	0.00	**-100.00**	0.00
329	771.82	**-12.62**	674.40	**-55.98**	339.77	**-83.25**	129.25
330	445.33	**-14.72**	379.79	**-34.39**	292.16	**-81.24**	83.53
331	283.22	**-16.30**	237.07	**-36.62**	179.51	**-79.16**	59.03
332	217.70	**-17.21**	180.23	**-41.53**	127.29	**-57.94**	91.57
333	152.43	**2.59**	156.37	**-19.41**	122.83	**-51.11**	74.51
334	147.44	**6.48**	156.99	**12.44**	165.79	**-50.52**	72.96
335	160.11	**5.49**	168.90	**8.07**	173.02	**-12.36**	140.32
336	233.42	**-16.66**	194.53	**-20.22**	186.23	**-10.25**	209.50
337	254.48	**9.98**	279.88	**3.28**	262.83	**-32.53**	171.69
338	360.49	**-18.63**	293.34	**-22.93**	277.82	**-53.01**	169.37
339	394.20	**-18.91**	319.65	**-19.87**	315.87	**-54.36**	179.90
340	369.28	**-1.16**	364.99	**-20.18**	294.76	**-40.97**	217.98
341	414.98	**-0.30**	413.72	**8.04**	448.35	**-39.12**	252.64
342	632.46	**-31.26**	434.73	**-23.26**	485.34	**-23.87**	481.46
343	520.77	**-19.08**	421.39	**-7.85**	479.91	**-8.62**	475.87
344	407.17	**6.52**	433.72	**14.97**	468.13	**-32.45**	275.06
345	436.29	**4.82**	457.30	**-41.67**	254.49	**-37.05**	274.65
346	0.00	**0.00**	179.79	**0.00**	0.00	**0.00**	0.00
347	0.00	**0.00**	181.11	**0.00**	191.85	**0.00**	0.00
348	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
349	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
350	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
351	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
352	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
353	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
354	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00

355	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
356	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
357	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
358	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
359	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
360	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
361	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
362	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
363	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
364	416.48	**-100.00**	0.00	**-100.00**	0.00	**-100.00**	0.00
365	543.29	**-34.18**	357.62	**-100.00**	0.00	**-100.00**	0.00
366	314.76	**-30.71**	218.09	**-100.00**	0.00	**-100.00**	0.00
367	207.76	**-27.49**	150.65	**-100.00**	0.00	**-100.00**	0.00
368	167.88	**-23.72**	128.05	**-48.21**	86.95	**-100.00**	0.00
369	173.56	**-3.71**	167.12	**-48.52**	89.35	**-47.84**	90.53
370	232.47	**-22.60**	179.94	**-60.02**	92.95	**-61.08**	90.48
371	194.44	**0.04**	194.52	**4.88**	203.92	**-50.85**	95.57
372	201.10	**4.48**	210.11	**4.24**	209.62	**-47.78**	105.02
373	216.52	**8.14**	234.14	**-21.40**	170.19	**-50.24**	107.74
374	255.71	**2.37**	261.78	**-19.67**	205.41	**-52.77**	120.76
375	317.63	**-28.36**	227.54	**-25.19**	237.60	**-23.67**	242.45
376	466.72	**-18.97**	378.17	**-40.39**	278.23	**-40.04**	279.84
377	486.58	**5.18**	511.78	**-38.61**	298.72	**-37.19**	305.60
378	499.73	**-16.20**	418.77	**-38.57**	307.00	**-38.53**	307.17
379	405.04	**-49.93**	202.79	**-100.00**	0.00	**-100.00**	0.00
380	199.14	**-100.00**	0.00	**-100.00**	0.00	**-100.00**	0.00
381	307.36	**-29.75**	215.91	**-100.00**	0.00	**-100.00**	0.00
382	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
383	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
384	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
385	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
386	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
387	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
388	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
389	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
390	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
391	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
392	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
393	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
394	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
395	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
396	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
397	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
398	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
399	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00

400	384.20	**-100.00**	0.00	**-100.00**	0.00	**-100.00**	0.00
401	368.98	**-47.63**	193.23	**-100.00**	0.00	**-100.00**	0.00
402	278.90	**-24.45**	210.70	**-100.00**	0.00	**-100.00**	0.00
403	215.08	**-27.43**	156.09	**-100.00**	0.00	**-100.00**	0.00
404	178.21	**-28.35**	127.68	**-100.00**	0.00	**-100.00**	0.00
405	150.80	**-20.91**	119.27	**-42.57**	86.61	**-100.00**	0.00
406	147.40	**-47.72**	77.06	**-41.18**	86.70	**-100.00**	0.00
407	173.99	**-16.27**	145.69	**-41.49**	101.81	**-100.00**	0.00
408	157.41	**3.88**	163.52	**-26.30**	116.01	**-100.00**	0.00
409	183.64	**-1.39**	181.09	**-67.52**	59.65	**-100.00**	0.00
410	226.45	**0.15**	226.79	**-67.63**	73.31	**-100.00**	0.00
411	260.38	**1.81**	265.10	**-35.08**	169.03	**-100.00**	0.00
412	264.14	**5.62**	278.98	**-70.12**	78.92	**-100.00**	0.00
413	273.20	**-29.96**	191.34	**-100.00**	0.00	**-100.00**	0.00
414	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
415	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
416	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
417	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
418	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
419	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
420	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
421	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
422	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
423	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
424	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
425	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
426	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
427	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
428	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
429	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
430	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
431	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
432	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
433	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
434	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
435	535.56	**-44.80**	295.63	**-100.00**	0.00	**-100.00**	0.00
436	488.67	**-10.88**	435.51	**-49.75**	245.55	**-100.00**	0.00
437	364.60	**-14.11**	313.17	**-56.93**	157.03	**-100.00**	0.00
438	196.68	**9.31**	215.00	**-73.06**	52.99	**-100.00**	0.00
439	150.32	**-57.90**	63.29	**-100.00**	0.00	**-100.00**	0.00
440	57.25	**-54.51**	26.04	**-100.00**	0.00	**-100.00**	0.00
441	66.60	**-58.57**	27.59	**-100.00**	0.00	**-100.00**	0.00
442	90.41	**-100.00**	0.00	**-100.00**	0.00	**-100.00**	0.00
443	120.66	**-8.72**	110.14	**-100.00**	0.00	**-100.00**	0.00
444	227.60	**-41.10**	134.05	**-100.00**	0.00	**-100.00**	0.00

445	318.17	**-51.56**	154.11	**-76.32**	75.33	**-100.00**	0.00
446	273.79	**-34.12**	180.37	**-100.00**	0.00	**-100.00**	0.00
447	95.72	**-100.00**	0.00	**-100.00**	0.00	**-100.00**	0.00
448	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
449	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
450	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
451	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
452	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
453	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
454	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
455	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00

Chapter 5: Drinking Water Supply and Wastewater Treatment

This chapter deals with the main impacts of climate change on water infrastructure and the required adaptation costs. We suggest that the main impacts of climate change on water utilities are likely to be on (a) the supply of drinking water, and (b) the treatment of wastewater, as the level of precipitation changes due to climate change. Sections 5.1, 5.1.1 and 5.1.2 give the national context of water availability, including consumption and prices of water in Canada. In Section 5.1.3, we provide an introduction to the impact of climate change on water resources. In Section 5.1.4, we outline some of the potential adaptations to municipal water infrastructure. This is followed by detailed case studies of water utilities in the different ecoclimatic zones of Canada. Section 5.2 is a case study of Toronto, for which the adaptation costs are considered in some detail. The remaining case studies are organized as follows: Section 5.3, The Region of Niagara; Section 5.4, Montréal; Section 5.5, Halifax; 5.6.1, Regina; 5.7, Humboldt; 5.8, Swift Current; 5.9, Lethbridge; 5.10, Prince George; 5.11, Penticton; 5.12, Yellowknife; 5.13, Norman Wells; and 5.14, Directions for Future Research.

5.1: Water in Canada: An Introduction

Canada is rich in natural resources, including water. The world's oceans contain more than 95% of the earth's water, but this water is too salty to use in its normal state, except as habitat for marine organisms and a medium for human transportation. The remaining water, less than 5%, is fresh. One-third of this water is stored in ice caps and glaciers, and most of the rest is groundwater, with only a very small portion, about 0.2% found in the soil and in surface waters, such as lakes and rivers.

According to Environment Canada, Canada probably has more lake area than any other country in the world. It shares with the United States the Great Lakes, which hold about 18% of the world’s entire surface freshwater. On average, about 9% of the world’s renewable freshwater supply flows in Canadian rivers. Since Canada occupies 7% of the earth’s land area, its freshwater supplies are not out of proportion. But with less than 1% of the world’s population, Canada is generously supplied with freshwater, though this supply is not evenly distributed throughout the country.

Because of Canada’s different climatic zones, some parts of British Columbia and the Prairies are so dry that they compare with northern Mexico and much of Australia. Other parts of Canada, such as southern Ontario, suffer water shortages only during extended dry periods. In these regions the climate is more like the mid-western United States and central Europe. Canada’s east and west coasts receive a good deal of rain, comparing more to Scandinavia. Thus, water management in Canada must be adapted to a wide range of conditions and can benefit from experience obtained in other parts of the world.

We can think of two basic ways in which we use water:

1. Instream uses, such as hydroelectric power generation, transportation, fisheries, wildlife, recreation, and waste disposal, take place with the water remaining in its natural setting, "in the stream.”
2. Withdrawal uses, such as thermal power generation, mineral extraction, irrigation, manufacturing, and municipal use. This use removes water from its natural setting for a period of time and for a particular use, and eventually returns all or part of it to the source. The difference between the amount of water withdrawn and the amount of water returned to the source is water "consumed" (for example, by evaporating and not returning to the local source).

Much of the land producing fruits and vegetables, as well as a significant amount of the land used to grow tobacco, is irrigated. In western Canada, irrigated forage crops sustain the livestock industry. According to the 1996 census, there were 21 448 farms in Canada reporting that they used irrigation on a total of 856 132 hectares of farmland. The provincial breakdown is as follows:

Alberta,	516 600 hectares
British Columbia,	115 374 hectares
Saskatchewan,	97 378 hectares
Ontario,	66 090 hectares
Quebec,	33 611 hectares
Manitoba,	22 190 hectares
Atlantic provinces,	4 889 hectares

Across Canada, 12% of the water used in Canadian municipalities comes from groundwater; the rest is from lakes and rivers. In cities, water is distributed through a series of pipes connected to a municipal water supply system. In rural areas, it is usually obtained from wells. Water supply systems typically have intake, treatment, storage, and distribution components. There are many different treatment types, depending on the characteristics of the source water. Likewise, the storage and distribution systems vary greatly between municipalities, depending on the unique characteristics of each city or town. Rural residents usually have individual groundwater supplies from wells.

Trucks in several regions of Canada deliver water. In the Far North, water may have to be trucked to homes that do not have conventional water supplies because the ground is frozen. Water is also delivered by truck in some rural areas of the east and in the Prairies where wells are shallow and unreliable year round.

Where there are piped systems in the North, the pipes are often buried very deep, up to 3 or 4 metres, to get below the worst of the frost, and are insulated to prevent the water from freezing. In permafrost areas, the heat lost from even insulated underground pipes would melt the permafrost and cause the ground to cave in. Therefore, above-ground utilidors (insulated boxes) are used to carry water, sewer, and sometimes hot water (for heating) pipes to individual residences. These are heated, insulated, metal or wood-clad enclosures that are generally installed on piles or blocking.

5.1.1: The Cost of Water in Canada

Water prices across Canada are generally low compared to other countries. The average household pays $27.65 per month, and uses about 30 000 litres per month, for water delivered to the residence. Monthly bills range between $15 and $90, the lowest being in Quebec, Newfoundland, and British Columbia and the highest in the Prairie Provinces and northern Canada.

Although the operating costs for trucked service are very high, the lower capital costs make it more economic than piped service for most northern communities. Consumption is much lower for areas with trucked service, about 200 litres per capita per day in the Northwest Territories and Nunavut. Several studies show that water revenues are not sufficient to cover operational, repair, upgrading, or expansion costs. They cover only a small part of the costs of supplying water. For example, irrigation water charges recover only about 10% of the development cost of the resource.

The cost of maintaining (repairing and upgrading) municipal water supply and sewage systems is estimated at $23 billion over the next 10 years in Canada as a whole. According to the Canadian Water and Wastewater Association there is an investment shortfall of $16.5 billion in water facilities (mains, storage tanks and treatment plants) and $36.8 billion in wastewater facilities (sewers, combined sewer and separations and treatment plants) (Source: Federation of Canadian Municipalities, Quality of Life Proposal). Over 1.5 million Canadians live in communities with no wastewater treatment, and almost five million live where only primary treatment is available. Investment in water infrastructure to meet the current climate requirements includes the Quality of Life Infrastructure Program, a combined Federal/Provincial/Municipal program. Capital investment in water systems will be $16.5 billion over 10 years, with $36.8 billion going to wastewater systems.

In Canada, the value of drinking water and wastewater utility assets is approximately $110 billion. On the assumption of a 40-year life of the infrastructure, each year a 2.5% replacement should occur. In Canada, close to a billion dollars a year is spent in the water resources sector on adapting to current climate conditions. Climate change will most likely increase these expenditures. The existing water supply infrastructure is aging; pipelines are corroded, clogged and requiring repairs. These old lines can be replaced with vinyl pipe and fittings, since they are immune to damage from corrosive soils, and perform better in the cold Canadian climate.

5.1.2: Water Prices in Canada

Provincial and municipal officials set water prices in Canada. Most provinces levy licence fees to major water users for access to the resource. The provincial licence fees for water are not set in accordance with any pricing principles, but rather are related to the cost of administering the licensing program. Municipalities also levy charges to water users. In many areas, users are charged a flat monthly, quarterly, or annual rate in exchange for access to unlimited amounts of treated water. In other places, the charges are based on the volume of water used, as measured by a water meter. Irrigation water fees are paid according to land area irrigated, not water volume used. Tap water is very inexpensive compared with some other liquids. For example, 1 litre of water costs about

0.001 dollar, while the same amount of bottled water would cost $1.50; cola, $0.85; milk, $1.10; and table wine, $9.00.

Water rates are a major source of revenue for municipal water utilities. According to the Federation of Canadian Municipalities, 63% of total water utility revenue was derived from water rates. The other 27% of revenue came from general taxes. Many Canadian municipalities charge a flat rate, allowing users unlimited consumption for a fixed payment. Some municipalities use a declining block structure that benefits high volume users. This structure also discourages the conservation of water as well as increasing capacity requirements.

Over 92% of urban households are serviced by municipal water and sewer systems. All other households, including most of the rural population, are serviced by private individual systems (usually groundwater), septic tanks and/or tile fields, or trucked services. In the Northwest Territories and Nunavut, for example, 16% of the communities have centralized water distribution systems either above or below ground, while 74% have trucked water supply and waste disposal systems. The remaining 10% use private systems, water buckets, privies, or trucked services. Specifically, in the Northwest Territories, seven communities have piped systems: Fort Smith, Hay River, Yellowknife, and Edzo have inground pipes while Norman Wells, Inuvik, and Rae have above-ground pipes, or utilidors (insulated boxes). In Nunavut, only Iqaluit, Rankin Inlet, and Nanisivic have piped aboveground systems.

5.1.3: The Implications of Climate Change for Municipal Water Infrastructure

Hydrological changes associated with climate change -- whether it will rain more or less, for instance -- are more speculative than are temperature projections, especially at the regional and local geographic scales of interest to water planners. The IPCC suggests that a greenhouse warming will have the following effects on water supplies:

- The timing and regional patterns of precipitation will change, and more intense precipitation days are likely.
- General circulation models (GCMs) used to predict climate change suggest that a 1.5 to 4.5 degree C rise in global mean temperature would increase global mean precipitation about 3 to 15 percent. Some of this is due to the conversion of snow into precipitation.
- Although the regional distribution is uncertain, precipitation is expected to increase in higher latitudes, particularly in winter. This conclusion extends to the mid-latitudes in most GCM projections.
- Potential evapotranspiration (FT) -- water evaporated from the surface and transpired from plants -- rises with air temperature. Consequently, even in areas with increased precipitation, higher FT rates may lead to reduced runoff; implying a possible reduction in renewable water supplies.
- More annual runoff caused by increased precipitation is likely in the high latitudes. In contrast, some lower latitude basins may experience large reductions in runoff and increased water shortages as a result of a combination of increased evaporation and decreased precipitation.
- Flood frequencies are likely to increase in many areas, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins. Floods may become less frequent in some areas.
- The frequency and severity of droughts could increase in some areas as a result of a

decrease in total rainfall and more frequent dry spells.

- The hydrology of arid land is particularly sensitive to climate variations. Relatively small changes in temperature and precipitation in these areas could result in large percentage changes in runoff, increasing the likelihood and severity of droughts and/or floods.
- Seasonal disruptions might occur in the water supplies of mountainous areas if more precipitation falls as rain than snow and if the length of the snow storage season is reduced.
- Water quality problems may increase where there is less flow to dilute contaminants introduced from natural and human sources.

The implications for municipal water infrastructure under a changed climate are as follows:

1) Risk of physical system failure. For example, there are key concerns in the Arctic that climate change will have destructive effects on water and wastewater collection and distribution systems built on the permafrost base, which is expected to become increasingly less stable (thaw slump).

2) Contamination due to water-borne disease and/or saltwater intrusion.

3) Seasonal unreliability of supply.

4) Higher demand, but less availability.

There are key concerns about the depletion of groundwater reserves and the ability of existing reservoirs to capture enough water to satisfy a longer demand season. In addition, if a greater proportion of rainfall occurs in extreme events, then less water is available for infiltration and groundwater recharge. In terms of surface water, if snow pack storage is insufficient to fill reservoirs it may necessitate the development of expanded reservoir capacity and expanded water conservation programs. In the case of municipalities that draw their water from the Great Lakes, projected falls in lake levels may necessitate modifications to the collection system.

5.1.4: Potential Adaptations of Municipal Water Infrastructure

New infrastructure may, in some instances, eventually prove to be an appropriate response to climate induced shifts in hydrological regimes and water demands. But it is difficult to plan for and justify expensive new projects when the magnitude, timing, and even the direction of the changes at the basin and regional levels are unknown. Narrowing the range of uncertainty for improved water planning depends on a better understanding of (1) the processes governing global and regional climates; (2) the links between climate and hydrology; (3) the impacts of the climate on unmanaged ecosystems; (4) the impacts of ecosystem changes on the quantity and quality of water; and (5) the impacts of increased atmospheric $C0_2$ on vegetation and runoff. In the meantime, the possibility that a warming could result in greater hydrological variability and storm extremes should be considered in evaluating margins of safety of long-lived structures such as dams and levees that are under consideration anyway. In particular, low-cost structural and managerial modifications that ensure against the possibility of a range of climate-induced impacts are likely to be sought. However, there may well be instances in which new infrastructure is the only answer and would include:

- Improving levels of wastewater treatment (especially upstream of municipal water intake) by replacing obsolete wastewater treatment facilities;
- Construction of new reservoirs to increase capacity;

- Replacement of freshwater collection systems if changes in water levels make extraction impossible; and
- Replacement of wastewater treatment plants if changing water levels make plant operation impossible.

More importantly, the prospect that a global warming will alter in unknown ways local and regional supplies and demands reinforces the need for institutions that facilitate adaptation to whatever the future brings and promote more efficient water management and use. Unlike the structural supply-side approach, demand management that introduces incentives to conserve and opportunities to reallocate supplies as conditions change does not require long lead times, large financial commitments, or accurate information about the future climate. Water demand management measures include metering, leak detection, water pricing, rational water permitting and recycling measures.

In the rest of this chapter we consider the impact of climate change on drinking water supply and the wastewater treatment in the major ecoclimatic zones of Canada. We consider a series of case studies that are representative of the ecoclimatic zones.

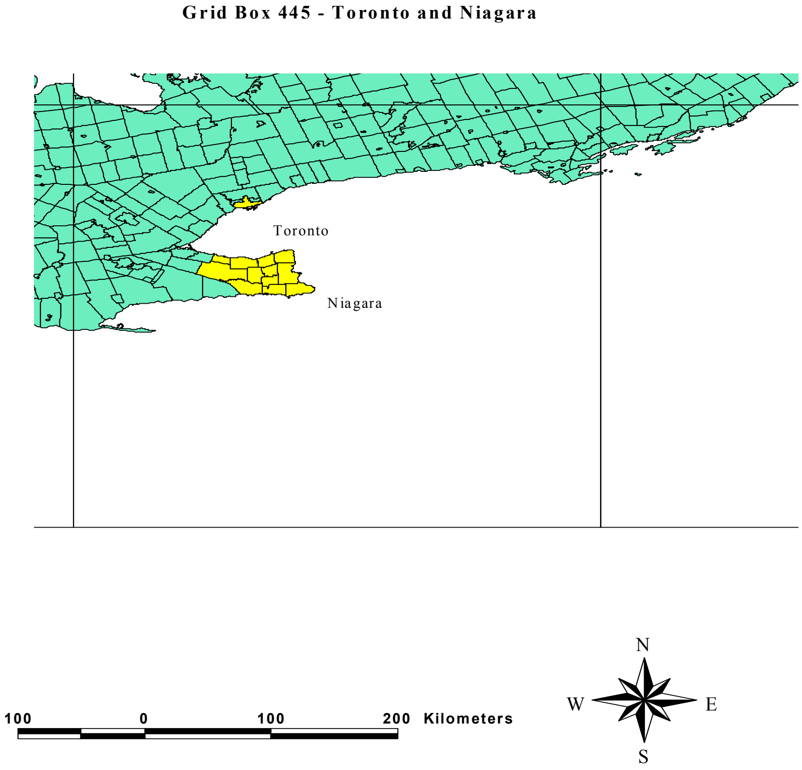
5.2: Toronto, ON

5.2.1: Introduction

The City of Toronto's Water and Wastewater Services Division was created by the amalgamation of the water and sewer functions from seven former municipalities and one public utility on January 1, 1998. The division supplies fresh water to over 3 million residents in Toronto and York region and treats all wastewater from Toronto, a portion of Peel region and the Greater Toronto Airport Authority (see Figure 5.2.1).

Although the Water and Wastewater Division is presently owned by the City of Toronto, the division is required to be a financially self-sustaining entity with distinctly separate budgets for each component of its operation. While this budget structure removes the burden from municipal taxes, it fails to provide an adequate mechanism to deal with the adaptation to climate change.

Figure 5.2.1: Toronto and Niagara



5.2.2: Great Lake Levels

The waters of the Great Lakes are a non-renewable resource, composed of numerous aquifers that flow into the tributaries of the Great Lakes and fill the lakes themselves. On average, less than 1% of the waters of the Great Lakes are renewed annually by precipitation, surface water runoff, and inflow from groundwater sources. The primary source of natural water supply to the Great Lakes is precipitation, and levels are determined by the combined influence of precipitation, upstream inflows, groundwater, surface water runoff, evaporation, and diversions into and out of the system, consumptive use, dredging, and water level regulation. Climatic conditions control precipitation, runoff, and direct supply to the lakes, as well as the rate of evaporation, and these are the primary factors in determining water levels. During dry, hot-weather periods, inflow is decreased and evaporation increased resulting in lower lake levels and reduced flows.

In the past, the Great Lakes have had a small range in lake levels, approximately 6.5 feet from the recorded monthly maximum to the recorded monthly minimum. Seasonal cycles can vary from 10 to 12 inches. During the past thirty years, lake levels have been the highest in recorded history, due to increased summer and fall precipitation. Recently lake levels have experienced the second largest decline in one hundred years. Results from computer climate models have been used to explore impacts on water levels, assuming likely scenarios of future atmospheric greenhouse gas concentrations. The information from these models has been used to develop climate scenarios that have been included in hydrologic models. Early impact assessments, based on equilibrium 2XCO2 scenarios, suggest global warming will result in a lowering of water supplies and lake levels and in a reduction of outflows from the Basin. Some projections show a lowering of lake levels by up to a meter or more by 2050. (*Preparing for Climate Change, The Potential Consequences of Climate Variability and Change, The Great Lakes; Great Lakes Regional Assessment Group, 2000).*

The General Circulation Model, CGCM1, like several other models, has shown an increase in lake surface temperature, a decrease in basin runoff and an increase in lake evaporation, resulting in reduced inter-lake channel flow and water levels on all of the Great Lakes. Mean annual runoff is reduced, and combines with an increase in lake surface evaporation due to a strong increase in lake surface temperature, to produce a reduction in net basin supply. Net basin supply is the water input to the lakes by runoff from its basin plus input from over-lake precipitation minus output to over-lake evaporation. The CGCM1 shows that lake level reductions from 0.7-2.4 feet are predicted by 2030. A one meter drop in the levels of Lakes Michigan and Huron in thirty years would have a severe impact on Lake St. Clair and Lake Erie, whose levels would drop by about 2 feet. A lake level drop of one meter in Lake Michigan could cause thousands of municipal water intakes and wells to be moved or extended. In general, municipal water intakes are located 20 to 40 feet from the water's edge, resulting in water supplies of superior quality.

5.2.3: The Water Supply Services Component

Lake Ontario is the only source of fresh water for the city. Water is drawn into the Toronto system from four filtration plants, which have intake pipes located one to three kilometres from shore and at a water depth of 15 metres. Once the raw water enters the system, it is screened, filtered and treated before entering a transmission network. The network consists of 487 kilometres of 15 centimetres to 250 centimetres in diameter steel and cast iron water mains. Water pressure is maintained in the network through the Central Pumping Control Facility. At this facility operators receive pipeline flow, distribution system pressures, reservoir levels, pumping equipment status and power demands from 12 separate pressure districts located on six different elevation levels.

During 1999, an average of 1,503 mega litres of water was pumped per day directly from filtration plants and associated pumping stations into the transmission system. In some cases, it was necessary to pump the water three or four times before reaching the consumer. On average 1,725 mega litres of water per day is re-pumped by 18 pumping stations to lift the water to higher elevations. If the water is not used immediately it is stored in large in-ground covered reservoirs or elevated tanks. In total there is approximately 1,745 mega litres of storage capacity in the Toronto system.

5.2.4: Water Supply and Adaptation to Climate Change

Because precipitation is expected to increase, it is unlikely that Toronto will experience a water supply problem. The City draws its water supply from Lake Ontario, and even supposing that lake levels drop by a metre in the future time periods, intake pipes are deep enough, and far enough into the lake to negate this effect. Lake levels would have to decrease substantially before intake pipes are affected. We therefore conclude that the supply of water to Toronto is unlikely to be affected by climate change, unless lake levels drop drastically (see Section 5.2.2).

5.2.5: The Wastewater Services Component

Wastewater originates from several sources; however, for the purpose of this study we shall focus on rainwater run off. During a rainstorm, water collects several pollutants as it travels over the landscape. If this water were to enter Lake Ontario untreated it would cause damage to the plant and animal life that depend on the lake for survival. To prevent this environmental damage from occurring, rainwater is collected and treated before entering the lake. The water is collected throughout the city by either storm sewers or combined sewers. Storm sewers are separate pipes designed to capture rainwater and snowmelt and direct it to one of four wastewater treatment plants.

Combined sewers by contrast, carry both sanitary sewer waste and rainwater run off. During the dry weather season, combined sewers can effectively carry all contaminants to the treatment plants. However, during a rainy month the volume of water may exceed the treatment plant's capacity and some of the water overflows untreated into Lake Ontario. The Water and Wastewater Services Division is responsible for 358 kilometres of trunk sewers and intercepts of which 30 percent are combined sewers.

5.2.6: The Major Components of Cost

5.2.6.1: Capital Costs

The capital assets of The Water and Wastewater Services Division are shown in Table 5.2.1.

Table 5.2.1: Capital Assets –Water and Wastewater Services Division

Capital Assets
4 Water Treatment Plants
4 Wastewater Treatment Plants
2 Central laboratories
7 Plant laboratories
18 Water pumping Stations
45 Wastewater pumping Stations
10 Water storage reservoirs
4 Elevated storage tanks
5 Wastewater storage and detention tanks
4,143 km of sanitary sewers
1,301 km of combined sewers
4,533 km of storm sewers
5,347 km of distribution water mains
487 km of trunk water mains
40,460 hydrants
120,000 maintenance holes
470,000 water service connections
371 km of watercourses
36 storm water management ponds
16 maintenance yards

Source: Water & Waster Services Division 1999/2000 Review

5.2.6.2: Operating Costs

As stated previously, the Water and Wastewater Services Division is divided into components. One of the components is the delivery and treatment of fresh drinkable water. The different proportions of the cost of water delivery are shown in Table 5.2.2.

Table 5.2.2: 1999 Water Services Budget Less Debt Charges

1999 Water Services Budget Less Debt Charges

Production of Water	31.3%
Water Distribution	46.0%
Quality Control and System Planning	1.8%
Department Charges	9.8%
Corporate Charges	5.9%
Payments in Lieu of Taxes	4.6%
Provision to corporate Vehicle Reserve	0.2%
Provision to Repair and Replacement	0.5%
Total	100.0%

Source: Water & Wastewater Services Division 1999/2000 Review

The proportions of wastewater treatment are shown in Table 5.2.3.

Table 5.2.3: 1999 Wastewater Services Budget Less Debt Charges

1999 Wastewater Services Budget Less Debt Charges

Wastewater Treatment	46.0%
Water Collection	29.3%
Quality Control and System Planning	2.9%
Department Charges	7.7%
Corporate Charges	7.5%
Payments in Lieu of Taxes	4.8%
Provision to corporate Vehicle Reserve	0.5%
Business Support	0.1%
Provision to Repair and Replacement	1.2%
Total	100.0%

Source: Water & Waster Services Division 1999/2000 Review

5.2.7: Water Production Statistics

In order to determine the costs of adaptation to climate change, information about plant capacities, consumption and average daily flows are required. Tables 5.2.4 to 5.2.7 show relevant statistics on potable water production.

Table 5.2.4: Potable Water Production

Supply

Plant	Total Filt Water Produced (Mega litres)	Percentage of Total	Number of Days in Operation	1999 Average Pumpage (Megalitres per day)	Maximum Daily Production (Megalitres)	Days of Maximum Production
Harris	251,898	44.7%	365	690	961	July 6, 1999
Clark	154,395	27.4%	355	434	632	August 26, 1999
Horgan	142,858	25.4%	358	399	594	July 29, 1999
Island	14,350	2.5%	91	157	292	July 29, 1999
Total	563,502					

Source: *Water & Waster Services Division 1999/2000 Review*

Table 5.2.5: 1999 Water Consumption by Toronto Communities

1999 Water Consumption by Toronto Communities

Communities	Consumption (Megalitres)	Daily Average (Megalitres)	Population	Per Capital Consumption (Litres per day)
East York	17,384	48	114,881	415
Etobicoke	71,037	195	350,240	556
North York	109,013	299	628,259	475
Scarborough	96,103	263	595,556	442
Toronto	150,309	412	696,535	591
York	22,986	63	156,128	403
Toronto Total	**466,833**	**1,279**	**2,541,600**	**503**
York Region Total	**80,662**	**221**	**525,027**	**421**
Total	**547495**	**1,500**	**3,066,627**	**489**

Source: Water & Waster Services Division 1999/2000 Review

Table 5.2.6: Plant Capacities & Average Daily Flows

Plant Capacities & Average Daily Flows

Plant	Capacity Square Meters per Day	Average Daily Flow Square Meters per Day
Ashbridges Bay	818,000	736,000
North Toronto	34,000	33,700
Highland Creek	218,000	168,100
Humber	472,000	364,510
Total	1,542,000,000	1,302,310,000

Source: Water & Waster Services Division 1999/2000 Review

Table 5.2.7: Pumping Station Capacities

Pumping Station Capacities

Pumping Station Capacities	Cubic Meters of Water per Day
Main	1,491,100
Ashbridges Bay	1,363,800
Cumber (Centennial)	68,200
West Rouge	31,800
Swansea	13,600
New Toronto	45,500
Long Branch	13,600
Mimico	68,200
Total	**3,095,800**

Source: Water & Waster Services Division 1999/2000 Review

Table 5.2.8 gives the descriptive statistics of the projections of precipitation from CGCM1, GG1, which we have downscaled for Toronto, following the methodology given in Chapter 2.

Table 5.2.8: Precipitation Descriptive Statistics for Toronto

	1961-2099	**1961-1990**	**2010-2039**	**2040-2069**	**2070-2099**
Maximum	1053.47	224.2	1053.47	1000.13	943.45
Minimum	2.12	10.1	3.66	2.12	3.83
Mean	88.56	75.61	92.96	89.27	96.42
Standard Deviation	78.98	34.43	96.25	83.29	85.83

Maximum precipitation increases from the baseline period to the 2020 period by a factor of 4.7 and the mean increases by 23 percent in the same period. The standard deviation increases a dramatic 179% from the baseline period to the 2020 period. It remains 141% to 149% higher than the baseline in the 2050 and 2080 time periods, respectively.

5.2.8: Regression Analysis

Given the average monthly precipitation for 1961-1990, 2010-2039, 2040-2069 and 2070-2099, for each period we estimate a regression model to analyze trend and seasonal differences. The conceptual foundations of these regression models are given in Chapter 2. The model takes the general form:

$$\mathbf{PPT_t = \beta_0 + \beta_2 D_2 + \beta_3 D_3 + \ldots \beta_{12} D_{12} + u}$$

Where PPT is precipitation in period t, and the D_i are dummy variables. The constant represents January, D_2 represents February and so on.

The estimated regression for 1961-1990 is:

$$\mathbf{PPT} = \underset{(11.26)}{\mathbf{70}} - \underset{(-0.72)}{\mathbf{6.39D_2}} + \underset{(0.34)}{\mathbf{3.06D_3}} + \underset{(0.18)}{\mathbf{1.64D_4}} + \underset{(0.29)}{\mathbf{2.58D_5}} + \underset{(0.17)}{\mathbf{1.5D_6}} + \underset{(0.61)}{\mathbf{5.38D_7}} + \underset{(1.95)}{\mathbf{17.23D_8}} + \underset{(1.19)}{\mathbf{10.53D_9}} -$$

$$\underset{(-0.25)}{\mathbf{2.25D_{10}}} + \underset{(1.45)}{\mathbf{12.83D_{11}}} + \underset{(2.4)}{\mathbf{21.16\,D_{12}}}$$

The estimated regression for 2010-2039 is:

$$\mathbf{PPT} = \underset{(4.7)}{\mathbf{83.27}} - \underset{(0.02)}{\mathbf{0.53D_2}} + \underset{(0.05)}{\mathbf{1.27D_3}} - \underset{(-0.05)}{\mathbf{1.35D_4}} - \underset{(-0.34)}{\mathbf{8.66D_5}} - \underset{(-0.59)}{\mathbf{14.73D_6}} + \underset{(0.96)}{\mathbf{24.06D_7}} + \underset{(0.16)}{\mathbf{4.18D_8}} +$$

$$\underset{(1.25)}{\mathbf{31.22D_9}} + \underset{(0.83)}{\mathbf{20.78D_{10}}} + \underset{(1.36)}{\mathbf{34D_{11}}} + \underset{(1)}{\mathbf{24.99D_{12}}}$$

The estimated regression for 2040-2069 is:

$$\mathbf{PPT} = \underset{(5.05)}{\mathbf{77.16}} + \underset{(0.07)}{\mathbf{1.57D_2}} + \underset{(0.74)}{\mathbf{16.04D_3}} + \underset{(0.64)}{\mathbf{13.89D_4}} + \underset{(0.22)}{\mathbf{4.87D_5}} - \underset{(-0.3)}{\mathbf{6.47D_6}} + \underset{(1.38)}{\mathbf{29.84D_7}} - \underset{(-0.18)}{\mathbf{4.02D_8}} +$$

$$\underset{(1.71)}{\mathbf{37.08D_9}} + \underset{(0.96)}{\mathbf{20.76D_{10}}} + \underset{(1.02)}{\mathbf{22.09D_{11}}} + \underset{(0.45)}{\mathbf{9.75D_{12}}}$$

The estimated regression for 2070-2099 is:

$$\mathbf{PPT} = \underset{(6.32)}{\mathbf{99.62}} - \underset{(-0.14)}{\mathbf{3.16D_2}} + \underset{(1.09)}{\mathbf{24.51D_3}} - \underset{(-0.45)}{\mathbf{10.08D_4}} - \underset{(-0.7)}{\mathbf{15.78D_5}} - \underset{(-0.74)}{\mathbf{16.53D_6}} + \underset{(0.28)}{\mathbf{6.39D_7}} + \underset{(0.17)}{\mathbf{3.81D_8}} -$$

$$\underset{(-0.03)}{\mathbf{0.73D_9}} - \underset{(-0.32)}{\mathbf{7.17D_{10}}} - \underset{(-1.01)}{\mathbf{22.58D_{11}}} + \underset{(0.12)}{\mathbf{2.88D_{12}}}$$

These regressions describe the relationship between precipitation and the constant and eleven dummy variables. The constant represents the mean precipitation for January. To determine the mean precipitation for any other month, the coefficient for that month is added to or subtracted from the constant. We can see that the constant has increased in each future scenario from the baseline. We can also see that the constant is significant in every regression. These regressions are used to determine the mean and 95% confidence interval around the mean. These results are graphed in Figures 5.2.2 to 5.2.5.

5.2.9: Graphical Results

Figure 5.2.2: Results for Toronto (1961-1990)

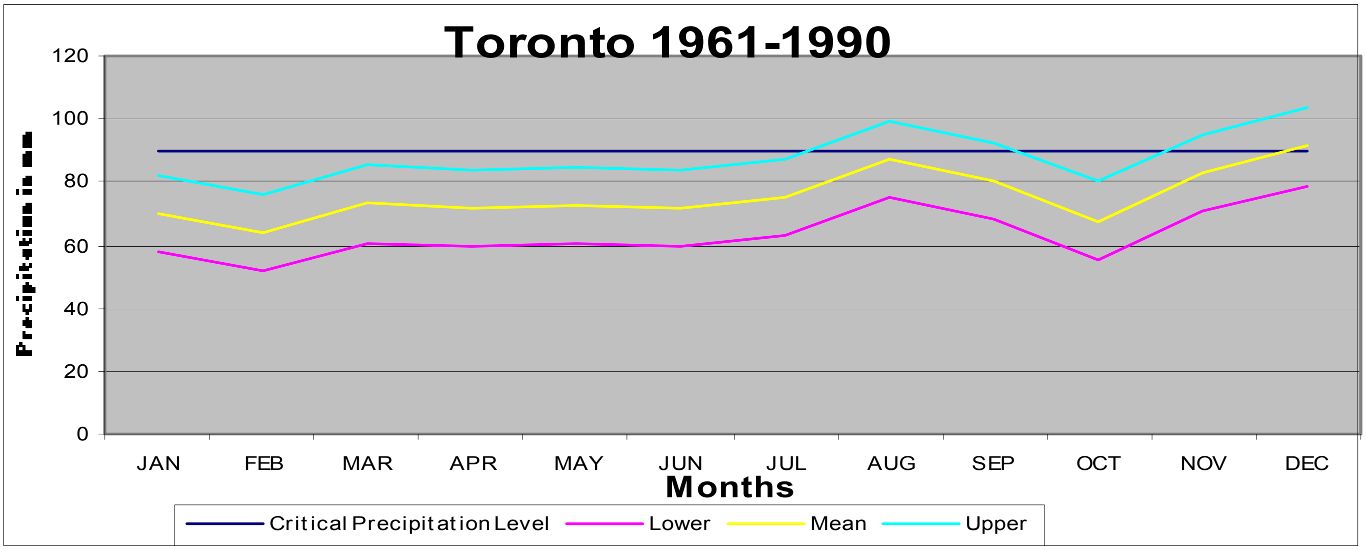


Figure 5.2.3: Results for Toronto (2010-2039)

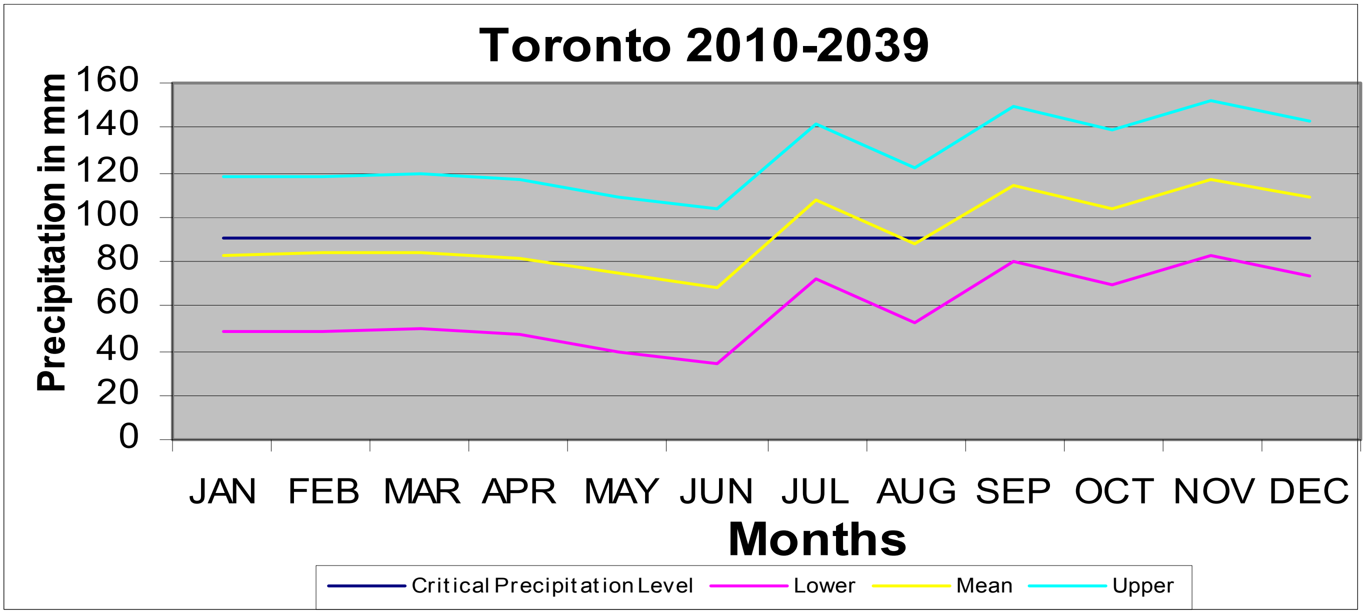


Figure 5.2.4: Results for Toronto (2040-2069)

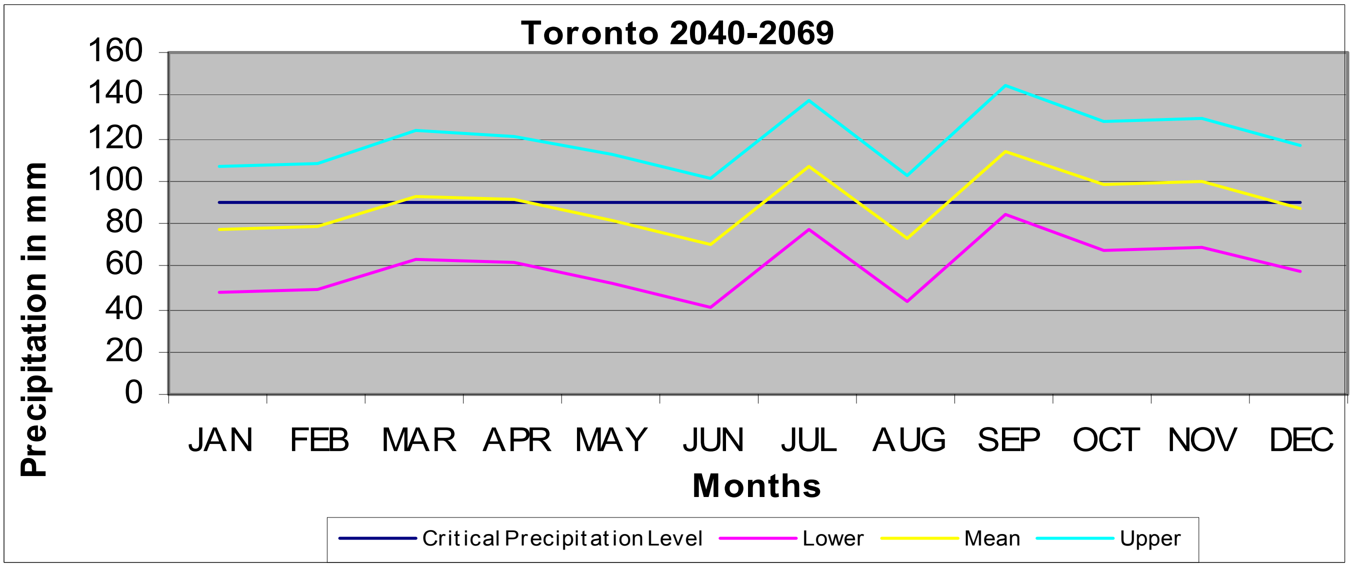
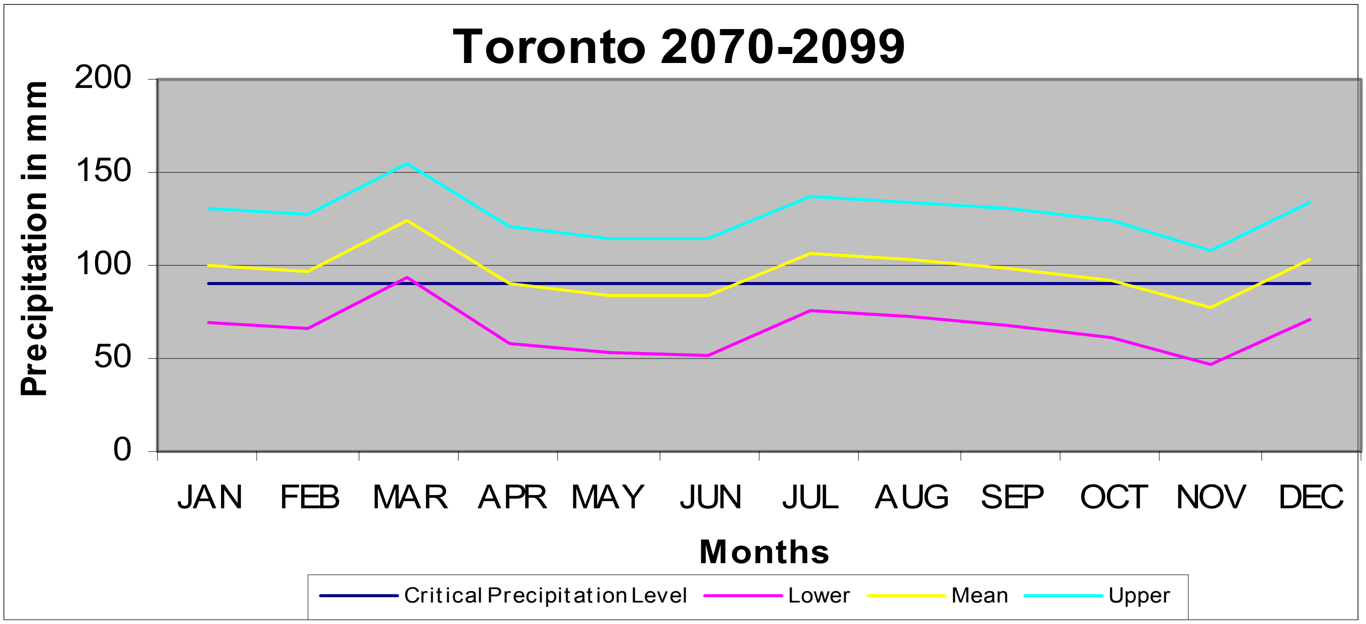


Figure 5.2.5: Results for Toronto (2070-2099)



In the graphs given in Figures 5.2.2 to 5.2.5 we are concerned with the mean and the upper and lower 95% confidence levels, and their relationship to the critical precipitation level. Note that the critical precipitation level can also be interpreted as the maximum capacity of the wastewater treatment plant. That is, precipitation that exceeds this level will cause the excess flow to be discharged untreated into Lake Ontario. We can see that in the baseline scenario, mean precipitation does not exceed the capacity, but the upper confidence level does in several months. The situation changes dramatically in the future scenarios where mean and upper 95% level exceeds capacity more frequently. This graphical representation allows us to see that increased precipitation will lead to wastewater treatment problems due to insufficient capacity.

5.2.10: Methodology

If we assume that the average base year precipitation represents the average precipitation for the Toronto area, then the amount of storm water requiring treatment equals approximately 1.302 billion cubic meters. According to the regression equation for the base year period (1961 to 1990) the average precipitation was 75 mm per month. Therefore, any increase in monthly precipitation beyond 75 mm requires a higher capacity utilization beyond average. By performing a simple cross multiplication we find that 89 mm of precipitation in a single month will force the wastewater treatment plants to operate at 100% capacity. Therefore, precipitation beyond 89 mm per month will cause storm water to flow directly into the ecosystem untreated and do environmental damage. The amount of precipitation expected to exceed the treatment plants capacity is summarized in Table 5.2.9.

Table 5.2.9: Predicted Precipitation to Exceed Toronto's Present Wastewater Capacity

	Precipitation Exceeding Toronto's Wastewater Capacity 1961 to 1990	Precipitation Exceeding Toronto's Wastewater Capacity 2010 to 2039	Precipitation Exceeding Toronto's Wastewater Capacity 2040 to 2069	Precipitation Exceeding Toronto's Wastewater Capacity 2070 to 2099
January	0	0	0	9.62
February	0	0	0	6.46
March	0	0	3.2	34.13
April	0	0	1.05	0
May	0	0	0	0
June	0	0	0	0
July	0	17.33	17	16.02
August	0	0	0	13.44
September	0	24.5	24.24	8.88
October	0	14.05	7.93	2.45
November	0	27.28	9.25	0
December	1.16	18.26	0	12.51
Totals	**1.16**	**101.42**	**62.67**	**103.51**

In the baseline scenario, only in December was capacity exceeded. In the 2020 scenario, capacity is insufficient in July, September, October, November and December. In the 2050 scenario, March, April, June, September, October and November are the affected months, and in the 2080 scenario, all but four months experience precipitation that exceeds capacity.

Table 5.2.10: Upper Confidence Interval to Exceed Toronto's Present Wastewater Capacity

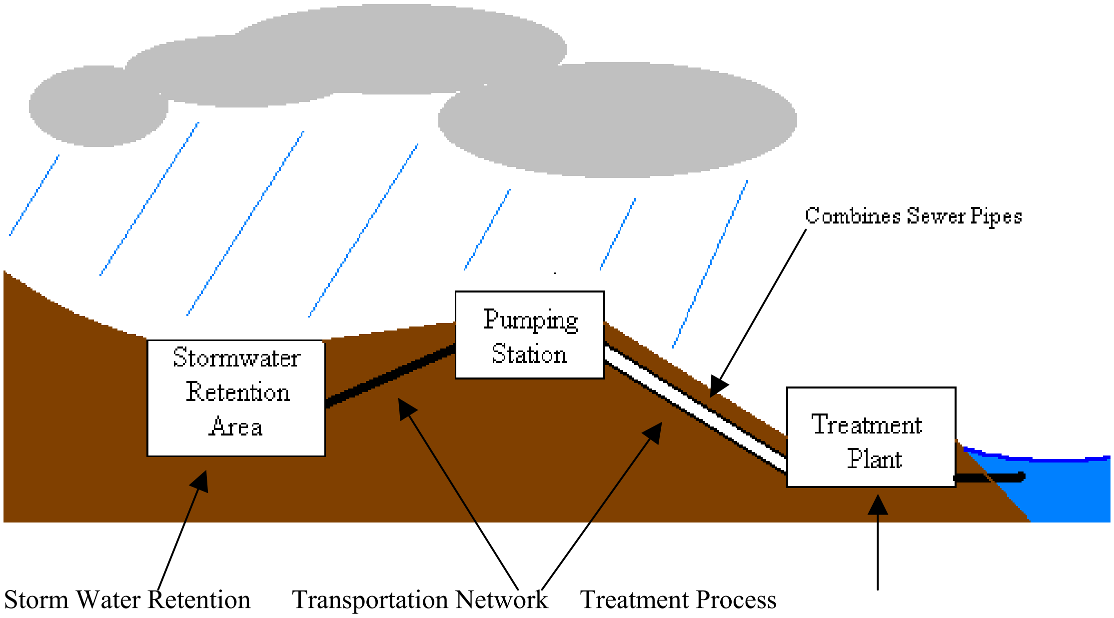
	Upper C.I Exceeding Toronto's Wastewater Capacity 1961 to 1990	Upper C.I. Exceeding Toronto's Wastewater Capacity 2010 to 2039	Upper C.I. Exceeding Toronto's Wastewater Capacity 2040 to 2069	Upper C.I. Exceeding Toronto's Wastewater Capacity 2070 to 2099
January	0	27.9	17.16	40.62
February	0	28.43	18.73	37.45
March	0	29.18	33.2	65.13
April	0	26.55	31.05	30.53
May	0	19.24	22.03	24.83
June	0	13.17	10.68	24.08
July	0	51.96	47	47.01
August	9.46	32.09	13.13	44.43
September	2.76	59.13	54.24	39.88
October	0	48.69	37.93	33.44
November	5.06	61.91	39.25	18.03
December	13.39	52.83	26.91	43.5
Totals	**30.67**	**451.2**	**351.36**	**448.99**

When we look at the upper confidence level, we see that in all months, in all future scenarios, there is insufficient treatment capacity.

5.2.11: Optimal Adaptation Costs of Wastewater Infrastructure for Toronto

After having established that Toronto has an inadequate wastewater management infrastructure and that this infrastructure is expected to fail by a greater extent in the future, we must determine the cost of adaptation.

Figure 5.2.6: Waste Water Process



From Figure 5.2.6 we see that Toronto's wastewater treatment process can be viewed as a system consisting of three components. The first component is the storm water retention areas. Storm water retention consists of 5 wastewater detention tanks and 36 storm water management ponds. In 1999, these areas could hold the first 25mm of rainfall after a storm and release the water slowly back into the transportation network.

The second component of the system is the transportation network. The network consists of 1,301km of combined sewers, 4,533 km of storm water sewers, 4,143 km of sanitary sewers and 18 pumping stations. This component is responsible for collecting storm water and delivering it from the detention areas to the treatment plants.

The third component is the wastewater treatment plant. In 1999, four treatment plants processed storm water. The total daily capacity of these treatment plants was 1,542,000 cubic meters or 3.3mm of rainfall.

Several different methods exist to build excess capacity into the wastewater infrastructure. The Wastewater Services Division could construct one or more new wastewater treatment plants, construct new water detention tanks (“storm water detention tunnels”) or improve the efficiency of their existing treatment plants. In order to estimate the cost of these improvements we have assumed that wastewater treatment technology is constant. This simplification allows us to dismiss the third option and treat the problem as a mixed-integer programming problem.

5.2.11.1: Experiment 1

By altering the capacity of storm water retention and treatment facilities the wastewater infrastructure can adequately treat different volumes of precipitation. The goal of our experiment is to minimize the total cost of infrastructure subject to the expected level and distribution of precipitation. This experiment uses CGCM1, GG1 precipitation data for the entire Grid 445. This first experiment is *without* downscaling.

Let A represent the average daily precipitation in millimeters.

Let x represent the incremental water treatment capacity in millimeters per day.

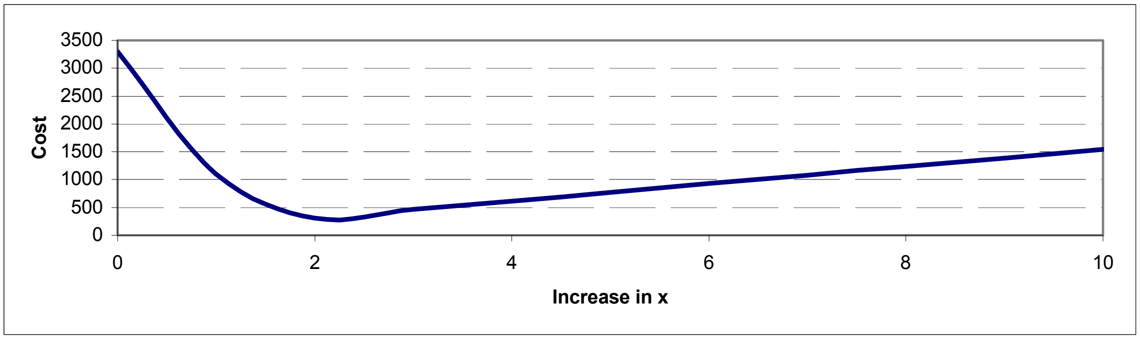
Let y represent the incremental capacity of the holding tanks.

Then the mixed-integer programming problem for finding the optimal x and y is:

$$
\begin{gathered}
\mathbf{Min}_{x,y}\ C = 154.30x + 78.57y \\
A - x \leq y \\
y \leq 2\ 5 \\
x \geq 3.3 \\
x \geq 0 \\
y \geq 0 \\
A = 5.53
\end{gathered}
$$

Using the relationship 25x = 3.3y, we can eliminate y from the objective function and using the Newton-Raphson method, find the optimal solution for x and y. The solution is displayed in diagram 5.2.7.

Figure 5.2.7: Solution – Experiment 1



The blue line represents the total cost of increasing x and y. The optimal solution x* and y* is the global minimum of this curve.

The optimal solution is x*=2, y*=0, where x* is the incremental change in storm water treatment capacity and y* is the incremental change in storm water holding tanks in millimeters of rainfall. That is, storm water treatment capacity increases by 2mm and the storm water holding tanks continue to hold 25mm of precipitation.

5.2.11.2: Experiment 2

In this experiment, once again we took precipitation data for CGCM1 Grid 445 without downscaling and distributed precipitation normally over the month. Now the mixed integer program problem is:

$$\mathbf{Min}_{x,y}\ \mathbf{C = 154.30x + 78.57y}$$

$$\mathbf{A(p) - x \le y}$$

$$\mathbf{y \le 2\ 5}$$

$$\mathbf{x \ge 3.3}$$

$$\mathbf{x \ge 0}$$

$$\mathbf{y \ge 0}$$

$$\mathbf{A(p) \ge 0}$$

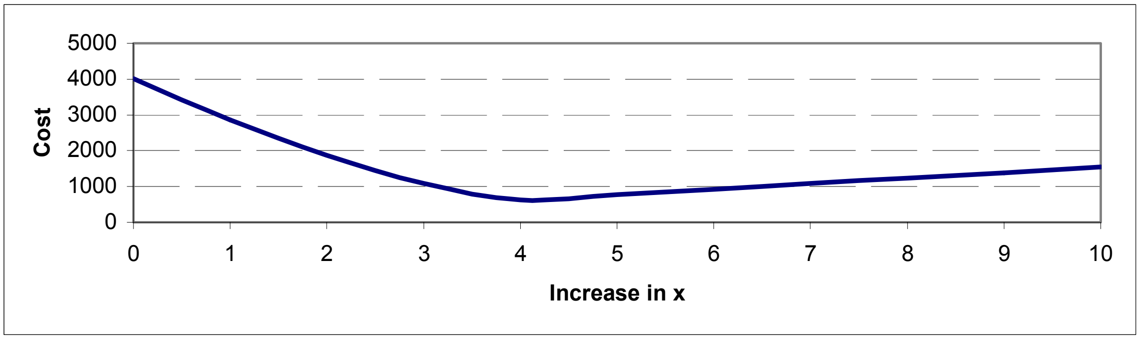
$$\mathbf{p \le 1}$$

$$\mathbf{p \ge 0}$$

where p is the probability of rain $p \sim N(\mu,\sigma^2)$, $p \le 1$

Using the same solution technique, we find that the optimal solution is Figure 5.2.8.

Figure 5.2.8: Solution – Experiment 2



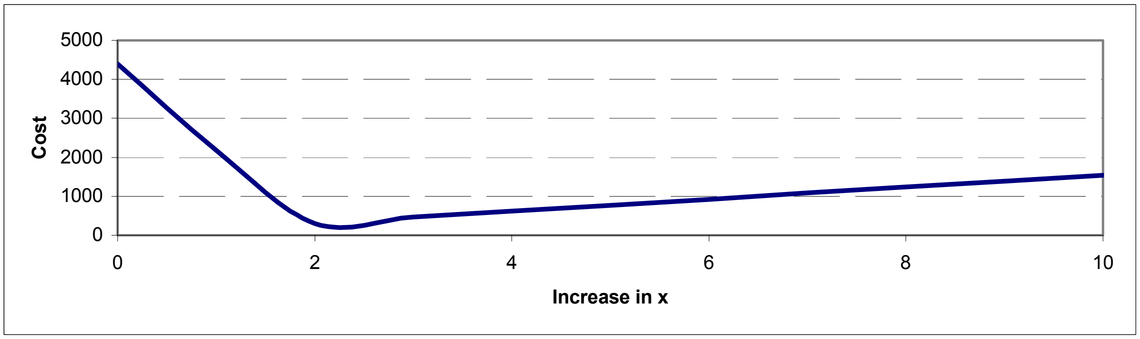
The optimal solution is x*=4 and y*=0. This means that without downscaling and with a normal distribution of precipitation, storm water treatment capacity increases by 4mm and the holding tanks continue to hold 25mm of precipitation.

5.2.11.3: Experiment 3

This experiment uses down-scaled precipitation data for Toronto; it is assumed that the rainfall is evenly distributed throughout the month.

$$
\begin{gathered}
\textbf{Min}_{x,y}\ C = 154.30x + 78.57y \\
A - x \leq y \\
y \leq 2\ 5 \\
x \geq 3.3 \\
x \geq 0 \\
y \geq 0 \\
A = 6.0
\end{gathered}
$$

Figure 5.2.9: Solution – Experiment 3



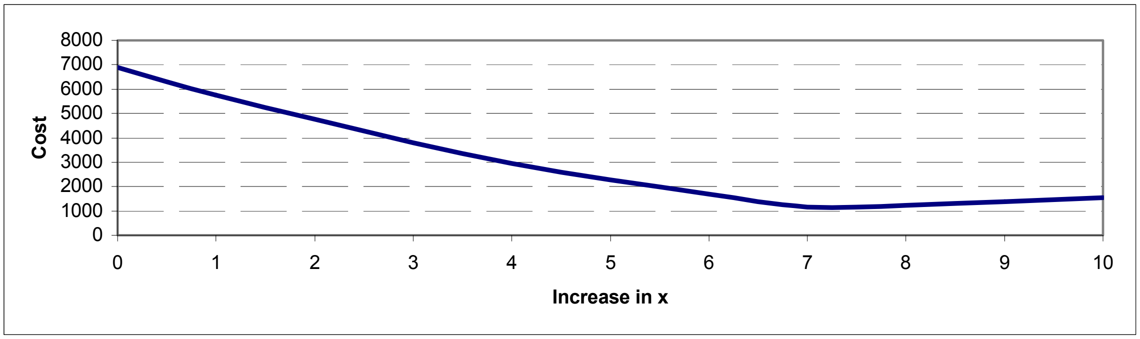
The optimal solution is x*= 2 and y*=0. This means that storm water treatment capacity increases by 2mm and the holding tanks continue to hold 25mm of precipitation.

5.2.11.4: Experiment 4

This experiment uses down-scaled data for Toronto with rainfall normally distributed throughout the month. The mixed integer program becomes:

$$
\begin{gathered}
\textbf{Min}_{x,y}\ C = 154.30x + 78.57y \\
B(p) - x \leq y \\
y \leq 2\ 5 \\
x \geq 3.3 \\
x \geq 0 \\
y \geq 0 \\
B(p) \geq 0 \\
p \leq 1 \\
p \geq 0
\end{gathered}
$$

Figure 5.2.10: Solution – Experiment 4



Now the solution is $x^* = 7$and $y^*=1$. This means that storm water treatment capacity increases by 7mm and the capacity of the holding tanks increases by 1mm to 26mm. This solution corresponds to the upper 95% confidence level for the downscaled data during the projected 2050s scenario.

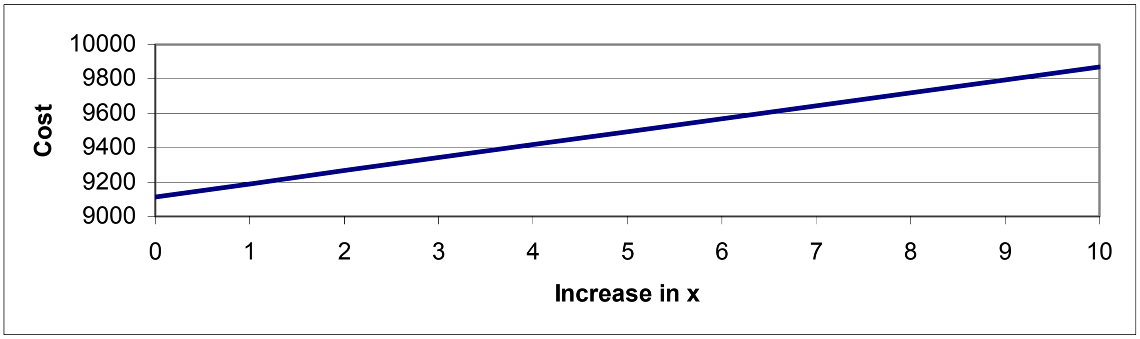
5.2.11.5: Experiment 5 Extreme Event

In this experiment we simulate the impact of an extreme event. We assumed a normal distribution of rain *throughout the day* (24-hours) with a total daily rainfall of 144mm.

Let B (p) represent the daily rainfall, where p is the probability of rain.

$$\mathbf{Min}_{x,y}\ C = 154.30x + 78.57y$$
$$B(p) - x \leq y$$
$$y \leq 2\ 5$$
$$x \geq 3.3$$
$$x \geq 0$$
$$y \geq 0$$
$$B(p) \geq 0$$
$$p \leq 1$$
$$p \geq 0$$

Figure 5.2.11: Solution – Experiment 5



The optimal solution is x*=0and y*=116. This means that storm water treatment capacity does not increase, but holding tank capacity increases by 116mm.

What do these experiments show? They show that wastewater treatment infrastructure (i.e. treatment capacity plus storage capacity) depends heavily on the nature of the distribution of precipitation. If rainfall is evenly distributed, then the optimal solution is always to increase treatment capacity. If however, the distribution of rainfall is such that the quantity of precipitation is greater than the treatment capacity, then it is optimal to add to storage capacity.

An additional factor in the above solution is the cost of land. In Toronto we have assumed the cost of land for holding tanks and storage to be $78.57 million per millimeter of rainfall. To obtain this estimate we surveyed storm water infrastructure costs in the state of California and multiplied the cost by 1.5 to obtain the cost in Canadian dollars. In smaller Californian cities the cost of storm water retention was as low as $43.18 million per millimeter of rain. We believe this lower cost is the result of lower land costs and therefore is not representative of a major city, like Toronto.

5.2.12: Combined Sewers

Although we have the ability to influence the cost of infrastructure by varying the capacity of wastewater treatment and wastewater storage, one cost that cannot be avoided is the conversion cost of separating combined sewers into separate sanitary and storm sewer lines. During wet weather months the volume of storm water exceeds the capacity of the wastewater treatment plants, which then causes the water in the sewers to mix. As the backup continues the water eventually overflows untreated into Lake Ontario. To solve this problem we have to construct separate sewers lines. The cost of this project was estimated to be $271 million in 1992. In 1999, this cost has risen by approximately 20% to $325 million.

5.2.13: Total Cost of Adaptation

The adaptation cost to wastewater infrastructure is the low estimate (Experiment 1) based on an even distribution of precipitation throughout the month with no downscaling.

Cost to increase wastewater capacity	(2) $154.30	$308.60
Cost to increase wastewater storage	(0) $78.57	
Cost of sewer replacement		$325.00
Total		**$633.60**

Therefore, using precipitation data for Grid 445, the total adaptation cost is $633,600,000. This is based on a 2mm increase in wastewater treatment capacity and no change in the holding tank storage capacity. The cost of sewer replacement is an actual cost based on previous sewer replacements.

The high estimate (Experiment 5) is based on an extreme event.

Cost to increase wastewater capacity	(0) $154.30	
Cost to increase wastewater storage	(116) $78.57	$9,114.12
Cost of sewer replacement		$325.00
Total		**$9,439.12**

Therefore, the cost of adaptation to an extreme event is equal to the cost of increasing holding tank storage plus the cost of sewer replacement. In the case of Toronto, the cost of adaptation is equal to $9,439,120,000, depending on how risk averse Toronto is. It should also be noted that throughout this study no discounting is used.

5.2.14: Summary and Conclusion

We conclude that the City of Toronto will face adaptation costs from a low of $633 million to a high of $9.4 billion. These are the costs associated with increasing wastewater treatment and storage capacity, as it seems likely that in the future scenarios, precipitation will increase beyond the existing capacity. Drinking water supply does not appear to be affected by climate change, as intake pipes are deeper than the expected 1 metre drop in lake levels.

5.3: Niagara, ON

In Niagara, the water distribution system consists of eight potable water systems, including seven water treatment plants and one well system together with the associated flow metering facilities, water mains, reservoirs, tanks and pumping stations. Water treatment consists of screening, coagulation, flocculation, sedimentation, pH correction and rapid gravity filtration. Granular activated carbon filter-adsorbers are used for taste and odour control, as well as powdered activated carbon.

There is an estimated $110 billion of in-ground water infrastructure assets in Canada and there is a population of approximately 30 million people. Therefore the per capita investment in water infrastructure in Canada is $3667. The population of the Region of Niagara is 415,600 (see Figure 5.2.1). Therefore, the estimated value of the water infrastructure in Niagara is about $1.5 billion.

Drinking water production in Niagara ranges from an actual high of 89,981,408 cubic metres (89,981,408,000 litres) in 1988 to a projected low of 61,327,047 cubic metres (61,327,047,000 litres) in 2010. The numbers indicate that there will be an average decrease in production of –1.63%. The average daily demand for water in litres per capita ranges from a low in 1997 of 539.843 to a high of 592.062 in 1991.

In the Region of Niagara, the Water & Wastewater division is responsible for the operation and engineering of water and sewer systems. The division is also accountable for master servicing plans, water & sewer approvals, laboratory services, environmental monitoring, industrial waste and training. The Region has the responsibility for the domestic water supply (including pumps, storage facilities and 39.5 km. of mains) and sewage treatment facilities (including pumping stations and forcemains). Water treatment is the process of cleaning and disinfecting water, and because water is a natural solvent, it attracts various pollutants and is not always safe to drink. The Region of Niagara operates and maintains eight potable water systems that include seven water treatment plants and one well system together with the associated remote treatment and flow metering facilities, water mains, storage reservoirs and tanks, and pumping stations. The systems vary in capacity from 227.3 ML/d to 4.3 ML/d. The total rated normal capacity for all potable water systems is 613.6 ML/d. In addition, screened raw water is supplied to the City of Thorold for industrial users.

A total of 80,717,236 cubic metres of potable water and 1,225,405 cubic metres of raw water were supplied by the various systems in 1998. Compared to the previous year this is a 5.6 percent increase in potable water and a 3.6 percent increase in the industrial raw water. The actual net expenditure for water operations, including administration and supervision, was $8,442,702. The uniform water rate for potable water was $ 1.25 per 1,000 gallons ($ 0.275 per cubic metre). The rate charged to the City of Thorold for raw water was $0.00605 per 1,000 gallons ($0.0013 per cubic metre) for system operation.

In 1999, a total of 81,014,957 cubic metres of potable water and 489,915 cubic metres of raw water were supplied. Compared to 1998, this is a 0.5 percent increase in potable water and a 61 percent decrease in the industrial raw water. In 1999, the actual net expenditure for water operations, including administration and supervision, was $8,868,559. The uniform rate for potable water was $1.323 per 1,000 gallons ($0.2910 per cubic metre).

5.3.1: Precipitation Trends

In 1999, total precipitation across Niagara was well below the normal as defined by Meteorological Services of Canada (MSC) of Environment Canada. The winter of 1998/1999 saw the beginning of a dry trend with well below normal precipitation in January and February. The Spring experienced the same trend with March being 80% below normal and April and May, 20 to 40% dryer than normal. A limited degree of variability in precipitation patterns was observed in the summer; however June and July were 40% below MSC normals and August was 30% below normal. Above normal precipitation values were observed in the fall, with three storms accounting for 60 to 70% of the rainfall for the season.

5.3.2: Precipitation and Water Flow

In 1999, the Niagara Region average monthly rainfall exceeded the MSC average monthly rainfall in September, October and November. The seven-year average monthly rainfall trend, from 1993 to 2000 was below the MSC average monthly rainfall except for December 1995, summer of 1996 and the winter of 1996. In 1999, the regional average precipitation was 578mm and the actual water flow was 81,014,957 cubic metres.

5.3.3: Niagara River Drainage, Lake Erie and Lake Ontario

The Niagara River drains an area of 254,708 square miles, including the Upper Great Lakes. The surface area of Lake Erie is 87,845 square miles, and it is the shallowest of the Great Lakes, averaging 60 feet in depth. The levels of the Great Lakes vary on an annual basis in relation to the season, rainfall, evaporation and runoff. The highest water levels occur in mid-summer and the lowest occur in mid-winter. The internal time required for an increase supply of water to show its effect upon the level of Lake Erie is approximately 76 days. The internal time required for a decrease in the supply of water to show its effect upon the level of Lake Erie is approximately 132 days. A variation in the level of Lake Erie of one foot at Buffalo, New York equates to a difference in the rate of flow discharge from Lake Erie into the Niagara River of 20,000 to 25,000 cubic feet per second. During storms, the water level of Lake Erie may vary as much as 15 feet. The average annual rainfall in the Great Lakes equals 36 inches, and the average annual evaporation rate equals 24 inches. In September 1999, water level at Lake Erie was at 571.19 feet above sea level. This was 4.3 inches (11 cm) below the long-term average. Lake Erie's water level was the lowest that has been recorded since 1967. In the summer of 1999, the Great Lakes water levels were 16-24 inches below those recorded in 1998. The average flow water rates are shown in Table 5.3.2.

Table 5.3.1: Average Flow Water Rates

Time Period	**Inflow (Lake Erie into Niagara River)**	**Outflow (from Niagara River)**
Sept.1999-Feb.2000	173,400 cubic ft/sec.	184,000 cubic ft/sec.
Mar-Aug1999	186,100 cubic ft/sec.	200,660 cubic ft/sec.

5.3.4: Drinking Water Supply Impacts

5.3.4.1: Capital Costs

The decrease in net precipitation results in a decrease in lake levels. This could have an impact on water supply, as water intake pipes must be either extended or moved in order to draw enough water of suitable quality. The Niagara Region has water intake pipes in Lake Ontario, Lake Erie, Niagara River via the Welland River Channel and Lake Erie via the Welland Canal.

The intake pipes that could be affected by lower lake levels are those in Lake Erie and Lake Ontario. The Lake Erie pipe is at a depth of 20 feet and extends about 800 metres into the lake. The Lake Ontario pipe is at a depth of 30 feet and extends 1950 metres into the lake.

Because the pipes are deep and extend so far into the lake, a decrease of 1 metre in lake level may not have an appreciable effect on the ability of the intake pipes to access suitable water. However, the marginal costs of adding pipe are calculated below in the event that water levels drop so far that additional pipes are needed to draw water.

5.3.4.2: Operating Costs

Lower lake levels might have an impact on operating costs in terms of raw water treatment. Higher evaporation rates will leave more suspended solids in raw water, increasing the water treatment costs. To estimate the costs of increased treatment due to a higher number of suspended solids, annual treatment costs and lake levels can be compared. This is a subject for future research.

5.3.4.3: Capital Projects

In 1999, capital projects carried out in the Niagara peninsula in the water supply system amounted to \$16,500,000 and for 2001 the amount is budgeted at \$17,400,000. Capital cost outlays can include water treatment plant upgrades, raw water supply improvements, reservoir connection piping, and booster pumping station upgrades, water main replacements and storage tank replacements.

5.3.5: Wastewater Treatment

5.3.5.1: Climate Induced Change in the Rainfall

The Region of Niagara operates and maintains fourteen wastewater systems that include nine full wastewater treatment plants, one lagoon augmented with chemical/physical treatment and four lagoon systems together with the associated flow metering facilities, force mains, gravity sewers, storage tanks, and pumping stations. The system consists of 103 Regional Niagara owned and/or operated pumping stations, 7 owned and operated by the municipalities, 3 odour control stations, 4 metering chambers and 1 storm water holding reservoir. In 1998 the quantity of sewage treated at Niagara's wastewater treatment plants was 84,083,335m^3. In 1999 this figure was 83,444,822m^3, a .76% decrease. The systems vary in capacity from 68,200 m^3/d to 500 m^3/d. The full treatment capacity rating for all wastewater systems is 329,880m^3/d. The peak storm rating for all systems is 707,480m^3/d. The actual net expenditure for wastewater operations, including administration and supervision was \$15,671,597 in 1999. The uniform water rate for wastewater treatment was $2.178 per 1,000 gallons ($0.4790 per cubic metre).

Wastewater flows in Niagara range from an actual high of 102,922,624 cubic metres (102,922,624,000 litres) in 1996 to a low of 77,050,775cubic metres (77,050,775,000 litres) in 1988. The numbers indicate that there will be an average increase in flow of 1.6%. The average daily sewage per capita ranges from a low in 1988 of 492.562 litres to a high of 697.728litres in 1996. The Region of Niagara has projected sewage flows to increase over the next decade. The average daily projected sewage flows in litres for the next decade are:

2001	266,030,443.8
2002	268,118,580.8
2003	270,206,720.5
2004	272,294,857.5
2005	274,382,997.3
2006	276,471,134.2
2007	278,559,274.0
2008	280,647,411.0
2009	282,735,550.7
2010	284,823,687.7

Periods of high precipitation cause an increase in sewage generation, due to the influx of extraneous flows via inflow and infiltration and resulting wet weather flows. In 2000, the Region experienced an increase in precipitation from 30mm to 160mm from January to June. In the same period sewage flows increased from 7,000,000 cubic metres to 10,000,000 cubic metres. Precipitation dropped from a high of 160mm in June to 55mm in July, and sewage flow similarly declined from 10,000,000 cubic metres to 7,000,000 cubic metres.

5.3.5.2: General Circulation Model-CGCM1 Greenhouse Gas Only Simulation

As indicated earlier, the climate change model used for predicting changes in climate variables is the CGCM1-GG1 from the Canadian Institute for Climate Studies. This model assumes there is no dampening effect of aerosols and there is no downscaling to the regional area in terms of the climate variables. This model is based on data covering a geographical area of 3.75^o longitude and 3.75^o latitude. The Region of Niagara is located in Grid Box 445; i.e. the same grid box as Toronto.

5.3.5.3: CGCM1-GG1 Proportional Downscaling

We carried out our own version of downscaling in order to reflect the statistical properties of actual data of precipitation. As the Welland data was available to us, we used it as the prototype for the Niagara peninsula. The downscaling method is described in Chapter 2.

Table 5.3.2: CGCM1-GG1 Proportional Downscaled Precipitation Statistics for Niagara

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	1310.92	247.5	1310.92	933.93	881
Minimum	3.61	12.9	6.45	3.61	6.75
Mean	104.33	88.58	110	105.25	113.49
Standard Deviation	89.44	37.11	114.04	92.01	94.07

Our proportional downscaling captures the essential statistical properties of real time series and reflects the plausible characteristics of the distribution of precipitation. Note that the mean and the standard deviation of the distribution increases (see Table 5.3.2). Maximum precipitation, a variable that reflects extreme events also increases dramatically from the baseline period.

5.3.5.4: Regression Results

To find the monthly pattern of precipitation, we regressed precipitation on eleven monthly dummy variables. The conceptual foundation for these regressions is given in Chapter 2.

The estimated regression for 1961 to 1990 is:

$$\mathbf{PPT} = \underset{(13.38)}{\mathbf{87.72}} - \underset{(-0.57)}{\mathbf{5.36D2}} - \underset{(-0.28)}{\mathbf{2.6D3}} - \underset{(-0.71)}{\mathbf{6.61D4}} - \underset{(-1.07)}{\mathbf{9.94D5}} + \underset{(0.34)}{\mathbf{3.19D6}} - \underset{(-1.52)}{\mathbf{14.14D7}} + \underset{(0.54)}{\mathbf{5.01D8}} +$$

$$\underset{(0.53)}{\mathbf{4.95D9}} - \underset{(-0.67)}{\mathbf{6.23D10}} + \underset{(1.23)}{\mathbf{11.45D11}} + \underset{(3.3)}{\mathbf{30.65D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT} = \underset{(4.86)}{\mathbf{101.1}} + \underset{(0.17)}{\mathbf{5.13D2}} + \underset{(0.55)}{\mathbf{16.24D3}} - \underset{(-0.1)}{\mathbf{3.15D4}} - \underset{(-0.7)}{\mathbf{20.86D5}} - \underset{(-0.35)}{\mathbf{10.57D6}} + \underset{(0.44)}{\mathbf{13.14D7}} - \underset{(-0.33)}{\mathbf{9.94D8}}$$

$$+ \underset{(0.65)}{\mathbf{19.93D9}} + \underset{(0.77)}{\mathbf{22.77D10}} + \underset{(1.43)}{\mathbf{42.19D11}} + \underset{(1.64)}{\mathbf{48.27D12}}$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT} = \underset{(5.48)}{\mathbf{92.6}} + \underset{(0.37)}{\mathbf{8.97D2}} + \underset{(0.62)}{\mathbf{15.03D3}} + \underset{(0.59)}{\mathbf{14.28D4}} - \underset{(-0.13)}{\mathbf{3.18D5}} + \underset{(0.13)}{\mathbf{3.13D6}} + \underset{(0.72)}{\mathbf{17.23D7}} - \underset{(-0.49)}{\mathbf{11.9D8}} +$$

$$\underset{(1.33)}{\mathbf{31.99D9}} + \underset{(1.06)}{\mathbf{25.45D10}} + \underset{(1.13)}{\mathbf{27.2D11}} + \underset{(0.97)}{\mathbf{23.38D12}}$$

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT} = \underset{(7.5)}{\mathbf{128.88}} - \underset{(-0.19)}{\mathbf{4.77D2}} + \underset{(0.65)}{\mathbf{15.88D3}} - \underset{(-0.86)}{\mathbf{21.11D4}} - \underset{(-1.75)}{\mathbf{42.63D5}} - \underset{(-0.83)}{\mathbf{20.15D6}} - \underset{(-1.05)}{\mathbf{25.54D7}} - \underset{(-1.14)}{\mathbf{27.79D8}}$$

$$- \underset{(-0.7)}{\mathbf{17.14D9}} - \underset{(-0.84)}{\mathbf{20.4D10}} - \underset{(-1.33)}{\mathbf{32.49D11}} + \underset{(0.47)}{\mathbf{11.49D12}}$$

We can see that the constant increases in each future scenario from the baseline. The constant is also significant in each scenario. This means that the mean precipitation for January is higher in the future scenarios than in the baseline. From these regressions we can determine the mean and the 95% confidence interval. These results are graphed in Figures 5.3.1 to 5.3.4.

Figure 5.3.1: Results for Niagara (1961-1990)

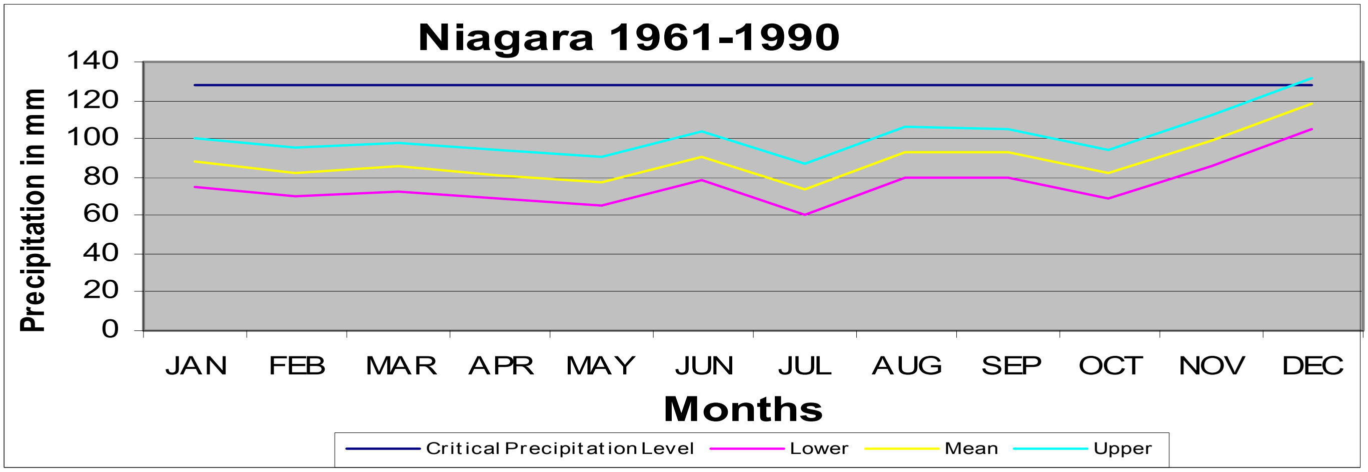


Figure 5.3.2: Results for Niagara (2010-2039)

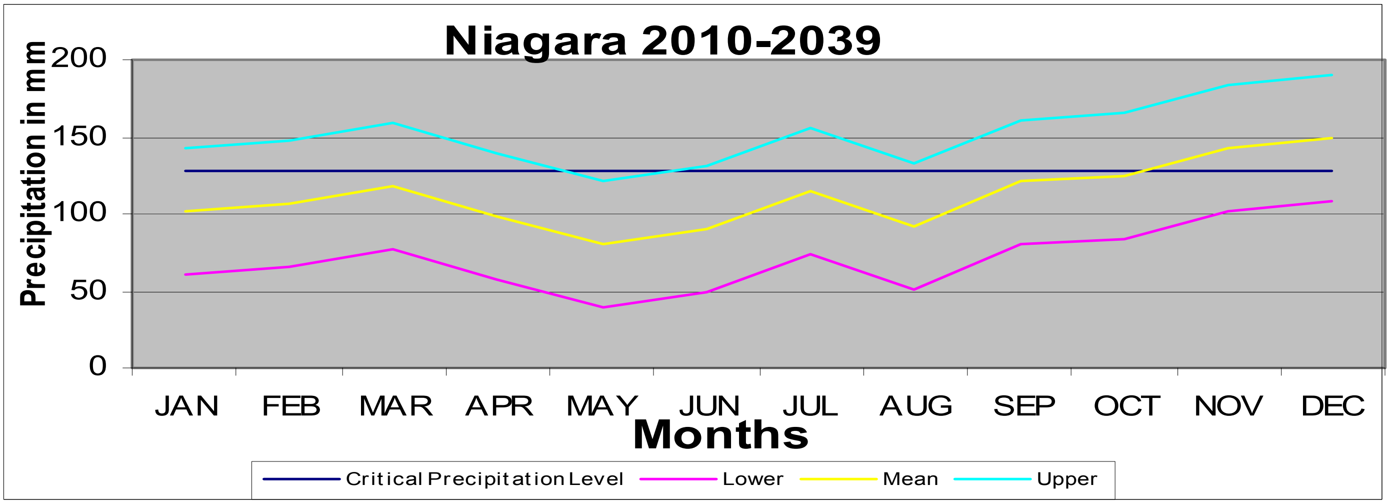


Figure 5.3.3: Results for Niagara (2040-2069)

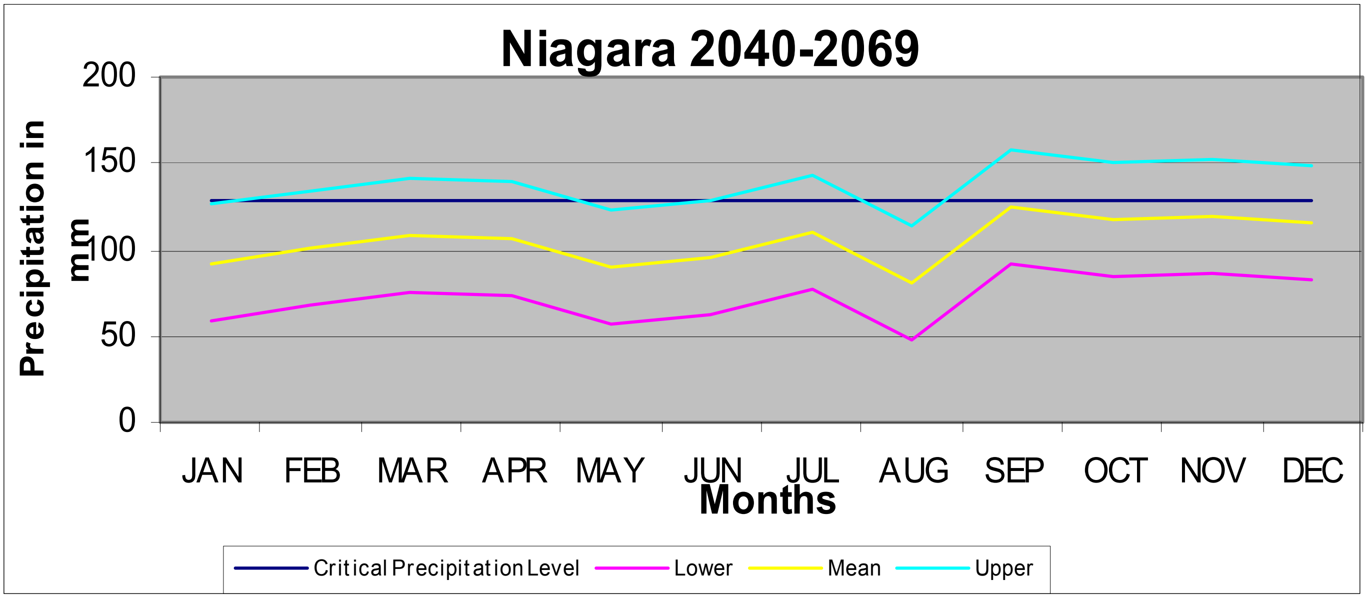
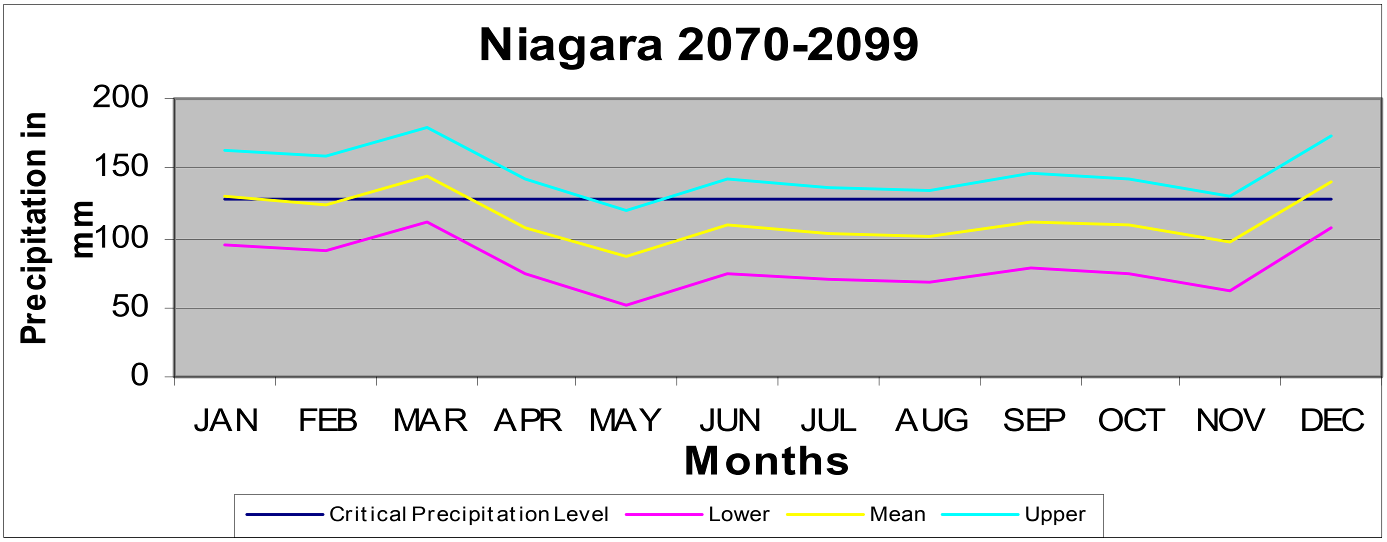


Figure 5.3.4: Results for Niagara (2070-2099)



In the baseline scenario, the mean does not exceed the capacity in any month, but in the 2020 scenario the mean exceeds the capacity in November and December. The mean also exceeds the capacity in several months of the 2080 scenario. As was the case in the Toronto study, the upper confidence level exceeds the capacity in almost all months of the future scenarios.

5.3.5.5: Capacities and Flows

Table 5.3.3 shows the capacity ratings and average daily flows of all Niagara Region wastewater treatment plant facilities and lagoons.

Table 5.3.3: Wastewater Treatment Plant and Lagoon Flow Ratings

Facility	Rating m^3/d	Peak Storm Rating m^3/d	Average Daily Flow m^3/d
Niagara Falls	68,200	136,400	56,822
Queenston	500	700	213.723
Port Dalhousie	61,350	122,700	40,722.173
Port Weller	68,100	136,200	41,475.367
Niagara-on-the-Lake	5,710	8,520	3841.444
Welland	54,550	136,200	42,784.129
Grimsby	22,750	45,460	16,336.811
Port Colborne	15,120	45,000	11,317.603
Fort Erie	24,500	49,000	10,946.477
Crystal Beach	9,100	27,300	3,048.597
Biggar	1,818.4		1,154.036
Port Robinson	441		267.981
Stevensville	2,273		1,069.602
Total	**334,412.4**	**707,480**	**229,999.943**

Source:Regional Municipality of Niagara Public Works Department 1999 Statistical Report

Average daily flow divided by capacity rating is equal to 68.7% (229,999/334,412). The mean precipitation for 1961 to 1990 is 88.48mm. A simple calculation will show that the precipitation level in a single month that will force the treatment plants to operate at 100% is 128 mm. Therefore, precipitation beyond 128mm a month will cause storm water to overflow into the ecosystem. That is, 128*.687 = 88. The amount of precipitation expected to exceed the treatment plants' capacity is summarized in the following tables.

Table 5.3.4: Predicted Precipitation to Exceed Niagara's Wastewater Capacity

	Precipitation Exceeding Niagara Wastewater Capacity 1961 to 1990	Precipitation Exceeding Niagara Wastewater Capacity 2010 to 2039	Precipitation Exceeding Niagara Wastewater Capacity 2040 to 2069	Precipitation Exceeding Niagara Wastewater Capacity 2070 to 2099
January	0	0	0	0.88
February	0	0	0	0
March	0	0	0	16.77
April	0	0	0	0
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	0	0	0	0
November	0	15.31	0	0
December	0	21.39	0	12.37
Totals	**0**	**36.7**	**0**	**30.02**

Table 5.3.5: Upper Confidence Level to Exceed Niagara's Wastewater Capacity

	Upper Confidence Level Exceeding Niagara Wastewater Capacity 1961 to 1990	Upper Confidence Level Exceeding Niagara Wastewater Capacity 2010 to 2039	Upper Confidence Level Exceeding Niagara Wastewater Capacity 2040 to 2069	Upper Confidence Level Exceeding Niagara Wastewater Capacity 2070 to 2099
January	0	13.98	0	34.63
February	0	19.12	6.81	29.86
March	0	30.23	12.87	50.52
April	0	10.82	12.12	13.52
May	0	0	0	0
June	0	3.41	0.97	14.47
July	0	27.13	15.08	9.08
August	0	4.04	0	6.83
September	0	33.38	29.84	17.48
October	0	36.75	23.29	14.22
November	0	56.18	25.05	2.13
December	3.26	62.26	21.22	46.12
Totals	**3.26**	**297.35**	**147.25**	**238.92**

The above tables indicate in which months precipitation will exceed the capacity of the wastewater treatment plant to treat it. In the case of the mean, precipitation exceeds capacity in November and December of the 2020 scenario and January, March and December of the 2080 scenario. In the case of the upper confidence interval, precipitation exceeds capacity in almost every month of the future scenarios.

5.3.5.6: Capital Costs

Capital cost outlays can include trunk sewer replacement, sewer system upgrade, sanitary sewer replacement, pumping station improvements and biosolids facility improvements. In 1999, capital cost spending on the wastewater system was $15.1 million. A significant portion of the total costs of wastewater is driven by capital costs. In wastewater, increased spending might be needed to accelerate wet weather flow control and minimize overflows. Increased precipitation will cause an increase in sewage flows. More containment tanks or separate storm and sanitary sewers will be needed.

5.3.6: Costs of Adaptation

The costs of adaptation for Niagara can be estimated using the same methodology as Toronto, but research needs to be done into costs specific to Niagara. For a rough estimate, we can use a rule-of –thumb approach by determining the extent to which the wastewater treatment plant must increase capacity.

Tables 5.3.4 and 5.3.5 show precipitation exceeding capacity to be at its greatest in the 2020 scenario. Maximum precipitation occurs in December when the mean precipitation exceeds capacity by 21.39 mm and the 95% upper confidence level is 62.26mm. The wastewater treatment has a capacity of 128 mm of precipitation. Therefore the capacity would have to expand a minimum of 16% and a maximum of 48% to prevent wastewater overflow. Based on the 1999 capital spending figure of $15.1 million, capital spending in the 2020 scenario, for any given year, would have to increase by $2.4 million to $7.2 million.

Based on an estimate of new wastewater treatment facilities costing $50 million (see Section 5.10.2), the costs of expanding capacity range from $8 million to $24 million.

5.3.7: Summary and Conclusion

In the Niagara Region, drinking water supply will not be affected by climate change in the next century. The water supply comes from Lake Erie and Lake Ontario and because lake levels will not fall below the depth of the intake pipes, water supply will remain secure. This, of course, assumes that the levels of water in the Great Lakes do not fall appreciably.

However, the capacity of wastewater treatment will be insufficient in the three future scenarios. The upper 95% confidence intervals indicate that wastewater flows will exceed treatment capacity. Therefore the costs of adaptation are those associated with expanding wastewater treatment plants.

These costs were estimated to be in the range of $8 million to $24 million for an investment in expansion of the wastewater treatment facilities and $2.4 million to $7.4 million on annual capital expenditures.

5.4: Montreal, PQ

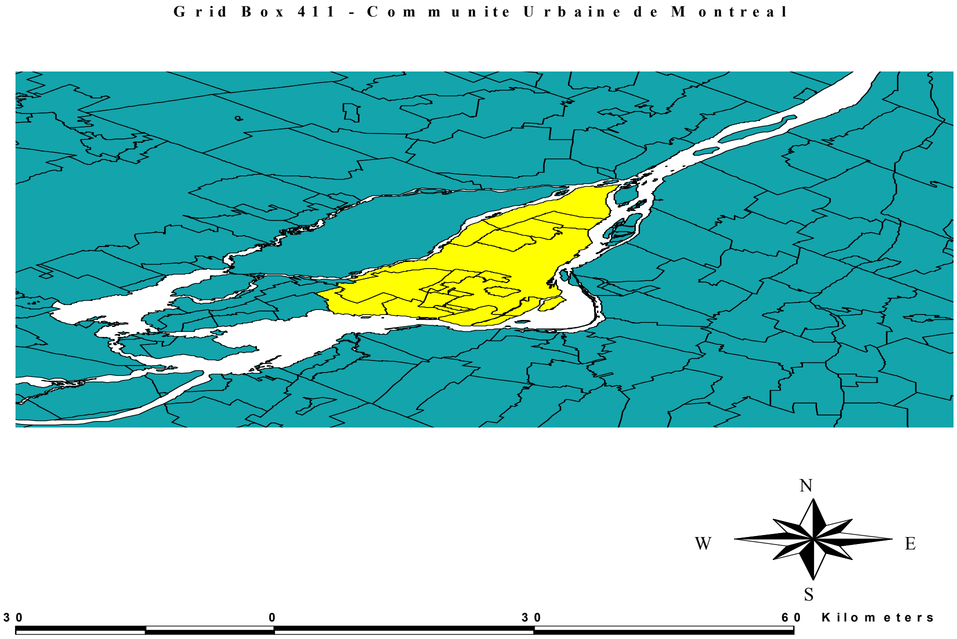
5.4.1: Drinking Water Supply

In the Communauté Urbaine de Montréal, the water is drawn from the St. Lawrence River and the average consumption of water per person per day is 1430 litres (see Figure 5.4.1). This figure is double that of Toronto and three times that of Edmonton. Annual consumption from 1995 to 1999 in thousands of cubic metres is as follows:

1995	647,348
1996	638,125
1997	618,112
1998	633,067
1999	649,763

Source: Communauté urbaine de Montréal General Statistics

Figure 5.4.1: Communité Urbaine de Montréal



5.4.2: CGCM1-GG1 Proportional Downscaling

As in the previous section, we downscaled the data for Montreal using the methodology described in Chapter 2. We used Grid box 411, which includes much of southwestern Ontario, including Montreal. Table 5.4.1 shows the descriptive statistics for precipitation.

Table 5.4.1: CGCM1-GG1 Proportional Downscaled Descriptive Precipitation Statistics

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	534.96	234	534.96	388.65	402.57
Minimum	11.99	16.3	11.99	12.11	14.18
Mean	98.91	89.9	100.05	102.3	103.36
Standard Deviation	62.22	37.4	66.88	69.78	68.22

Note that the mean increases slightly over the four time periods and the standard deviation increases 78.8% from the baseline scenario to the 2020 scenario. The maximum increases from the baseline to the 2020 scenario by 128%, decreases in the subsequent years but remains 66% to 72% above the baseline.

Based on this analysis, precipitation is expected to increase in the next one hundred years, and so Montreal is unlikely to face droughts. Therefore we assume that water supply is not expected to be adversely affected by a changing climate.

5.4.3: Wastewater Treatment

Some 180 outfalls located throughout the island of Montreal drain the Communauté Urbaine de Montréal. The outfalls in the northern part of the territory used to drain their wastewater into rivière des Prairies and lac les Deux Montagnes, but since 1984, it has been directed toward the Plant via the northern interceptor (41km). Similarly, wastewater from the outfalls located in the southwestern area of the territory was discharged into Lac Saint-Louis until 1987. Since then, it has been directed toward the Plant through the southwestern interceptor (18 km), which is hooked up to the northern interceptor. Wastewater from the remaining outfalls located in the southern area of the territory was discharged into the Saint-Laurent until 1990. Since that time, it was progressively channelled to the Plant as work on the southeastern interceptor (30.5 km) was completed. The northern, southwestern and southeastern interceptors, which measure a total of 89.5 km in length, constitute the Community's wastewater interception network. Their diameter varies from 1.8 to 5.4 metres. Since August 1995, the Community's Treatment Plant has processed, in dry weather flow periods, all of the wastewater from the islands of Montreal and Bizard.

The average flow rate received at the Treatment Plant is approximately 2,500,000 m^3/d. During heavy rainfalls, the wastewater flow rate can reach a maximum of 7,600,000 m^3/d. The drainage networks for approximately one third of Montreal's territory, mainly the western sector, were developed as part of a separate system. The latter is made up of a sanitary sewer for collecting residential, industrial, commercial and institutional wastewater and a storm water sewer for rainwater. The drainage networks in the remaining central and eastern sectors were almost exclusively developed as part of a combined system with a single sewer collecting all wastewater and rainwater. The Community's interception network and the Wastewater Treatment Plant were built to collect and treat approximately 75% of all rainwater from the combined system's drainage networks, representing 50% of all rainwater from the whole of the Montreal area. About 60% of the territory is developed in a combined system. Each interception structure can collect from 12 to 40 times the average dry weather flow. The supplementary volume of water from rainwater accounts for about 13% of the total volume of wastewater treated at the plant. This volume of water is negligible compared to that from infiltration, which is estimated at more than 30% of the waters found at the plant.

Directly connected to the interceptors, the 68 hookup structures (36 of which are equipped with regulating structures) direct wastewater from the trunk sewers through the interceptors to the Wastewater Treatment Plant. The hookup structures for the sanitary trunk sewers are equipped with a diversion structure and a drop shaft linked to the interceptor. Wastewater is being collected at all times.

In the case of the combined trunk sewers, the total flow rate is diverted toward the interceptor during dry weather flow periods. However, during periods of heavy rainfall, some of the runoff and wastewater may be channelled directly toward Rivière des Prairies or the St. Lawrence River.

The diversion structure consists of a diversion box built under the invert of the trunk sewer. In the event the trunk sewer should become submerged or affected by the water level of the receiving waterway at the interception point, a flap gate chamber is added to the trunk sewer to prevent the collection of water from the receiving waterway. During rainy weather, sluice gates mounted in the regulating structure control the inflow of wastewater and rainwater to the interceptor in response to signals from the control centre at the Wastewater Treatment Plant or the local control panel. The wastewater is directed toward a drop shaft, up to 30 metres deep, to the interceptor and flows by gravity to the Wastewater Treatment Plant, located on the eastern tip of the island of Montreal. The water is treated at the Plant, before being returned to the St. Lawrence.

The pumping station has a maximum capacity flow rate of 88 cubic metres per second. When wastewater reaches the Plant, it is brought up to the surface by 17 pumps and discharged into a peripheral channel. Eight of these pumps, each with a 6.3 m^3/s capacity, service the northern interceptor, while nine others, with a 6.9 m^3/s capacity, serve the southern interceptor.

The daily capacity of the wastewater treatment plant is 7.6 million cubic metres per day and the average flow rate received at the plant is approximately 2.5 million cubic metres per day. This capacity of 7.6 million cubic metres per day makes the Montreal Wastewater Treatment Plant the largest primary physico-chemical treatment plant in North America. Because on a given day, only 32% of the capacity of plant is utilized, Montreal has a great deal of excess capacity already built into the system. During heavy rainfalls, when the wastewater flow can reach 7.6 million cubic metres per day, 100% of plant capacity is utilized. In the baseline period, the maximum amount of precipitation was 234mm, and the mean was 89.9mm. By a simple calculation, we can conclude that the maximum amount of precipitation the plant can treat is 280mm. Any precipitation exceeding this amount will be discharged into the river, untreated. Before the construction of this facility, wastewater was dumped directly into the St. Lawrence. The Plant treats 44% of all wastewater processed in treatment plants within Quebec and has one of the highest pumping capacities in all of North America (see Table 4.5.2).

Table 5.4.2 Average Flows and Treated Volumes

	Average Flow (m^3/s)	Pumped Volume (Mm^3)	Average Daily Flow (m^3)
Jan	30.2	80,904	2,609,800
Feb	29.3	75,879	2,709,900
Mar	28.9	69,796	2,251,400
Apr	34.1	91,248	3,041,600
May	25.3	67,706	2,184,000
Jun	28.1	72,825	2,427,500
Jul	28.3	75,683	2,441,000
Aug	27.1	72,681	2,344,500
Sept	33.9	87,915	2,930,500
Oct	31.0	82,976	2,676,600
Nov	25.0	64,835	2,161,000
Dec	29.5	79,068	2,550,000
Average	**29.25**		
Total		**921,516**	

Source: MUC Water and Wastewater website; www.cum.qc.ca/sewage

5.4.4: Wastewater Treatment Plant Costs

The total cost of this major wastewater treatment project required an investment of $1.375 billion, of which $750 million was invested in the construction of the Wastewater Treatment Plant and $625 million in the construction of the interceptor network.

In 1998, the operational costs of the treatment plant were $42,909,500. $16,212,000 are variable costs, which represent about 38% of the total operating costs.

Capital expenditures on sewers from 1995 to 1999 are:

1995	$28,406,000
1996	37,787,000
1997	18,084,000
1998	10,235,000
1999	8,599,000

Source: Ville de Montréal Capital Expenditure Fund

5.4.5: Regression Results

As with the other case studies, we now carry out some regressions to consider the change in the pattern of precipitation for Montreal. The conceptual foundation for these regressions is given in Chapter 2. The estimated regression for the 1961 to 1990 period is:

$$\begin{array}{ccccccccc} \mathbf{PPT=73.73} & \mathbf{-\ 3.01D2} & \mathbf{+\ 8.9D3} & \mathbf{+\ 5.76D4} & \mathbf{+\ 8.91D5} & \mathbf{+\ 19.93D6} & \mathbf{+\ 26.27D7} & \mathbf{+\ 33.39D8} & \mathbf{+} \\ (11.23) & (-0.32) & (0.95) & (0.62) & (0.96) & (2.14) & (2.83) & (3.59) & \end{array}$$

$$\begin{array}{cccc} \mathbf{21.86D9} & \mathbf{+\ 8.83D10} & \mathbf{+\ 28.33D11} & \mathbf{+\ 35.02D12} \\ (2.35) & (0.95) & (3.05) & (3.77) \end{array}$$

The estimated regression for the 2010 to 2039 period is:

PPT= 68.61 + 18.02D2 + 34.39D3 + 19.96D4 + 22.57D5 + 40.24D6 + 37.25D7
(5.66) (1.05) (2) (1.16) (1.31) (2.35) (2.17)

39.33D8 + 36.58D9 + 44.15D10 + 25.29D11 + 59.5D12
(2.29) (2.13) (2.57) (1.47) (3.47)

The estimated regression for the 2040 to 2069 period is:

PPT= 78.96 + 4.19D2 + 24.56D3 + 30.75D4 + 18.93D5 + 28.67D6 + 21.59D7 + 1.37D8
(6.18) (0.23) (1.36) (1.7) (1.04) (1.58) (1.19) (1.18)

+ 22.86D9 + 38.45D10 + 27.63D11 + 41.04D12
(1.26) (2.13) (1.53) (2.27)

The estimated regression for the 2070 to 2099 period is:

PPT= 76.35 + 21.1D2 + 39.05D3 + 41.38D4 + 21.18D5 + 39.16D6 + 31.11D7 + 5.71D8
(6.17) (1.2) (2.23) (2.36) (1.21) (2.24) (1.78) (0.89)

+ 18.18D9 + 31.3D10 + 11.32D11 + 54.56D12
(1.04) (1.79) (0.64) (3.12)

These results indicate the mean precipitation in January (the constant) decreases in the 2020 scenario then increases in 2050 and 2080. The constant is significant in all scenarios.

The four regression results are plotted in Figures 5.4.2 to 5.4.5 respectively.

Figure 5.4.2: Results for Montreal (1961-1990)

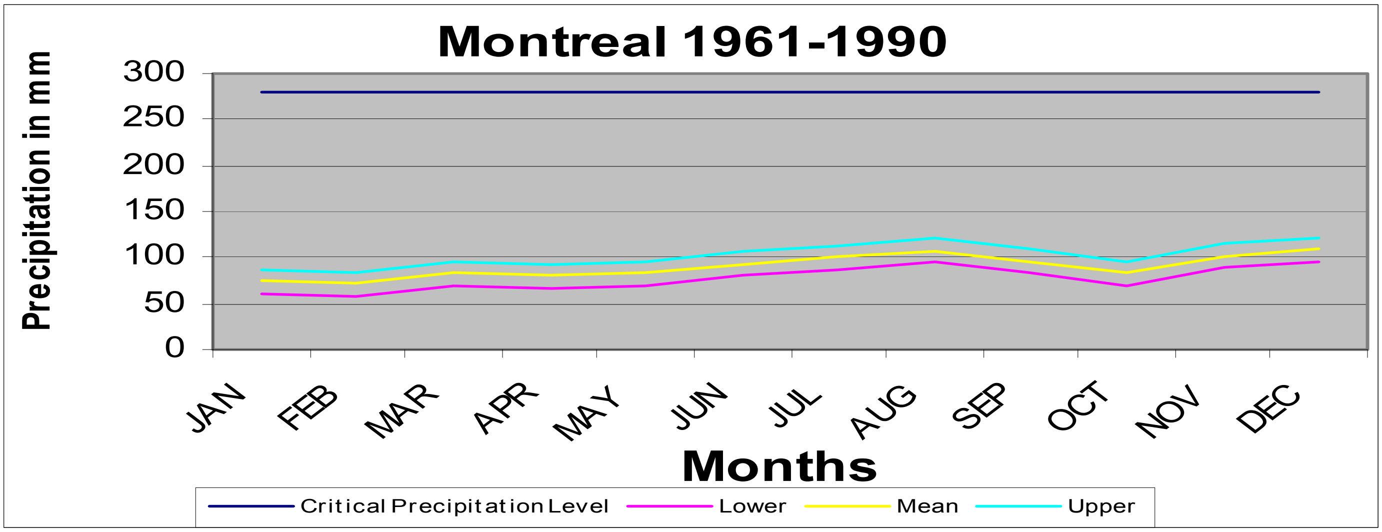


Figure 5.4.3: Results for Montreal (2010-2039)

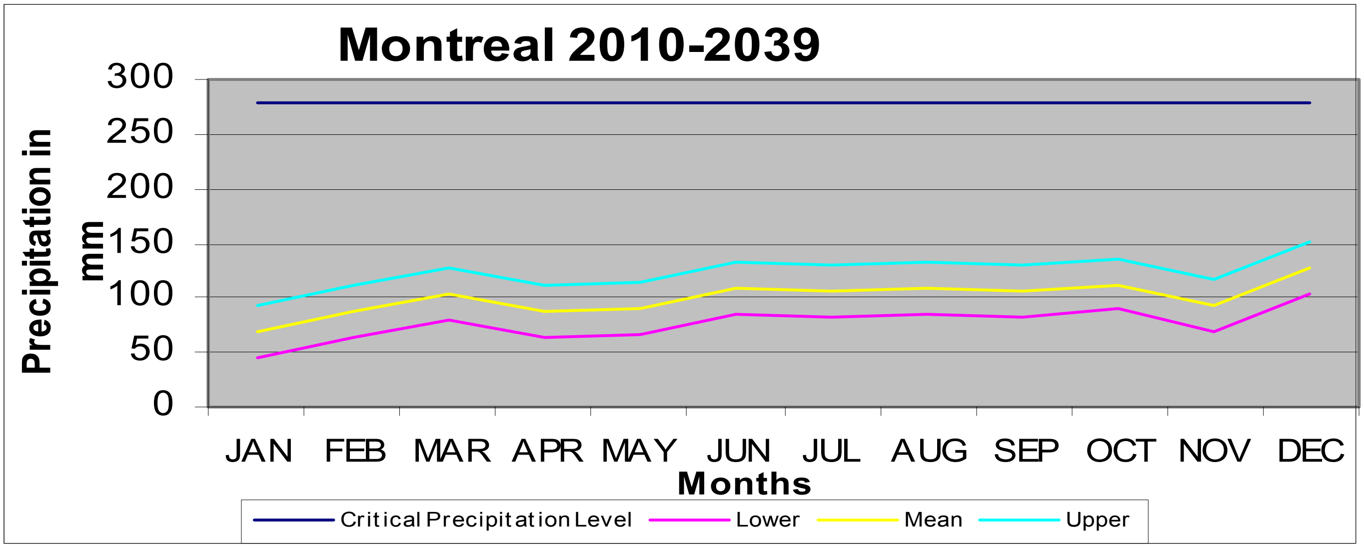


Figure 5.4.4: Results for Montreal (2040-2069)

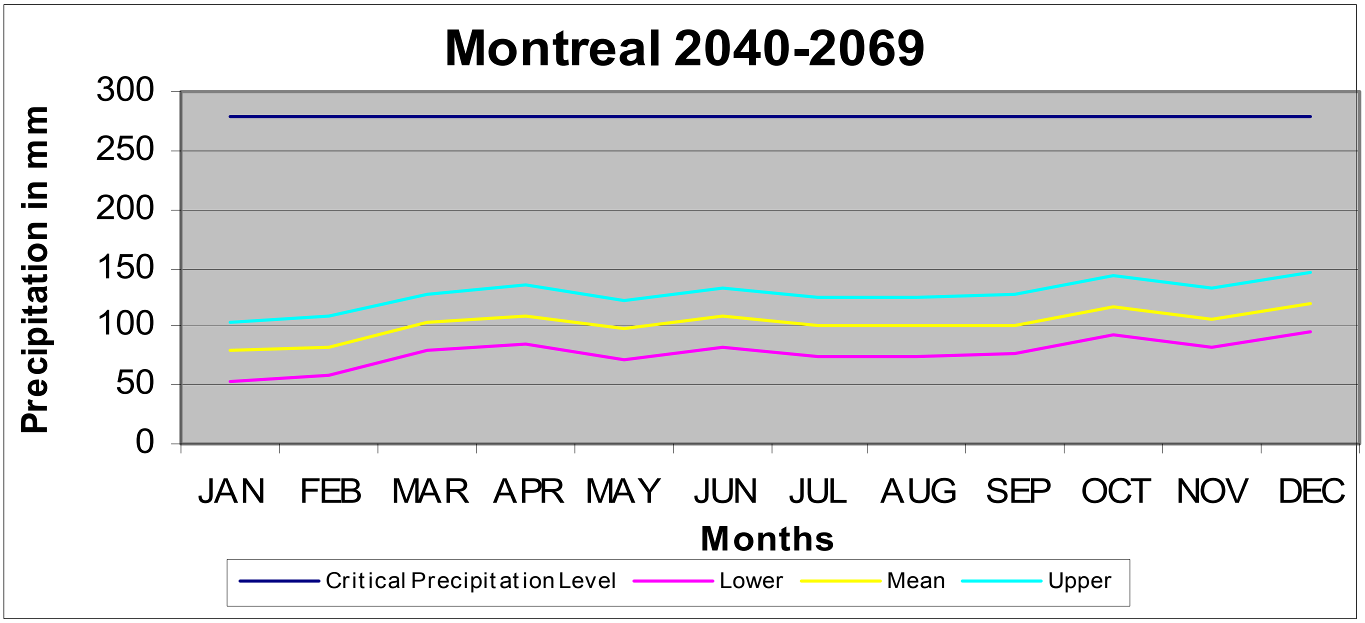
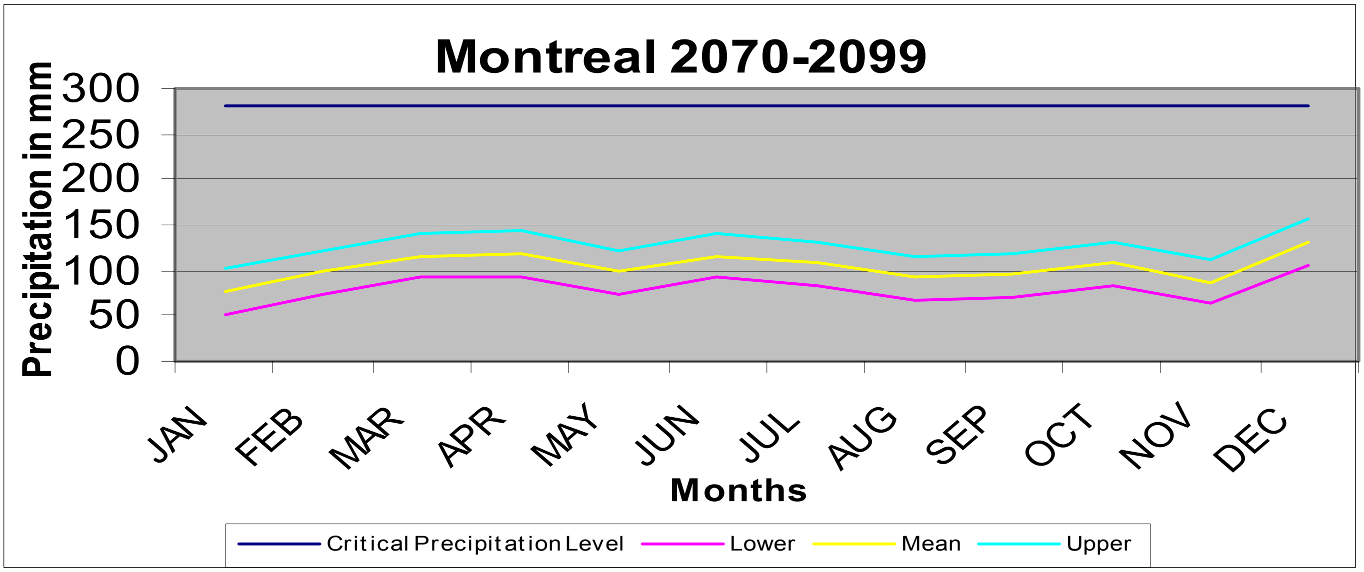


Figure 5.4.5: Results for Montreal (2070-2099)



As can be clearly seen from the above graphs, precipitation does not exceed total capacity in any scenario for any month. It appears that the excess capacity already built into the system will absorb any increases in precipitation. For this reason, we do not foresee any increase in costs associated with increased wastewater treatment due to climate change.

5.4.6: Summary and Conclusion

Based on our analysis, Montréal will not have climate change adaptation costs associated with drinking water supply and wastewater treatment. Because the drinking water source is the St. Lawrence River, Montréal has an abundant water supply.

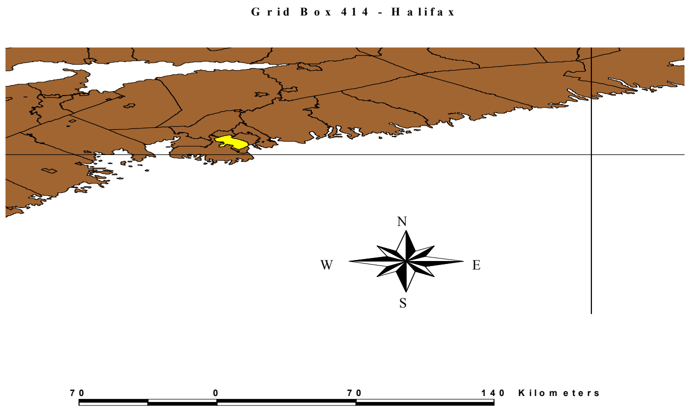
Excess capacity is already built into the wastewater treatment facilities, and our analysis does not indicate any future scenarios when wastewater flows will exceed capacity.

5.5: Halifax, NS

5.5.1: Drinking Water Supply

Atlantic Canada is expected to experience an increase in rainfall in the future scenarios, and as a result, will not be facing droughts or water shortages (see Figure 5.5.1). Any climate change impacts will occur in wastewater treatment.

Figure 5.5.1: Halifax



5.5.2: Wastewater Treatment

Halifax Regional Municipality treats 12 mega gallons/day for all sewage treatment plants and the yearly volume increases over the past four years have averaged 4% a year. The Halifax Harbour Solutions project, which is starting shortly, will construct 2 wastewater treatment plants. The first of these is to be commissioned in 2003. Both plants will have a flow capacity of 25 mega gallons/day. Each year, approximately 16 mega gallons of untreated sewage is discharged directly into Halifax Harbour. Older areas of the City have primarily combined sewers and the newer areas have separate sanitary and storm sewers.

The treatment costs per cubic metre vary with the size and technology of the sewage treatment plant. Operational costs are fairly constant, peaking during winter months due to additional heating and snow removal. At the largest secondary plant treatment costs are $0.85 per cubic metre and at the largest primary plant the costs are $0.06 per cubic metre. Heavy rain periods do impact on treatment plant performance due to hydraulic peaking, but periods of intense rainfall do not impact costs of sewage treatment plants as compared to pump stations.

We now consider the possible impact of changing precipitation patterns expected in the next 100 years based on the CGCM1 model. Table 5.5.1 gives the descriptive statistics of downscaled precipitation for Halifax.

Table 5.5.1 Descriptive Precipitation Statistics for Halifax

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	1543.68	371.7	1543.68	928.49	1234.04
Minimum	2.42	18	6.65	2.42	5.75
Average	149.3	131.88	155.1	153.55	156.69
Stand. Dev.	120.9	60.51	134.02	131.99	138.33

Table 5.5.1 shows that maximum precipitation increases a dramatic 315% from the baseline period to the 2020 period. It remains 149% to 232% higher in the subsequent periods. The standard deviation also increases in the future time periods from the baseline. It shows a 121%, 118% and 128% increase in the respective time periods.

Average daily flow divided by capacity rating is equal to 48%. The mean precipitation for 1961 to 1990 is 131mm. A simple calculation will show the precipitation level in a single month that will force the treatment plants to operate at 100%, which is 273 mm. Therefore, precipitation beyond 273mm a month will cause storm water to overflow into the ecosystem.

5.5.3: Regression Results for Halifax

As with the other case studies, we now report on regressions on precipitation for Halifax.

The estimated regression for 1961 to 1990 is:

$$\begin{array}{lllllllll}
\mathbf{PPT = 166.22} & \mathbf{-31.31D2} & \mathbf{-33.56D3} & \mathbf{-40.28D4} & \mathbf{-49.73D5} & \mathbf{-53.9D6} & \mathbf{-64.48D7} & \mathbf{-54.55D8} \\
(16.19) & (-2.15) & (-2.31) & (-2.77) & (-3.42) & (-3.71) & (-4.44) & (-3.75) \\
\\
\mathbf{-63.71D9} & \mathbf{-29.04D10} & \mathbf{-3.45D11} & \mathbf{+11.99D12} \\
(-4.38) & (-2) & (-0.23) & (0.82)
\end{array}$$

The estimated regression for 2010-2039 is:

$$\begin{array}{lllllllll}
\mathbf{PPT = 202.54} & \mathbf{-62.29D2} & \mathbf{-31.5D3} & \mathbf{-58.62D4} & \mathbf{-67.27D5} & \mathbf{-76.09D6} & \mathbf{-100.34D7} & \mathbf{-94.78D8} \\
(8.68) & (-1.88) & (-0.95) & (-1.77) & (-2.04) & (2.3) & (-3.04) & (-2.87) \\
\\
\mathbf{-100.9D9} & \mathbf{-32.54D10} & \mathbf{+61.79D11} & \mathbf{-6.72D12} \\
(-3.06) & (-0.98) & (1.87) & (-0.2)
\end{array}$$

The estimated regression for 2040-2069 is:

$$\begin{array}{lllllllll}
\mathbf{PPT = 196.58} & \mathbf{-42.27D2} & \mathbf{-39.62D3} & \mathbf{-33.74D4} & \mathbf{-63.88D5} & \mathbf{-71.96D6} & \mathbf{-91.87D7} & \mathbf{-94.62D8} \\
(8.46) & (-1.28) & (-1.2) & (-1.02) & (-1.94) & (-2.19) & (-2.79) & (-2.88) \\
\\
\mathbf{-96.73D9} & \mathbf{-7.05D10} & \mathbf{+44.46D11} & \mathbf{-19D12} \\
(-2.94) & (-0.21) & (1.35) & (-0.57)
\end{array}$$

The estimated regression for 2070 to 2099 is:

$$\begin{array}{lllllllll}
\mathbf{PPT = 187.83} & \mathbf{-9.46D2} & \mathbf{-45.88D3} & \mathbf{-13.52D4} & \mathbf{-58.13D5} & \mathbf{-39.24D6} & \mathbf{-83.33D7} & \mathbf{-101.93D8} \\
(7.75) & (-0.27) & (-1.33) & (-0.39) & (-1.69) & (-1.14) & (-2.43) & (-2.97) \\
\\
\mathbf{-93.77D9} & \mathbf{+21D10} & \mathbf{+49.21D11} & \mathbf{+1.37D12} \\
(-2.73) & (0.61) & (1.43) & (0.04)
\end{array}$$

These regression results, which are graphed in Figures 5.5.2 to 5.5.5, show the relationship between precipitation and the eleven dummy variables. The constant, which is also the mean precipitation for January, is higher in the future scenarios than in the baseline. The constant is significant in each scenario. The regression results and 95% confidence intervals are plotted in Figures 5.5.2 to 5.5.5.

Figure 5.5.2: Results for Halifax (1961-1990)

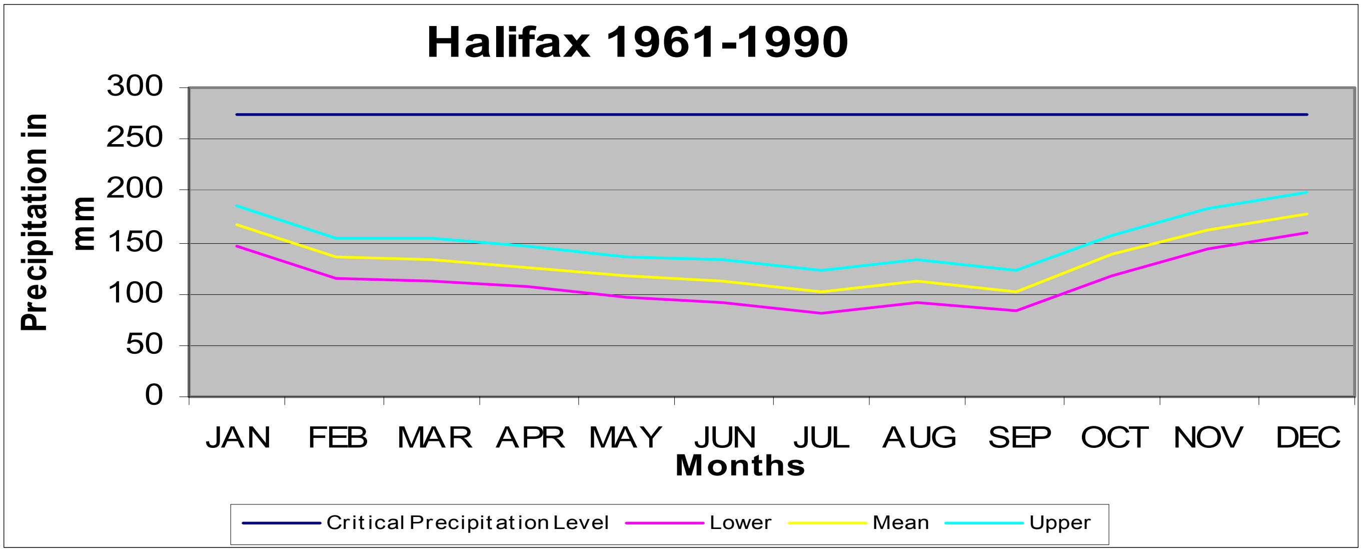


Figure 5.5.3: Results for Halifax (2010-2039)

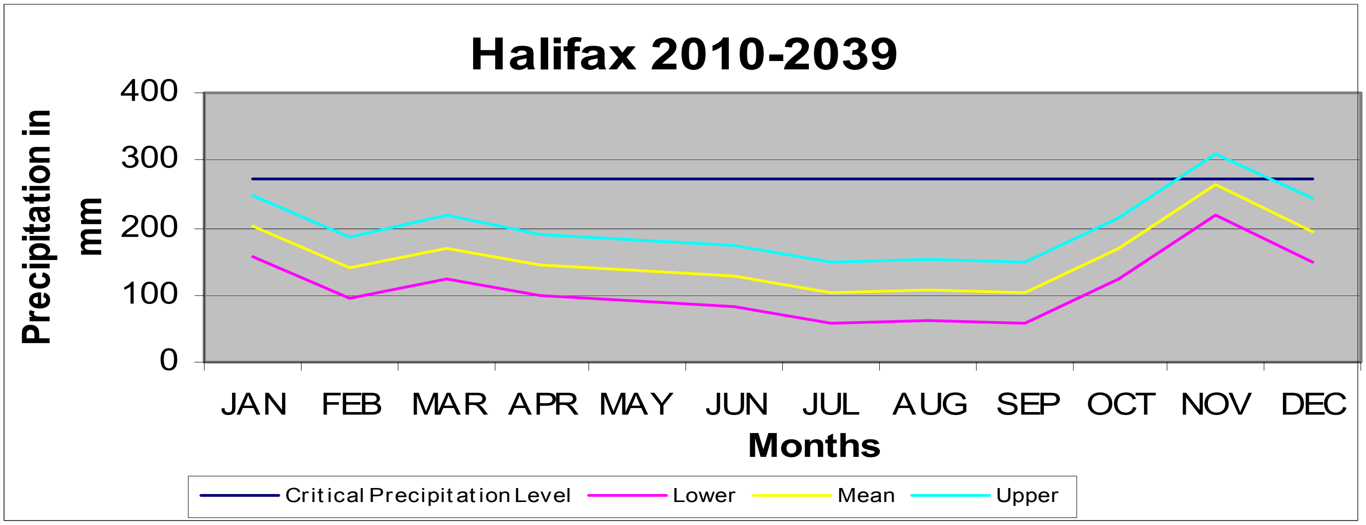


Figure 5.5.4: Results for Halifax (2040-2069)

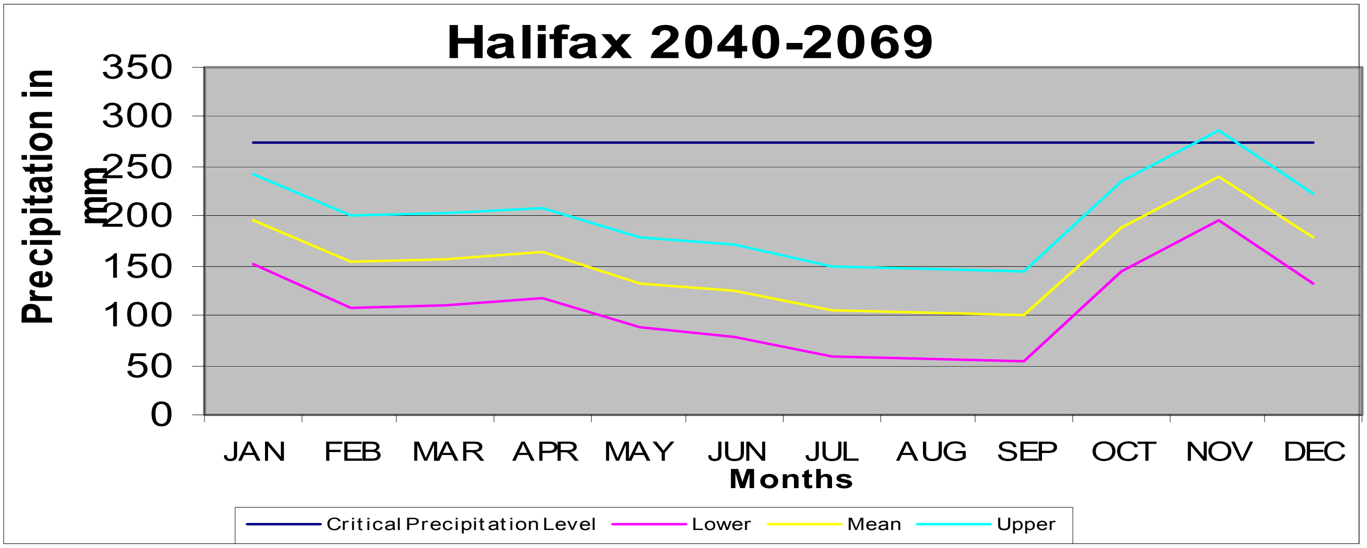
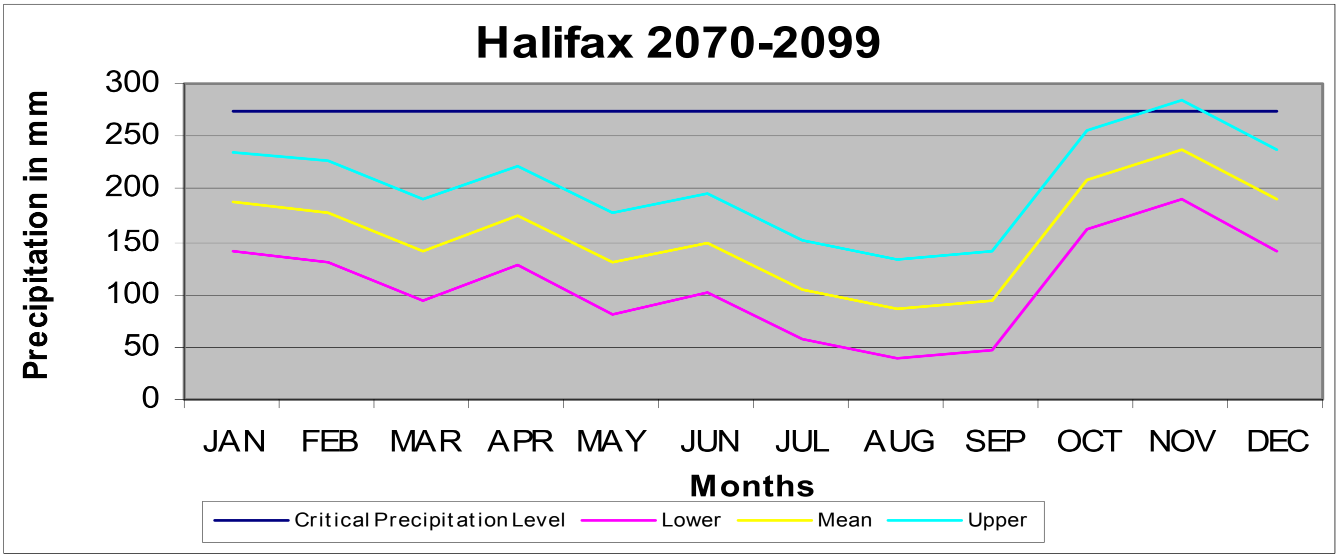


Figure 5.5.5: Results for Halifax (2070-2099)



The graphs indicate that Halifax will be facing a wastewater treatment capacity problem in November of the future scenarios as the upper confidence level exceeds the maximum capacity. Precipitation decreases in the summer months and then increases in October and November in the future scenarios.

Table 5.5.2: Upper Confidence Level to Exceed Halifax's Wastewater Capacity

	Upper Confidence Level Exceeding Halifax's Wastewater Capacity 1961 to 1990	Upper Confidence Level Exceeding Halifax's Wastewater Capacity 2010 to 2039	Upper Confidence Level Exceeding Halifax's Wastewater Capacity 2040 to 2069	Upper Confidence Level Exceeding Halifax's Wastewater Capacity 2070 to 2099
January	0	0	0	0
February	0	0	0	0
March	0	0	0	0
April	0	0	0	0
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	0	0	0	9
November	0	36	12	37
December	0	0	0	0
Totals	**0**	**36**	**12**	**46**

Halifax will be facing a wastewater treatment capacity problem when the upper confidence level exceeds the maximum treatment capacity. This occurs in November of every future scenario and in October of the 2080 scenario (see Table 5.5.2).

5.5.4: Costs of Adaptation

The maximum treatment capacity is 273 mm of precipitation and in the 2020 scenario, this is exceeded by 36 mm in November. This means that the treatment plant would have to expand capacity by 13% to prevent overflows. In order to determine the costs of adaptation, the capital expenditures and investments in the wastewater system are required. This is a subject for further research.

In lieu of specific numbers associated with Halifax, we use the estimate of the costs of new wastewater treatment facilities as described in Section 5.10.2. Assuming expanding capacity costs $50 million, a conservative estimate of adaptation costs is $6.5 million.

5.5.5: Summary and Conclusion

At present, Halifax discharges 16 mega gallons of untreated sewage per day into the Halifax Harbour. However, new planned treatment capacity will come on stream in 2003. Based on this information and the regression analysis, it appears that Halifax will experience a wastewater treatment capacity shortfall in the future scenarios. The costs associated with climate change adaptation will include those that expand treatment capacity, and a rough estimate of this cost is $6.5 million.

5.6: The Prairies

Although the Prairies are a semi-arid to sub-humid area, Saskatchewan has excellent natural sources of water, including surface water systems and large underground aquifers. In the Prairies, most runoff begins as snowmelt each spring. Groundwater supplies are recharged in the spring by replenishing water in the aquifer. Groundwater maintains a water flow during dry periods through its gradual discharge to rivers and streams. From 1998 to 2000, southwest Saskatchewan experienced a below normal spring runoff, resulting in very little or no stored water in many dugouts and reservoirs. Only 40% of the population has access to a truly secure supply of water: those served by the North and South Saskatchewan Rivers and the various dams, canals, pipelines, pump stations and water works associated with these two river systems

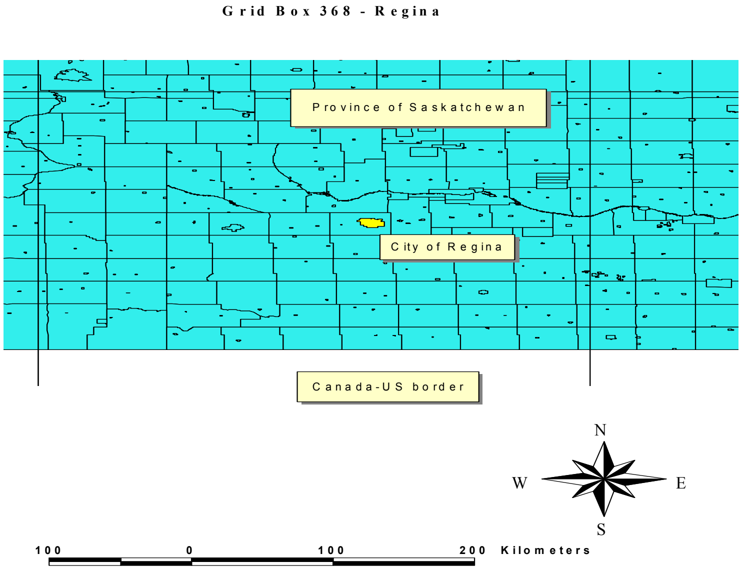
In Saskatchewan, the major withdrawal uses of water are agriculture (75.3%), residential (8.3%), power (1.9%), industrial (0.4%) and mining (14.1%). The average Saskatchewan resident uses about 380 litres of water per day. The average shower uses 135 litres, washing dishes by hand 40 litres, washing dishes by machine 55 litres, washing car 75 litres, daily food and drink 2 litres, flushing the toilet 20 litres and watering the lawn for 30 minutes uses 900 litres *(Sask Water Education Website 2001; www.saskwater.com/htdocs/educatn/waterall.htm).*

Some areas of southwest Saskatchewan, including Assiniboia, Swift Current, Leader and Val Marie, have received only 40 to 70% of normal precipitation from November 1 to January 1, 2000. In these same areas, fall soil moisture levels prior to freeze-up ranged from dry to very dry, and as a result, a significant portion of the snowmelt will be lost to infiltration before contributing to runoff.

5.6.1: Regina, SK

The City of Regina draws water from the South Saskatchewan River (see Figure 5.6.1). Lake Diefenbaker is 150 km from the river, and there is a reservoir 60 km from the river called Buffalo Pound Lake. Because of these sources of water, rainfall is irrelevant for local water supplies. Groundwater provides the strategic water supply, as Regina has access to an aquifer over 10,000 years old, from which 60,000,000 litres of water a day can be pumped indefinitely (Source: personal communication with City of Regina Municipal Engineering Department). The investment in capital assets, which is comprised of the property, plant and equipment for the City of Regina totals $36,837,079.

Figure 5.6.1: Regina



5.6.1.2: Buffalo Pound Lake

Buffalo Pound Lake is a shallow reservoir in the Qu'Appelle Valley that supplies water for Regina and Moose Jaw. The lake is 29 km long, 1 km wide and has an average depth of 3 metres. The surface area is 2900 hectares and it has a capacity of 90 million cubic metres at full supply level. The water levels in the lake are maintained by the release of water from the Qu'Appelle Dam on Lake Diefenbaker. Typically, there is a mean annual water release of 1 to 5 cubic metres, resulting in an average residence time of water in the lake from six to thirty months. Very little water enters Buffalo Pound Lake from rain or spring run-off except in abnormally wet years. The main source of water for the lake is rain and snowmelt in the mountains of Alberta, collected by various tributaries draining into the South Saskatchewan River and stored in Lake Diefenbaker.

Raw water from Buffalo Pound Lake passes through a series of treatment stages designed to remove impurities such as clay particles, bacteria, algae and dissolved organic materials. The treatment process consists of six stages: chlorination, cascade degasification, coagulation and flocculation, clarification, filtration and carbon adsorption. Pre-chlorinated raw water is pumped to the treatment plant from a pumping station located on the shore of the lake. The pipeline connecting the pumping station to the plant is 1.05 metres in diameter, extends a distance of 3000 metres and rises 82 metres. When the water reaches the plant, it goes through the six stages of treatment.

Water production and sales in mega litres in 1999 are given in Table 5.6.1.

Table 5.6.1: 1999 Water Sales (mega litres)

Month	Regina	Moose Jaw	SaskWater
Jan	2104.89	434.76	12.72
Feb	1908.17	402.01	11.43
Mar	2116.00	462.72	13.72
Apr	2032.30	475.78	12.63
May	2410.00	502.75	14.99
Jun	2322.44	554.70	17.42
Jul	2577.75	589.70	18.43
Aug	2833.28	638.00	21.68
Sept	2289.20	525.60	18.12
Oct	2140.57	472.83	12.78
Nov	2038.40	405.57	12.10
Dec	2057.35	428.80	14.17
Totals	26830.05	5893.13	180.18

Source: Buffalo Pound Water Administration Board Annual Report 1999

The Buffalo Pound Water Treatment Plant annual raw water production from 1955 to 1999 is shown in Table 5.6.2.

Table 5.6.2: Annual Raw Water Production

Year	Raw Water Produced in Megalitres
1955	3500
1960	11500
1965	11500
1970	20000
1975	24000
1980	26000
1985	32500
1990	37000
1999	34000

Source: Buffalo Pound Water Administration Board Annual Report 1999

Annual costs of treatment for the Buffalo Pound Water Treatment Plant for 1999 were $118.15/ML based on a production of 32,903.4ML. The cost of treatment varies primarily with volume of water produced, though summer treatment also includes filtering through granular activated carbon to improve taste and odour. Storm events do have an impact on treatment. As stated before, Buffalo Pound is a shallow lake (6 m typical depth), which is easily and thoroughly disturbed by storms, which leads to increased flocculation costs.

5.6.1.3: Operations and Capital Projects

All critical plant equipment at the Buffalo Pound Treatment Plant is inspected, tested and maintained at least annually to help ensure satisfactory operation during peak flow demands. Several projects were completed with funds from the Capital Replacement Reserve for a total cost of $366,535. The control systems and boiler were replaced in the carbon regeneration plant, and an all-terrain forklift was replaced with a new four-wheel drive unit. There were also several maintenance projects including: the installation of new chlorine residual analysers, new chlorine weigh scales at the lake pumping station, new gas projection heaters were installed in the granular activated carbon contactor area, new steam projection heaters were installed in the clarifier area, the effluent valves on several carbon contactors were overhauled, and a 1750 HP motor from the lake pumping station was serviced. The cost of the capital asset additions from 1998 and 1999 are:

LPS Ventilation Intake Filter	$3,677
Particle Counters	60,847
Ion Chromatograph	28,829
Regeneration Plant Boiler	41,275
Clarifier Effluent Turbidimeter	14,869
Spectrophotometer	18,709

Source: Buffalo Pound Water Administration Board Annual Board 1999

The combined property, plant and equipment and work in progress capital expenditures from the Capital Replacement Reserve fund in 1999 totalled $366,535. In 1998, the figure was $228,814.

The total operations and maintenance expenditures equal $5,028,462. The proportion of the operations and maintenance budget that is spent on equipment maintenance is 11.35%. Some of these items are:

Pumping Station Equipment Maintenance	$48,310
Raw Water Pipe Maintenance	26,168
Building Maintenance	52,217
Electrical Maintenance	19,194
Plant Equipment Maintenance	282,233

Source: Buffalo Pound Water Administration Board Annual Report 1999

5.6.2: Drinking Water Supply

Regina's primary source of water supply is Buffalo Pound Lake, which has a production capacity of 150 ML/day. The water is treated and delivered to Regina from the Buffalo Pound Water Treatment Plant, a facility that is jointly owned by the Cities of Regina and Moose Jaw. It has a peak capacity of 205 ML/day. The secondary source comes from the many large wells that are located around the city with a production capacity of 62 ML/day. The water from these wells is used mainly in the summer months when there is high water demand. During these periods, the water from both sources is mixed together in large reservoirs, to ensure consistent water quality. Water delivered from the Buffalo Pound Water Treatment Plant passes through a 57 km long, 900mm (36 inch) diameter steel pipeline. There is a second larger pipeline being constructed, scheduled for completion in 2003. The purpose of this pipeline is to ensure supply security in the event of problems in the original pipeline, to increase the maximum amount of water the plant can deliver to the City, and to eliminate the need to supplement Buffalo Pound water supply with well water. The lake intake and the raw water pipeline from the lake pumping station is to be twinned, along with the replacement of the fish screen. In October 2000, the Buffalo Pound Lake control structure and dam enhancement project was officially opened. The project was initiated in order to sustain the long-term viability of the water supply. The 1,100 cubic metres of concrete, 85,000 kilograms of steel, 50,000 cubic metres of excavation and 20,000 cubic metres of new embankment cost $3 million to complete.

The City differentiates between two types of pipeline: supply and distribution. There are 155.2km of supply pipeline and 792.3km of distribution pipeline. Supply pipeline connects sources of supply with reservoirs and pumping stations and distribution piping accounts for all pipes between the pumping station and the customer. The pipes range in size from 100mm (4 inch) to 1050mm (42 inch). There are three water-pumping stations located within the City limits. There are five treated water storage reservoirs situated around the city that hold 160 million litres of water. These reservoirs are used to maintain water supply during times of high demand, to provide water supply during a power failure or other emergencies, and to provide additional water for fire fighting. There are three pumping stations to pressurize and deliver water through the water mains and they can deliver water continuously, even during power failures.

The peak demand per day is 150,000,000 litres. Water is priced on a full cost recovery basis, at a rate of $0.75 per cubic metre. All water is used for domestic consumption and light industry; none is used for irrigation. The monthly drinking water production for the year 2000 is shown in Table 5.6.3.

Table 5.6.3: Monthly Drinking Water Production, 2000

Month	Potable Water Production (ML)
Jan	2,050
Feb	1,924
Mar	2,056
Apr	2,028
May	2,411
Jun	2,285
Jul	2,595
Aug	2,721
Sep	2,266
Oct	2,259
Nov	2,082
Dec	2,049
Total	26,726

Source: City of Regina Municipal Engineering Department

Regina's annual water losses are 8% of the total volume of water produced. Water conservation initiatives over the past decade have resulted in large decreases in water consumption. Per capita water use has since levelled off and water demand is currently constant, if not slightly decreasing. The population of the City is currently 189,400 people and is growing in the range of 1.5% to 2% per annum. The per capita consumption of water is 386.6 litres/day/capita. This figure includes all uses of water, residential, commercial, recreational and losses.

5.6.3: Wastewater Treatment

The annual costs for treatment for the City of Regina Wastewater Treatment Plant are:

Treatment cost/volume treated	$147.21/ML
Treatment cost/tonnes of contaminants removed	$250.32/tonne
Treatment cost/capita	$20.08/person

Source: City of Regina Municipal Engineering Department

The City of Regina has 725 km of sewers and 15 lift stations that collect domestic sewage across the City. The wastewater is treated at the sewage treatment facilities using a UV radiation treatment rendering it a better quality than the water in Buffalo Pound Lake. There are about 80 million litres of sewage moving through the system each day. The treated water is then discharged into the Qu'Appelle system. Storm runoff is collected by approximately 850km of underground storm sewers that drain into the north and south channels and Wascana Creek.

Table 5.6.4 show the descriptive statistics for precipitation for the four time periods.

Table 5.6.4: Precipitation Descriptive Statistics for Regina

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	895.85	211.5	770.44	895.85	842.8
Minimum	0.69	0.9	0.69	0.78	1.11
Average	48.31	38.09	49.66	52.14	53.35
Stand. Dev.	64.87	29.75	69.34	70.68	77.67

A comparison of the mean values for the baseline and four scenarios, 2020, 2050 and 2080 show that the average precipitation will increase over this time period by 40% by the 2080 scenario from the baseline. The standard deviation increases by 133% from the baseline period to the 2020 scenario. The standard deviation continues to increase over the next two periods.

5.6.4: Regression Results

In order to consider changes in the pattern of precipitation due to climate change, we carried out some regressions, just as we did with the other case studies.

The estimated regression for 1961 to 1990 is as follows:

$$\mathbf{PPT = 27.4 - 3.8D2 - 0.12D3 - 0.07D4 + 29.14D5 + 44.55D6 + 36.39D7 + 16.86D8 +}$$

(5.97) (-0.58) (-0.01) (-0.01) (4.49) (6.87) (5.61) (2.6)

$$\mathbf{11.47D9 - 1.38D10 - 7.16D11 + 2.39D12}$$

(1.76) (-0.21) (-1.1) (0.369)

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT = 30.77 + 0.96D2 + 1.7D3 + 4.9D4 + 40.74D5 + 72.55D6 + 63.21D7 + 22.51D8 +}$$

(2.57) (.057) (.101) (0.29) (2.41) (4.29) (3.74) (1.33)

$$\mathbf{26.36D9 - 0.21D10 - 2.75D11 - 3.24D12}$$

(1.56) (-0.01) (-0.16) (-0.19)

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT = 27.89 + 4.04D2 + 9.87D3 + 24.32D4 + 50.58D5 + 57.11D6 + 37.86D7 + 60.6D8}$$

(2.24) (0.23) (0.56) (1.38) (2.88) (3.25) (2.15) (3.45)

$$\mathbf{+ 38.08D9 + 9.06D10 - 3.2D11 + 2.6D12}$$

(2.16) (0.51) (-0.18) (0.14)

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT = 28.26 + 7.99D2 + 17.21D3 + 19.21D4 + 53.06D5 + 47.91D6 + 65.08D7 +}$$

(2.05) (0.41) (0.88) (0.98) (2.72) (2.45) (3.33)

$$\mathbf{54.49D8 + 19.64D9 + 10.24D10 - 1.82D11 + 7.99D12}$$

(2.79) (1) (0.52) (-0.09) (0.41)

The results of the above regressions are plotted in Figures 5.6.2 to 5.6.5. The regressions give the mean precipitation and 95% confidence interval.

Figure 5.6.2: Results for Regina (1961—1990)

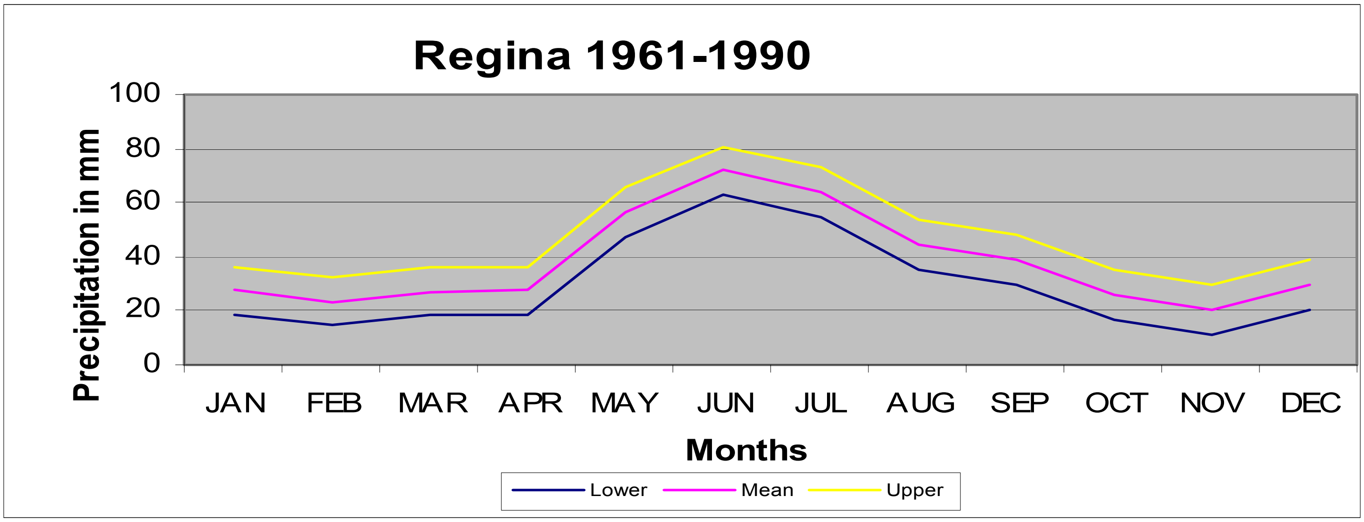


Figure 5.6.3: Results for Regina (2010-2039)

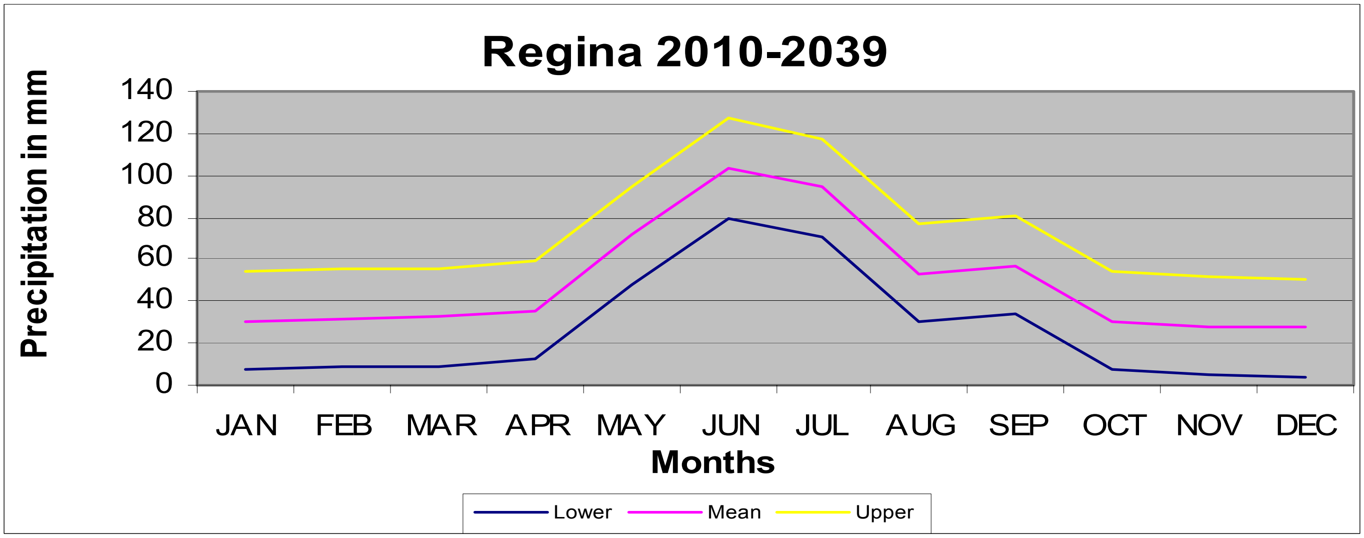


Figure 5.6.4: Results for Regina (2040-2069)

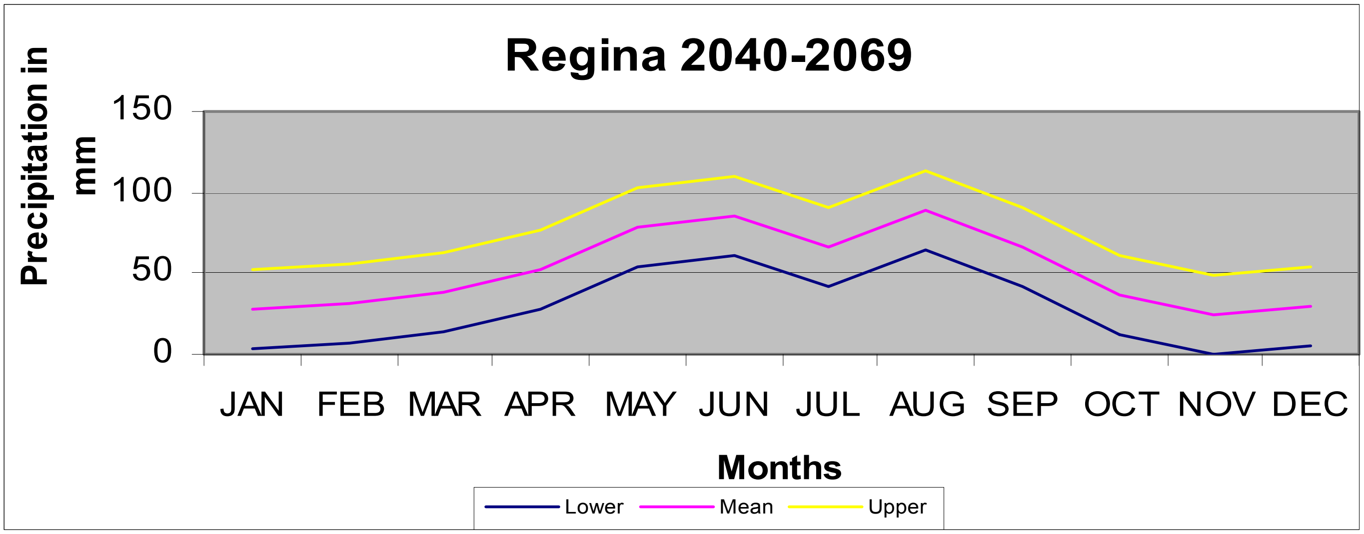
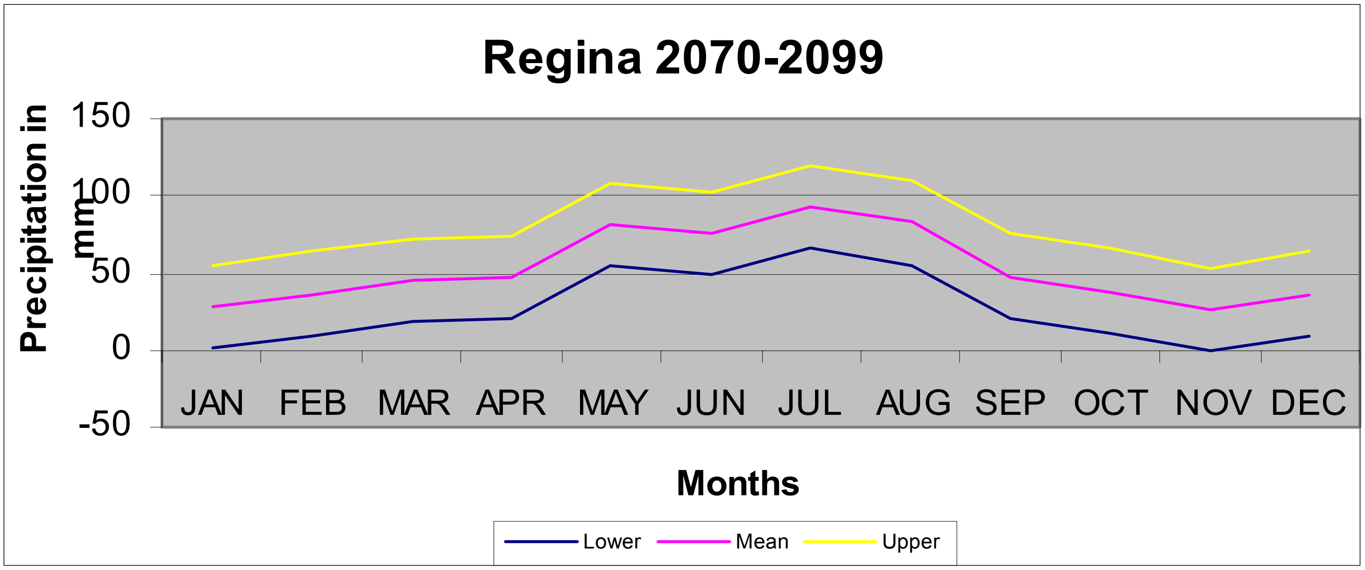


Figure 5.6.5: Results for Regina (2070-2099)



The graphs indicate that precipitation will increase in the future scenarios in the summer months and that water supply will not be severely depleted. In the 2050 scenario, precipitation decreases dramatically in July.

5.6.5: Summary and Conclusion

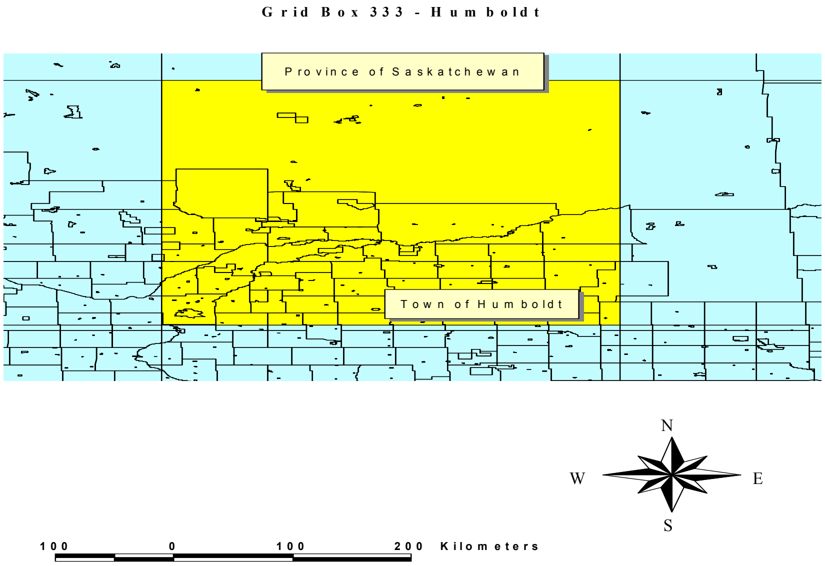
The City of Regina would incur adaptation costs if the South Saskatchewan River were seriously depleted or the aquifer were to dry up. On the basis of local expert opinion, there does not appear to be either a water supply or wastewater treatment problem. However, a further study must be done on a watershed basis to determine if climate change will adversely affect water flows in the South Saskatchewan River (see Section 5.14).

5.7: Humboldt, SK

The Wakaw-Humboldt area has long suffered from serious water shortages, as groundwater supplies can be shallow even in times of normal runoff (see Figure 5.7.1). Local surface supplies are difficult to treat because of high organic content, and the deep groundwater sources are highly mineralized and expensive to treat. Well maintenance is also expensive. Because of these issues, Sask Water built a regional water supply system. The area now uses water from the South Saskatchewan River, and the system distributes water to 10 000 people in nine communities and eight rural municipalities. These communities are Hoey, St. Isidore-de-Bellevue, Domremy, Wakaw, Bruno, Humboldt, Muenster, Annaheim and Lake Lenore. These rural municipalities get their water from the North Central Rural Pipeline Association, and the SHL Rural Pipeline Association. The system consists of a pump station on the South Saskatchewan River, two booster pump stations, a water treatment plant at Wakaw and 190 kms of pipeline. The total cost of the system was $32.3 million, of which $2.8 million was contributed by the Canada-Saskatchewan Infrastructure Works Program; $3.8 million by the federal-provincial Partnership Agreement on Water-Based Economic Development (PAWBED).

The remaining $25.7 million is being financed by Sask Water and will be recovered over a 30 year period through charges to water users.

Figure 5.7.1: Humboldt



5.7.1: Drinking Water Supply and Sask Water

Sask Water is Saskatchewan’s water manager and is mandated to provide quality water to rural Saskatchewan residents including those living in Humboldt and Melfort.

The utility operations of Sask Water include 135 km of canal, 5 reservoirs, 32 pumping facilities and 4 water treatment plants. There are 725 km of pipeline ranging in diameter from 76mm to 750mm. The utility supplies both treated and raw water to industrial, municipal and domestic customers. The rural municipal population served by Sask Water is approximately 38,000 customers. In 2000, the total consumption of raw water was 168,716,436 gallons, and for treated water, this figure was 730,957,427 gallons.

Lake Diefenbaker is the largest body of water in southern Saskatchewan, and two dams, the Qu'Appelle River Dam and Gardiner Dam, formed it. The Qu'Appelle Dam controls flows in the Qu'Appelle River, and the Gardiner Dam controls flows in the South Saskatchewan River. The dams were officially opened in 1967.

The South Saskatchewan River Project consists of the Gardiner Dam, the Qu'Appelle Dam and Lake Diefenbaker. Sask Water owns and operates the Project and is responsible for its operation and maintenance.

The Qu'Appelle Dam has a length of 3,100 metres, a height of 27 metres and has a volume of 10,400,000 cubic metres. The Gardiner Dam is 5,000 metres long, 64 metres high and has a volume of 65,000,000 cubic metres. Lake Diefenbaker has a design full supply level of 556.87 metres and a drainage area of 126,000 square km. It is 225 km long and has a maximum depth of 58 metres at the full supply level. At the full supply level the area is 43,000 hectares and the storage is 9,400,000,000 cubic metres.

Table 5.7.1 gives the descriptive statistics of precipitation for Humboldt.

Table 5.7.1: Humboldt Precipitation Descriptive Statistics

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	678.35	182.6	441.33	454.66	678.35
Minimum	0.21	0.3	0.21	0.42	0.23
Average	46.61	38.39	47.64	47.64	52.77
Stand. Dev.	55.38	30.42	56.28	53.46	72.37

From the above statistics, we can see that the maximum precipitation increases by 141% from the baseline to the 2020 scenario. It continues to increase in the subsequent scenarios by 148% and 271%. The mean increases 24% and 37% from the baseline and the standard deviation also shows an increase from the baseline scenario.

5.7.2: Regression Results

As with the other case studies, we did the regressions.

The estimated regression for 1961 to 1990 is as follows:

$$\mathbf{PPT} = \underset{(5.13)}{\mathbf{23.95}} - \underset{(-0.72)}{\mathbf{4.77D2}} + \underset{(0.26)}{\mathbf{1.76D3}} + \underset{(0.11)}{\mathbf{0.78D4}} + \underset{(3.15)}{\mathbf{20.79D5}} + \underset{(6.36)}{\mathbf{41.95D6}} + \underset{(7.13)}{\mathbf{47D7}} + \underset{(4.96)}{\mathbf{32.72D8}} +$$

$$\underset{(3.19)}{\mathbf{21.03D9}} + \underset{(0.97)}{\mathbf{6.44D10}} - \underset{(-0.1)}{\mathbf{0.71D11}} + \underset{(0.95)}{\mathbf{6.31D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT} = \underset{(3.25)}{\mathbf{31.31}} - \underset{(-0.46)}{\mathbf{6.26D2}} - \underset{(-0.23)}{\mathbf{3.14D3}} - \underset{(-0.04)}{\mathbf{0.56D4}} + \underset{(1.94)}{\mathbf{26.43D5}} + \underset{(2.59)}{\mathbf{35.28D6}} + \underset{(3.42)}{\mathbf{46.56D7}} + \underset{(4.53)}{\mathbf{61.66D8}} +$$

$$\underset{(2.23)}{\mathbf{30.39D9}} + \underset{(0.37)}{\mathbf{5.12D10}} - \underset{(-0.24)}{\mathbf{3.29D11}} + \underset{(0.27)}{\mathbf{3.71D12}}$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT} = \underset{(3.71)}{\mathbf{34.14}} - \underset{(-0.85)}{\mathbf{11.12D2}} - \underset{(-0.16)}{\mathbf{2.17D3}} + \underset{(0.32)}{\mathbf{4.24D4}} + \underset{(1.78)}{\mathbf{23.21D5}} + \underset{(2.69)}{\mathbf{35.05D6}} + \underset{(3.93)}{\mathbf{51.13D7}} + \underset{(3.4)}{\mathbf{44.32D8}}$$

$$+ \underset{(1.66)}{\mathbf{21.64D9}} + \underset{(0.04)}{\mathbf{0.6D10}} - \underset{(-0.37)}{\mathbf{4.88D11}} + \underset{(0.006)}{\mathbf{0.08D12}}$$

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT} = \underset{(2.42)}{\mathbf{30.68}} - \underset{(-0.47)}{\mathbf{8.56D2}} + \underset{(0.36)}{\mathbf{6.6D3}} + \underset{(0.68)}{\mathbf{12.15D4}} + \underset{(1.85)}{\mathbf{33.21D5}} + \underset{(1.81)}{\mathbf{32.4D6}} + \underset{(3.73)}{\mathbf{66.74D7}} + \underset{(3.93)}{\mathbf{70.28D8}} +$$

$$\underset{(1.7)}{\mathbf{30.55D9}} + \underset{(0.38)}{\mathbf{6.84D10}} + \underset{(0.09)}{\mathbf{1.66D11}} + \underset{(0.73)}{\mathbf{13.15D12}}$$

In these regressions the constant is significant and increases slightly from the baseline to the 2020 scenario. The regression results are graphed in Figures 5.7.2 to 5.7.5 and show the 95% confidence interval and the mean. These regression results show the likely change in the pattern of precipitation.

Figure 5.7.2: Results for Humboldt (1961-1990)

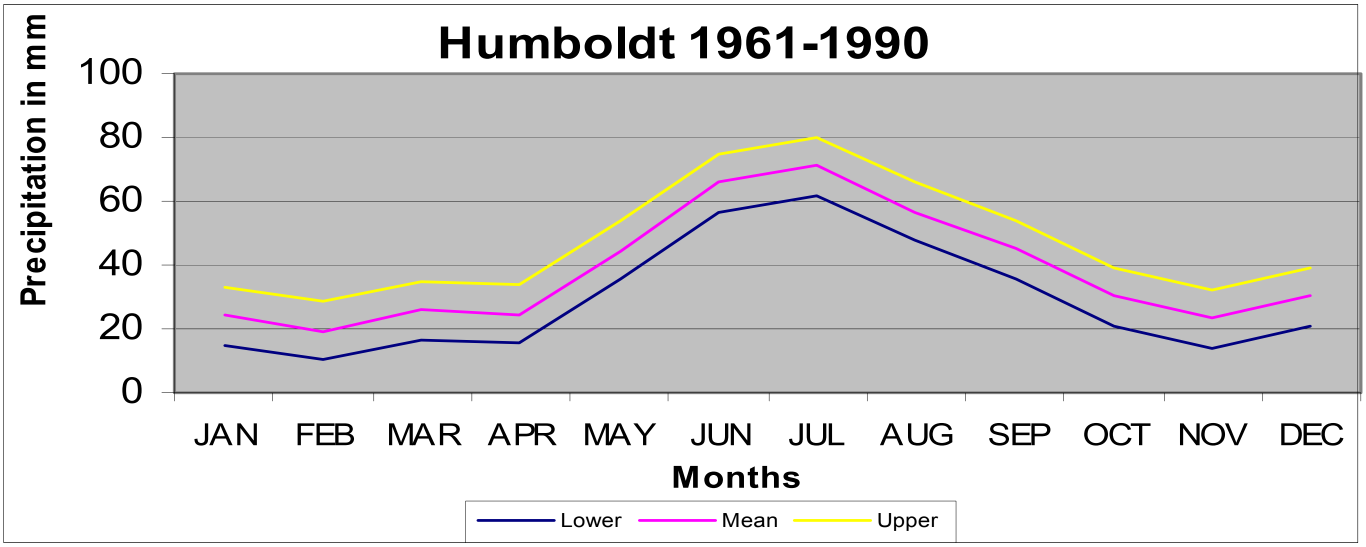


Figure 5.7.3: Results for Humboldt (2010-2039)

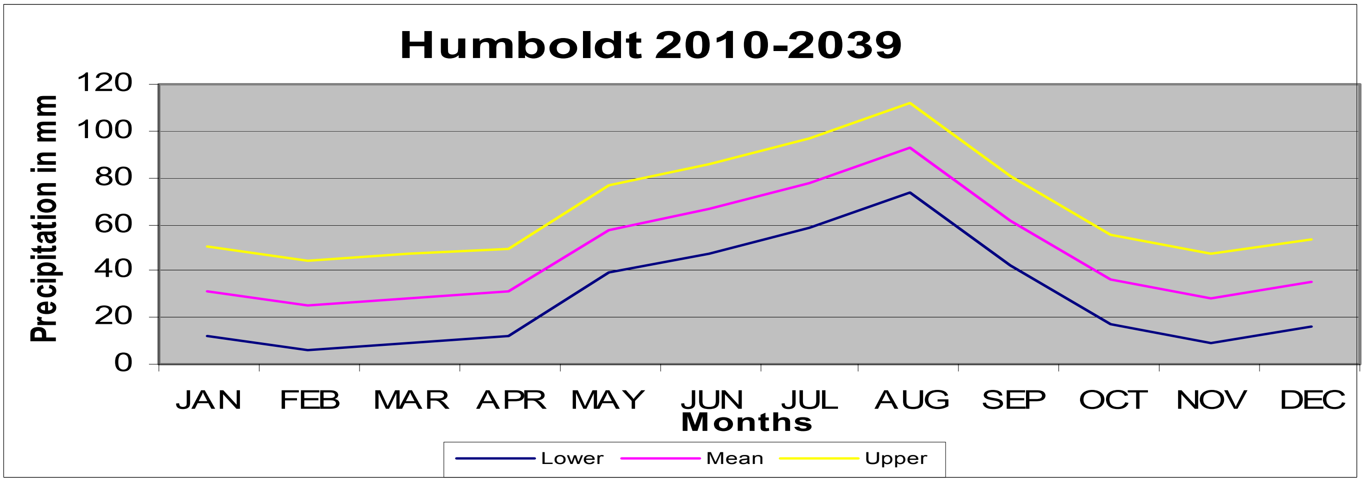


Figure 5.7.4: Results for Humboldt (2040-2069)

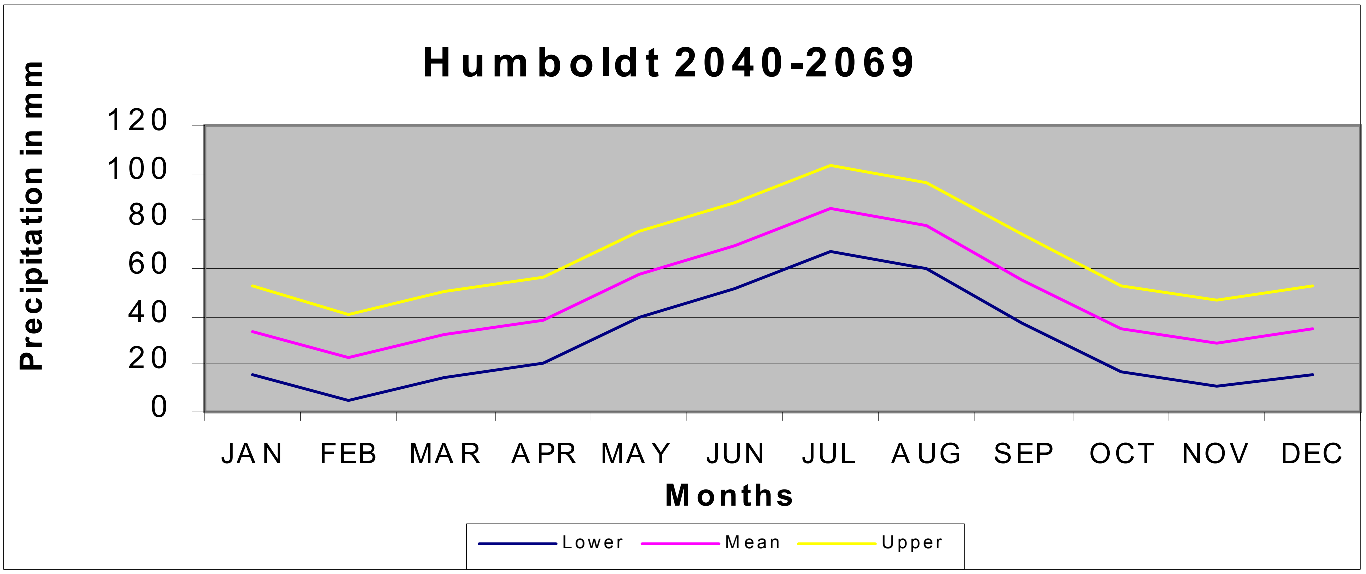
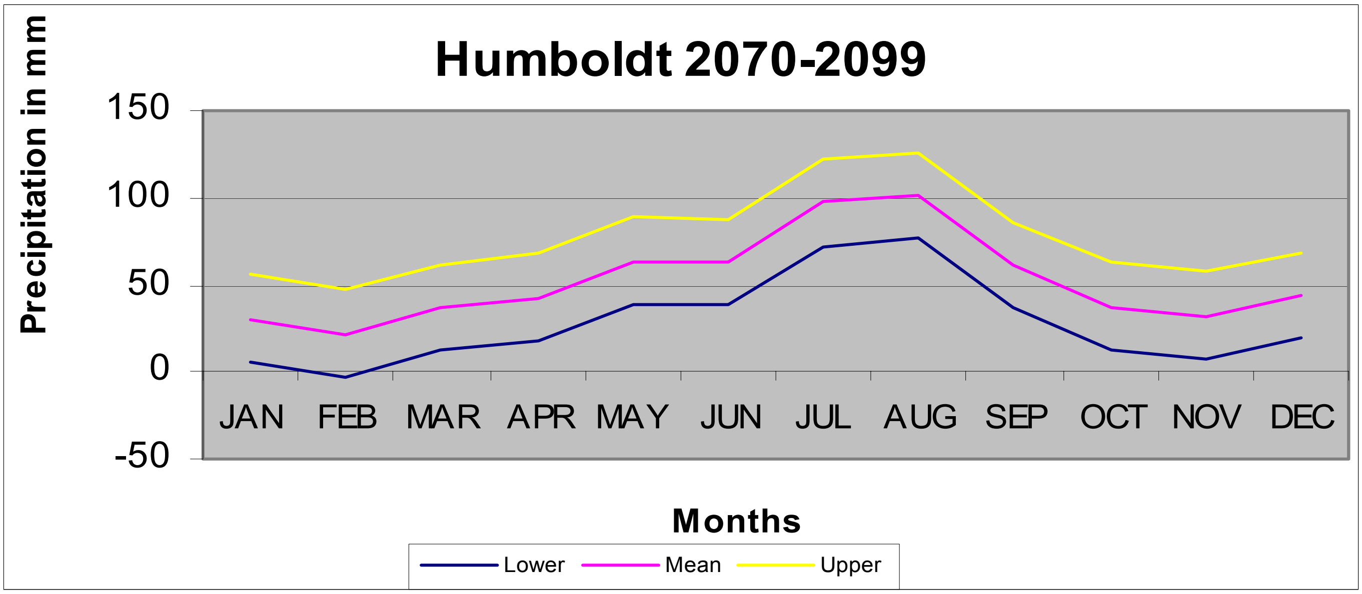


Figure 5.7.5: Results for Humboldt (2070-2099)



The graphs indicate that the upper confidence interval is increasing over the four scenarios as well as the mean. We can see that precipitation peaks in July and August and is at its lowest in February and November.

5.7.3: Summary and Conclusions

The graphical representation of the downscaled future scenarios shows that precipitation will increase in the summer months indicating that Humboldt is unlikely to be affected by drought. As in the case of Regina, there is also a need to study the effects of a change in rain to snow ratio (see Section 5.14).

5.8: Swift Current, SK

5.8.1: Drinking Water Supply

Swift Current draws its water from Swift Current Creek that is replenished from the water shed in the Cypress Hills (see Figure 5.8.1). In the winter, water consumption is 1.4 million gallons per day and in the summer it is 2.8 million gallons per day. Swift Current has not experienced water supply problems in recent years, even during years of drought, due to the availability of water in the Cypress Hills water shed. If in the future, the Swift Current Creek could not meet the demand for water, water could be piped from the Saskatchewan River 30 miles away.

Figure 5.8.1: Swift Current

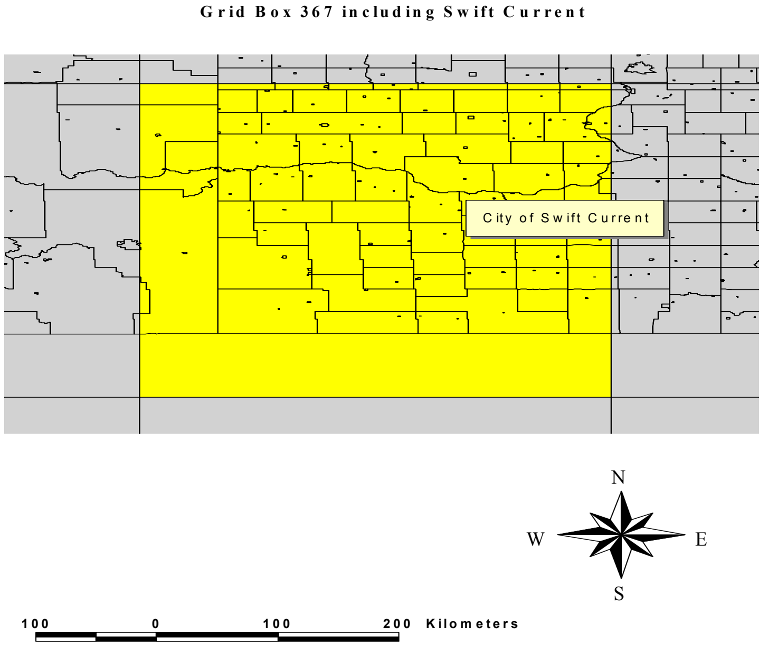


Table 5.8.1 gives the precipitation descriptive statistics for the four time periods.

Table 5.8.1: Precipitation Descriptive Statistics for Swift Current

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	685.49	227.9	685.49	598.77	483.7
Minimum	0.78	2.6	1.15	1.01	0.78
Average	44.18	36.16	45.66	45.84	49.06
Stand. Dev.	52.51	29.09	59.79	53.07	61.01

Mean precipitation increases in the future scenarios from the baseline by as much as 35%, and maximum precipitation also increases dramatically. The standard deviation increases by as much as 109% by the 2080 scenario.

5.8.2: Regression Results

The following regressions consider the likely change in the pattern of precipitation for Swift Current.

The estimated regression for 1961 to 1990 is as follows:

$$\mathbf{PPT} = \underset{(5.99)}{\mathbf{27.6}} - \underset{(-0.82)}{\mathbf{5.38D2}} - \underset{(-0.05)}{\mathbf{0.33D3}} + \underset{(0.4)}{\mathbf{2.61D4}} + \underset{(3.6)}{\mathbf{23.48D5}} + \underset{(6.83)}{\mathbf{44.53D6}} + \underset{(3.9)}{\mathbf{25.43D7}} + \underset{(2.11)}{\mathbf{13.8D8}} +$$

$$\underset{(1.63)}{\mathbf{10.62D9}} - \underset{(-0.95)}{\mathbf{6.23D10}} - \underset{(-1.17)}{\mathbf{7.65D11}} + \underset{(0.27)}{\mathbf{1.78D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT} = \underset{(3.07)}{\mathbf{31.64}} - \underset{(-0.38)}{\mathbf{5.56D2}} + \underset{(0.25)}{\mathbf{3.68D3}} + \underset{(0.24)}{\mathbf{3.59D4}} + \underset{(1.87)}{\mathbf{27.22D5}} + \underset{(4.83)}{\mathbf{70.33D6}} + \underset{(2.77)}{\mathbf{40.37D7}} + \underset{(0.52)}{\mathbf{7.58D8}} +$$

$$\underset{(2.09)}{\mathbf{30.42D9}} - \underset{(-0.14)}{\mathbf{2.1D10}} - \underset{(-0.32)}{\mathbf{4.66D11}} - \underset{(-0.18)}{\mathbf{2.71D12}}$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT} = \underset{(3.28)}{\mathbf{30.36}} - \underset{(-0.44)}{\mathbf{5.82D2}} + \underset{(0.6)}{\mathbf{7.91D3}} + \underset{(1.36)}{\mathbf{17.81D4}} + \underset{(2.84)}{\mathbf{37.2D5}} + \underset{(3.5)}{\mathbf{45.9D6}} + \underset{(2.06)}{\mathbf{27.03D7}} + \underset{(2.52)}{\mathbf{33.03D8}} +$$

$$\underset{(2.42)}{\mathbf{31.79D9}} - \underset{(-0.12)}{\mathbf{1.67D10}} - \underset{(-0.59)}{\mathbf{7.76D11}} + \underset{(0.02)}{\mathbf{0.33D12}}$$

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT} = \underset{(3.14)}{\mathbf{33.61}} - \underset{(-0.36)}{\mathbf{5.45D2}} + \underset{(0.62)}{\mathbf{9.43D3}} + \underset{(1.07)}{\mathbf{16.25D4}} + \underset{(2.2)}{\mathbf{33.38D5}} + \underset{(3.88)}{\mathbf{58.77D6}} + \underset{(2.87)}{\mathbf{43.47D7}} + \underset{(1.01)}{\mathbf{15.35D8}}$$

$$+ \underset{(1.34)}{\mathbf{20.43D9}} - \underset{(-0.1)}{\mathbf{1.58D10}} - \underset{(-0.4)}{\mathbf{6.11D11}} + \underset{(0.09)}{\mathbf{1.51D12}}$$

These regression results show the likely pattern of precipitation in the future scenarios. The constant is significant in each scenario but only increases slightly from the baseline. The 95% confidence intervals are graphed in Figures 5.8.2 to 5.8.5.

Figure 5.8.2: Results for Swift Current (1961-1990)

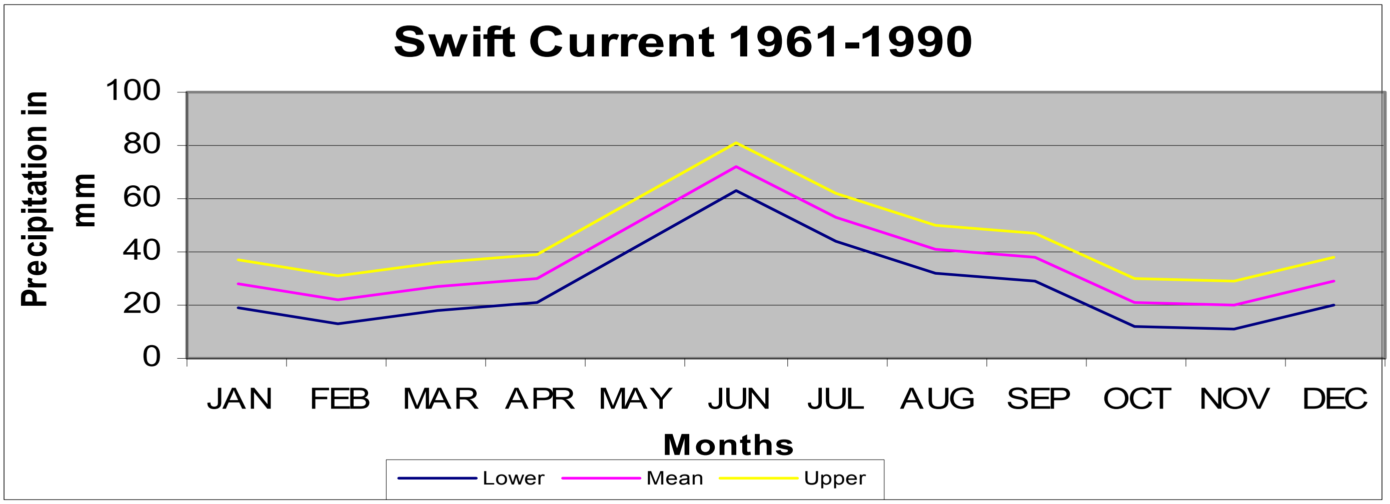


Figure 5.8.3: Results for Swift Current (2010-2039)

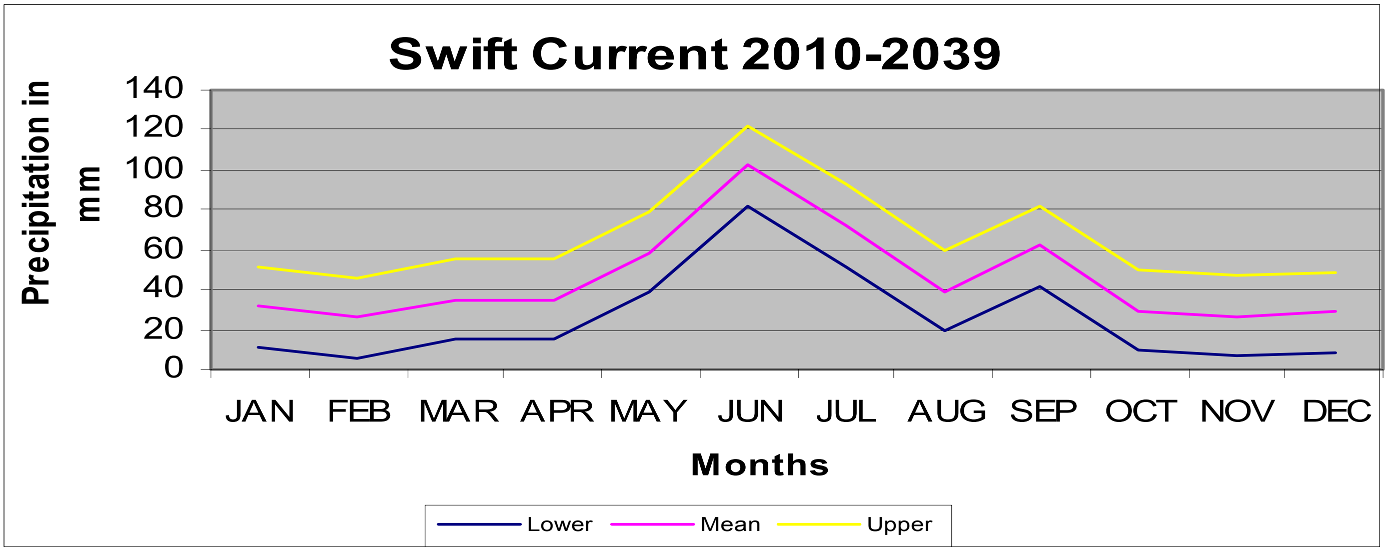


Figure 5.8.4: Results for Swift Current (2040-2069)

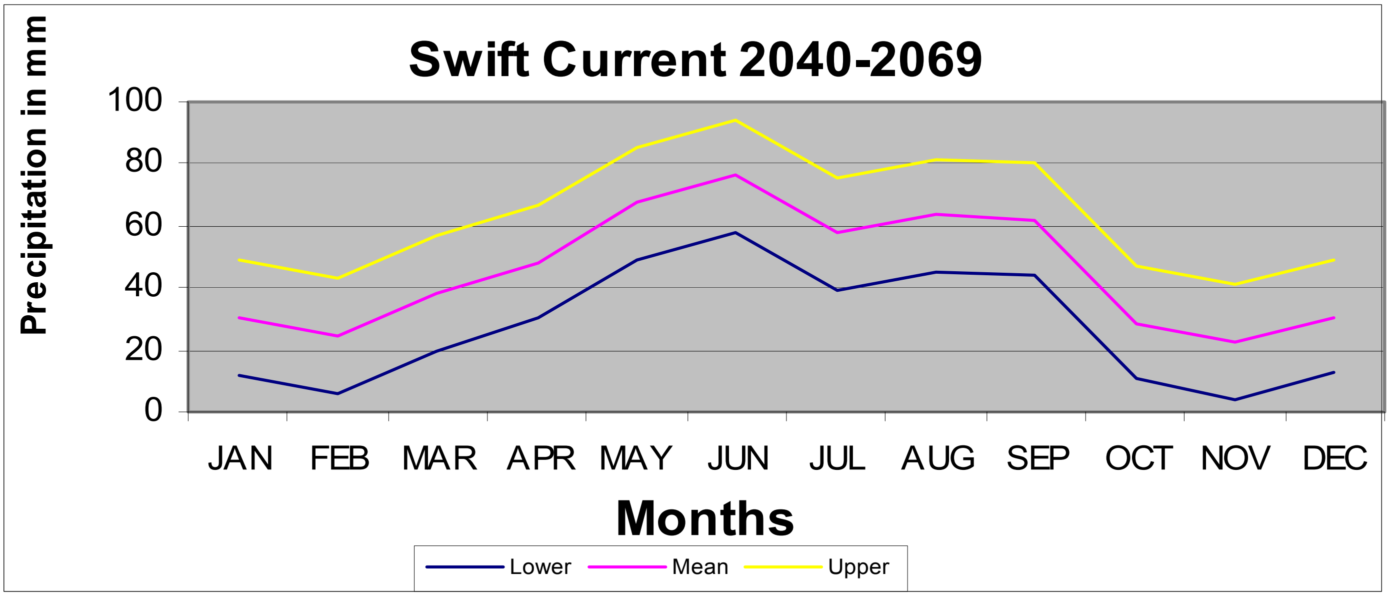
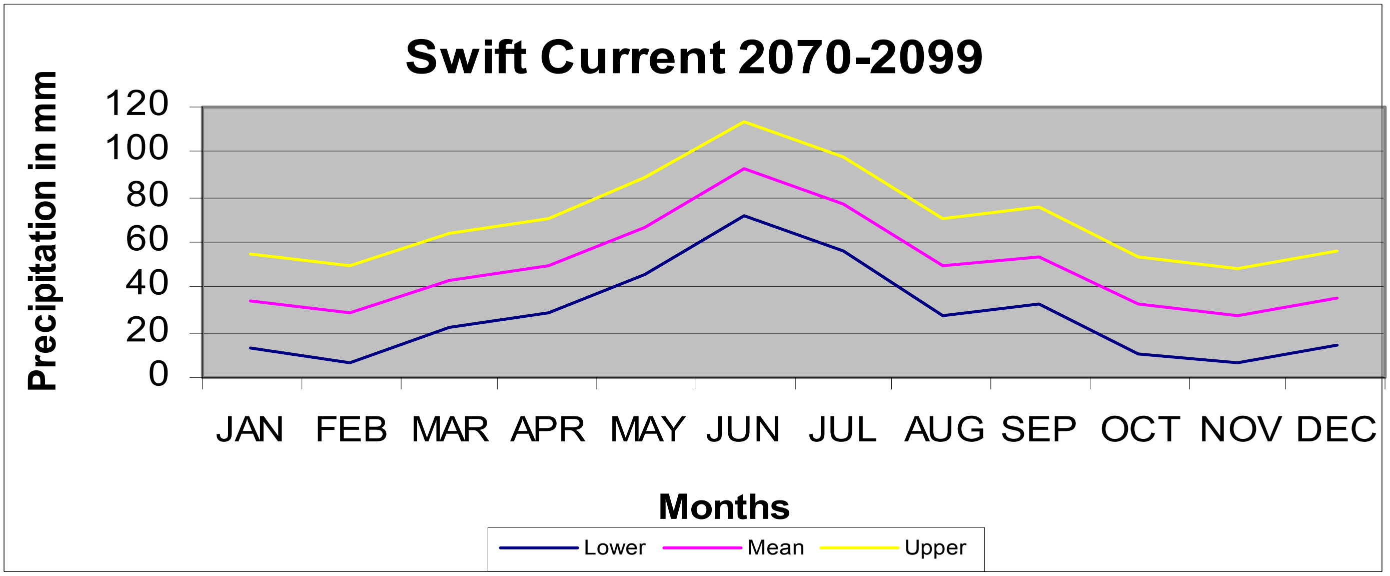


Figure 5.8.5: Results for Swift Current (2070-2099)



In the 2050 scenario, precipitation is projected to decrease in July and increase in August and September to the June level. In the 2080 scenario, it decreases in July and August and increases slightly in September. In the 2020 scenario, precipitation also decreases dramatically in August. The pattern of precipitation indicates that the late summers will be dry in the future scenarios.

5.8.3: Summary and Conclusions

The conclusions for Swift Current are similar to those of Humboldt, in that mean precipitation and maximum precipitation increase over time. There is accessibility to other water sources in the event that the current source becomes inadequate. It does not appear that Swift Current will experience any water supply problems that will result in increased adaptation costs. However, here too a further study of the viability of the watershed would be warranted. As in the previous prairie case studies, there is a need to study the effects of a change in rain to snow ratio (see Section 5.14).

5.9: Lethbridge, AB

5.9.1: Drinking Water Supply

All major cities in Alberta are close to surface water and the main threat to these supplies of water is disappearing snowmelt. Lethbridge has a population of 77,000 people, and growth has been about 1.5% over the period 1989-1999 (see Figure 5.9.1).

Figure 5.9.1: Lethbridge

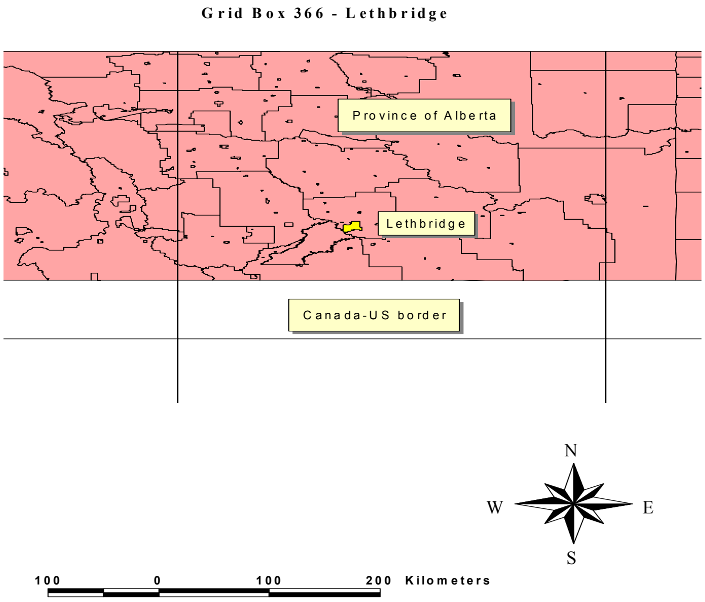


Table 5.9.1 gives the ten-year average water production by month for Lethbridge.

Table 5.9.1: Ten Year Average Water Production in Millions of Litres (ML)

January	984.0
February	932.7
March	1036.0
April	1099.2
May	1478.2
June	1587.6
July	1880.4
August	1931.0
September	1457.7
October	1101.3
November	971.5
December	1011.0
Total	**15,470.6 ML**

Source: Personal Communication from Doug Kaupp, Lethbridge WaterUtilities Manager

The demand for water is within 10% of the production values. The average day demand is about 42.4 ML/day and peak day demand is about 102 ML/day. Production capacity is 150 ML/day.

The average demand for water is increasing at about 2% per annum. Peak demand per capita is decreasing. The water works system includes 4 storage reservoirs and each has a pump station. The total treated water storage capacity is 77 ML. The system is comprised of 425 km of distribution pipes.

The average price of water is \$0.43 per cubic metre, with the commercial average at \$0.38 per cubic metre. Because the pricing is structured on a full cost recovery basis, the water utility is able to contribute 8% of revenues to the city in lieu of taxes.

The City of Lethbridge has not imposed bans on water use and no formal conservation programs are in place. Normal rainfall is 262mm per annum and there is 160 cm of annual snowfall.

The source of water is the Oldman River within the South Saskatchewan Basin. The Oldman River runs through the City and flows into the Bow River, and the Bow flows into the South Saskatchewan River. Upstream of Lethbridge is the Oldman River Dam with a reservoir capacity of about 500,000,000 cubic meters. The water release is controlled by the province to the benefit of large irrigation districts and in stream requirements, including those determined by inter-provincial flow through agreements. Water is distributed to users on a first come, first serve, licensing basis.

Repeated drought is of concern; however no supply strategies are in place. A weir was built forty years ago to guard against low summer flows. Another dam was built in 1990, and before it was completed, 50% of volume of water flow occurred in May, June and July. The security of the water supply depends upon the snow pack. Recently, three consecutive dry years have caused severe problems.

5.9.2: Wastewater Treatment

Lethbridge has state-of-the-art wastewater treatment; biological nutrient removal (BNR) and UV disinfection removes phosphorus and nitrogen. Average daily flow received at the treatment plant is 35,000 cubic metres per day, and the plant has a capacity of 80,000 cubic metres per day. The treated water is discharged further downstream and the sludge is used on farms. More thunderstorms and concentrated rainfall could result in infiltration problems. Generally, infiltration does not result in untreated discharges, and no untreated water is dumped into the river.

Table 5.9.2 shows the descriptive statistics of actual and projected precipitation for Lethbridge.

Table 5.9.2: Descriptive Precipitation Statistics for Lethbridge

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	585.28	183.5	335.92	430.46	585.28
Minimum	0.18	0.5	0.18	0.19	0.26
Average	41.85	36.4	41.45	42.33	47.24
Stand. Dev.	45.76	29.5	44.9	47.58	56.42

The maximum precipitation increases 83% from the baseline to the 2020 time period. In the subsequent time periods the maximum remains 134% and 218% above the baseline level, respectively. The mean increases slightly over the four scenarios. The standard deviation increases 52%, 61% and 91% from the baseline in the subsequent periods.

On any given day, because daily flow is 35,000 m^3, and capacity is 80,000 m^3, 43% of the plant capacity is utilized. In the baseline period, the mean precipitation was 36mm. A simple calculation shows that if precipitation exceeded 83mm in a given month, then untreated wastewater would be discharged.

5.9.3: Regression Results

The estimated regression for 1960 to 1991 is:

$$\mathbf{PPT} = \underset{(6.17)}{\mathbf{29.13}} - \underset{(-1.73)}{\mathbf{11.54D2}} + \underset{(0.15)}{\mathbf{1D3}} + \underset{(1.45)}{\mathbf{9.67D4}} + \underset{(3.35)}{\mathbf{22.34D5}} + \underset{(5.94)}{\mathbf{39.61D6}} + \underset{(2.02)}{\mathbf{13.52D7}} + \underset{(2.8)}{\mathbf{18.72D8}} +$$

$$\underset{(2.46)}{\mathbf{16.41D9}} - \underset{(-1.73)}{\mathbf{11.55D10}} - \underset{(-1.32)}{\mathbf{8.85D11}} - \underset{(-0.31)}{\mathbf{2.11D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT} = \underset{(4.27)}{\mathbf{32.53}} - \underset{(-1.38)}{\mathbf{14.87D2}} + \underset{(0.1)}{\mathbf{1.14D3}} + \underset{(1)}{\mathbf{10.81D4}} + \underset{(2.53)}{\mathbf{27.28D5}} + \underset{(4.53)}{\mathbf{48.85D6}} + \underset{(1.11)}{\mathbf{12.05D7}} +$$

$$\underset{(2.14)}{\mathbf{23.13D8}} + \underset{(2.09)}{\mathbf{22.58D9}} - \underset{(-1.32)}{\mathbf{14.24D10}} - \underset{(-0.35)}{\mathbf{3.77D11}} - \underset{(-0.55)}{\mathbf{6.01D12}}$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT = 32.61 - 13.66D2 + 8.66D3 + 25.26D4 + 28.86D5 + 34.81D6 + 4.8D7 + 23.82D8}$$
(3.93) (-1.16) (0.73) (2.15) (2.46) (2.96) (0.4) (2.03)

$$\mathbf{+ 24.43D9 - 11.39D10 - 6.73D11 - 2.16D12}$$
(2.08) (-0.97) (-0.57) (-0.18)

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT = 35.09 - 14.15D2 + 11.99D3 + 29.61D4 + 28.96D5 + 35.47D6 + 12.14D7 +}$$
(3.51) (-1) (0.84) (2.09) (2.05) (2.51) (0.86)

$$\mathbf{24.37D8 + 32.07D9 - 9.19D10 - 2.69D11 - 2.77D12}$$
(1.72) (2.27) (-0.65) (-0.19) (-0.19)

These regression results indicate that the constant, the mean precipitation for January, is only increasing slightly in the future scenarios from the baseline. These regression results show the likely change in precipitation patterns and the 95% confidence intervals are graphed in Figures 5.9.2 to 5.9.5.

Figure 5.9.2: Results for Lethbridge (1961-1990)

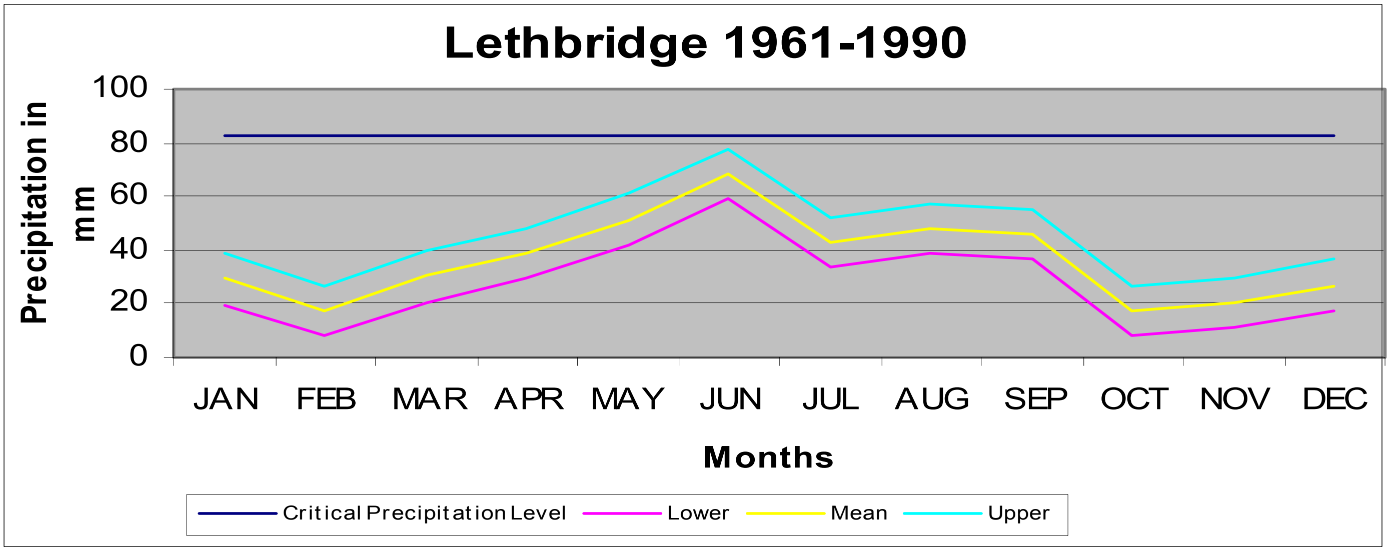


Figure 5.9.3: Results for Lethbridge (2010-2039)

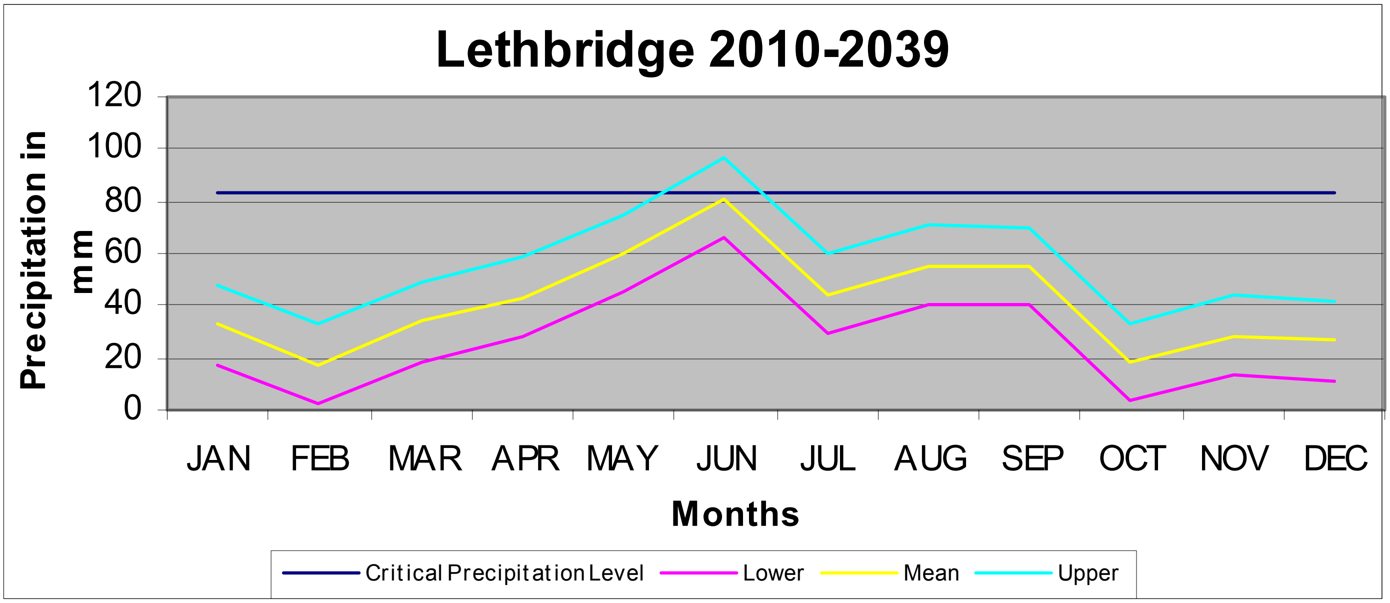


Figure 5.9.4: Results for Lethbridge (2040-2069)

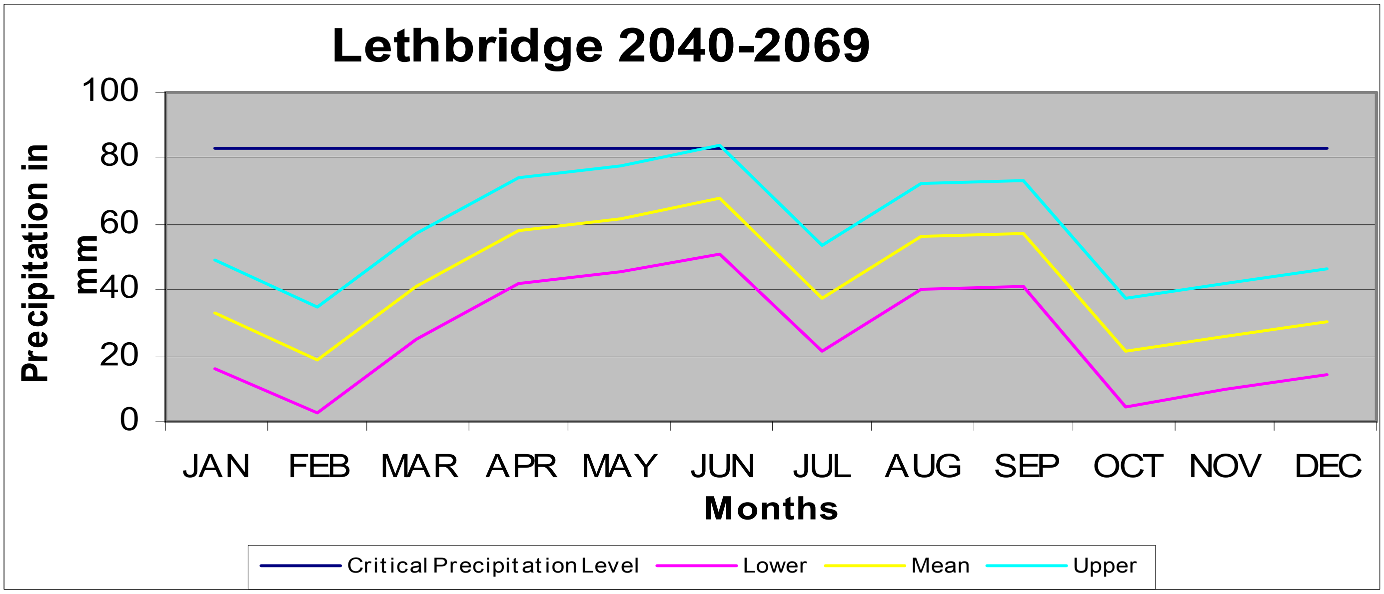
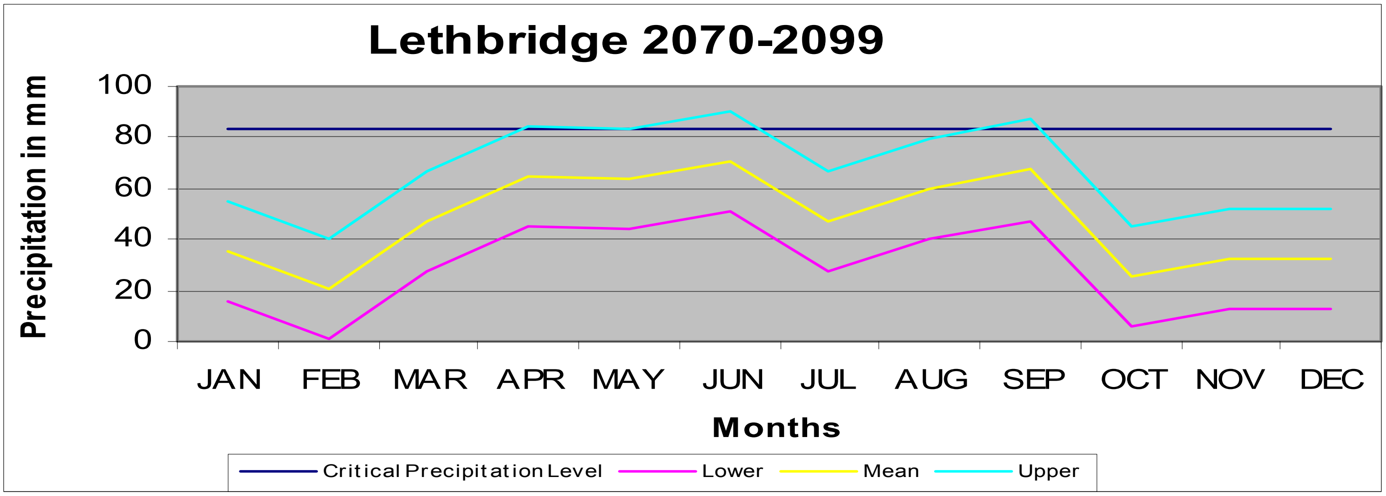


Figure 5.9.5: Results for Lethbridge (2070-2099)



The graphs show that neither the mean nor the upper confidence interval exceeds the maximum wastewater treatment capacity in the baseline. However, in the future scenarios, upper confidence interval of precipitation exceeds the capacity in several different months.

Table 5.9.3: Upper Confidence Level Exceeding Lethbridge's Present Wastewater Capacity

	Upper C.I Exceeding Lethbridge's Wastewater Capacity 1961 to 1990	Upper C.I. Exceeding Lethbridge's Wastewater Capacity 2010 to 2039	Upper C.I. Exceeding Lethbridge's Wastewater Capacity 2040 to 2069	Upper C.I. Exceeding Lethbridge's Wastewater Capacity 2070 to 2099
January	0	0	0	0
February	0	0	0	0
March	0	0	0	0
April	0	0	0	1.34
May	0	0	0	0.69
June	0	13.36	0.73	7.2
July	0	0	0	0
August	0	0	0	0
September	0	0	0	3.81
October	0	0	0	0
November	0	0	0	0
December	0	0	0	0
Totals	**0**	**13.36**	**0.73**	**13.04**

5.9.4: Costs of Adaptation

In Table 5.9.3, precipitation exceeds the maximum treatment capacity of 83mm by 13.36mm. This means that capacity would have to expand by 16% to prevent overflow. In order to determine the costs of adaptation, the amount of capital investment in the wastewater treatment facilities is required. This is a subject for future research. In lieu of specific costs for Lethbridge, we can use an estimate of expanding treatment facilities of $50 million (see Section 5.10.2). Based on this, a rough approximation of the costs of adaptation to climate change is $8 million.

5.9.5: Summary and Conclusions

As can be seen from Table 5.9.3 precipitation will exceed wastewater treatment capacity in June of the 2020, 2050 and 2080 scenario and in April, May and September of the 2080 scenario, indicating that Lethbridge will have to increase its capacity to deal with effects of climate change. However, the projected increases in precipitation are small. As with all the prairie case studies, the viability of water supply should be investigated at the watershed level. In particular, Lethbridge could be vulnerable to changes in snowpack (see Section 5.14).

5.10: Prince George, BC

5.10.1: Drinking Water Supply

Prince George is a city of 80,000 people located at the confluence of the Fraser and Nechako Rivers in central British Columbia (see Figure 5.10.1). Although the city has access to two rivers, it draws its water from 8 producing wells. The pulp and paper industry discharges huge amounts of pollutants into the Fraser River. There does not appear to be a water supply problem as the recharge rate is greater than the draw down rate. The demand for water is unchanged, with some water restrictions in the summer, due to the lack of pumping capacity. Residents pay a flat rate of $13.95/month for water and $14 for sewage. Overall water production capacity is in excess of 50 gallons per day. The 8 wells are part of a system consisting of pump stations, 20 booster stations and 400 km of water main line. Water consumption is 513 litres per capita per day. In 2000, water production is shown in Table 5.10.1.

Figure 5.10.1: Prince George

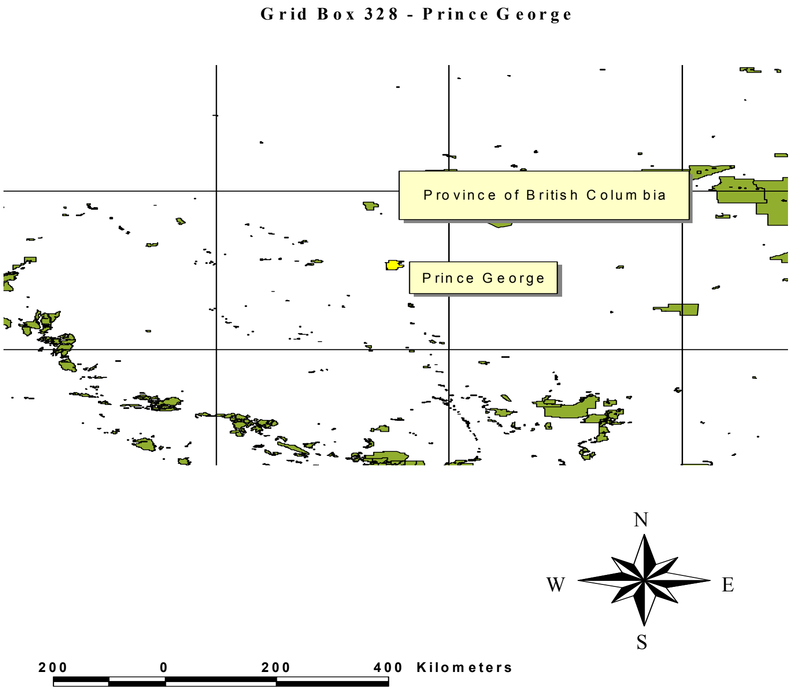


Table 5.10.1: Monthly Water Production 2000

Month	Monthly Total (litres)
Jan	1,098,009,822
Feb	1,084,015,774
Mar	1,156,172,451
Apr	921,447,987.6
May	1,485,575,281
Jun	1,500,986,414
Jul	1,452,084,875
Aug	1,544,515,268
Sep	1,217,727,050
Oct	1,226,041,843
Nov	1,167,031,710
Dec	1,140,858,808
Total	14,994,467,284
Avg. Daily	41,080,733.08

5.10.2: Wastewater Treatment

Wastewater is treated at the primary and secondary levels, and the secondary treatment results in water having a biological oxygen demand and suspended solids of 20 milligrams/litre. All sanitary sewers are separate from storm sewers and the storm water is discharged untreated into the Fraser River. The maximum capacity of the wastewater treatment plant is 15 million gallons a day or 68.1 million litres per day. Wastewater treatment costs are $1.1 million per year. Provincial legislation is pending that will require treatment of storm water before it is discharged. This will require separate treatment facilities at a cost of $10 to $50 million.

The 2000 wastewater flows in Prince George are shown in Table 5.10.2.

Table 5.10.2: Monthly Wastewater Flows 2000

Month	ML
Jan	945.814
Feb	894.261
Mar	974.909
Apr	957.543
May	951.497
Jun	905.536
Jul	942.632
Aug	920.447
Sep	919.310
Oct	907.718
Nov	883.396
Dec	881.987
Total	11085.054
Average	923.765
Avg Daily	30.276972

Source: City of Prince George Environmental Services Water Production 2000 Summary

Table 5.10.3: Prince George Descriptive Statistics

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	351.64	173.6	270.9	314.81	351.64
Minimum	3.25	5	4.7	5.1	3.25
Average	62.49	58.03	64.7	63.89	63.34
Stand. Dev.	44.32	30.19	49.37	47.08	47.77

Table 5.10.3 gives the descriptive statistics of precipitation and its changing pattern over the next 100 years. Maximum precipitation increases 56% from the baseline period to the 2020 period and continues to increase in the 2050 and 2080 scenarios by 81% and 102% respectively. The standard deviation increases by 63% from the baseline to the 2020 time period.

5.10.3: Regression Results

The estimated regression for 1961 to 1990 is:

$$\mathbf{PPT}=\underset{(13.15)}{\mathbf{67.44}}-\underset{(-3.49)}{\mathbf{25.35D2}}-\underset{(-3.79)}{\mathbf{27.54D3}}-\underset{(-4.86)}{\mathbf{35.28D4}}-\underset{(-1.43)}{\mathbf{10.43D5}}+\underset{(0.34)}{\mathbf{2.53D6}}-\underset{(-0.32)}{\mathbf{2.39D7}}-\underset{(-0.17)}{\mathbf{1.23D8}}\ -$$

$$\underset{(-0.4)}{\mathbf{2.96D9}}-\underset{(-0.39)}{\mathbf{2.87D10}}-\underset{(-0.7)}{\mathbf{5.13D11}}-\underset{(-0.3)}{\mathbf{2.28D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT}=\underset{(9.3)}{\mathbf{80.3}}-\underset{(-2.87)}{\mathbf{35D2}}-\underset{(-3.41)}{\mathbf{41.69D3}}-\underset{(-3.94)}{\mathbf{48.18D4}}-\underset{(-1.25)}{\mathbf{15.33D5}}-\underset{(-0.72)}{\mathbf{8.79D6}}-\underset{(-1.52)}{\mathbf{18.65D7}}+\underset{(0.53)}{\mathbf{6.47D8}}\ -$$

$$\underset{(-0.29)}{\mathbf{3.54D9}}-\underset{(-0.84)}{\mathbf{10.33D10}}-\underset{(-0.53)}{\mathbf{6.56D11}}-\underset{(-0.44)}{\mathbf{5.42D12}}$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT}=\underset{(8.93)}{\mathbf{73.72}}-\underset{(-2.31)}{\mathbf{27.07D2}}-\underset{(-2.66)}{\mathbf{31.06D3}}-\underset{(-3.13)}{\mathbf{36.55D4}}-\underset{(-0.88)}{\mathbf{10.36D5}}-\underset{(-1.5)}{\mathbf{17.6D6}}-\underset{(-1.69)}{\mathbf{19.79D7}}+\underset{(0.51)}{\mathbf{6.03D8}}$$

$$+\underset{(0.56)}{\mathbf{6.53D9}}+\underset{(0.09)}{\mathbf{1.13D10}}+\underset{(0.3)}{\mathbf{3.52D11}}+\underset{(0.62)}{\mathbf{7.29D12}}$$

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT}=\underset{(8.26)}{\mathbf{68.98}}-\underset{(-2.28)}{\mathbf{26.97D2}}-\underset{(-2.4)}{\mathbf{28.36D3}}-\underset{(-2.81)}{\mathbf{33.29D4}}-\underset{(-0.62)}{\mathbf{7.33D5}}-\underset{(-1.31)}{\mathbf{15.58D6}}+\underset{(0.09)}{\mathbf{1.08D7}}+\underset{(1.2)}{\mathbf{14.2D8}}\ +$$

$$\underset{(1.23)}{\mathbf{14.63D9}}+\underset{(0.47)}{\mathbf{5.57D10}}+\underset{(0.54)}{\mathbf{6.38D11}}+\underset{(0.16)}{\mathbf{1.99D12}}$$

The purpose of the regressions is to show the pattern of precipitation in the future time periods. We can see that the constant increases in the future scenarios from the baseline and is significant in every case. The regression results and 95% confidence intervals are plotted in Figures 5.10.2 to 5.10.5.

Figure 5.10.2: Results for Prince George (1961-1990)

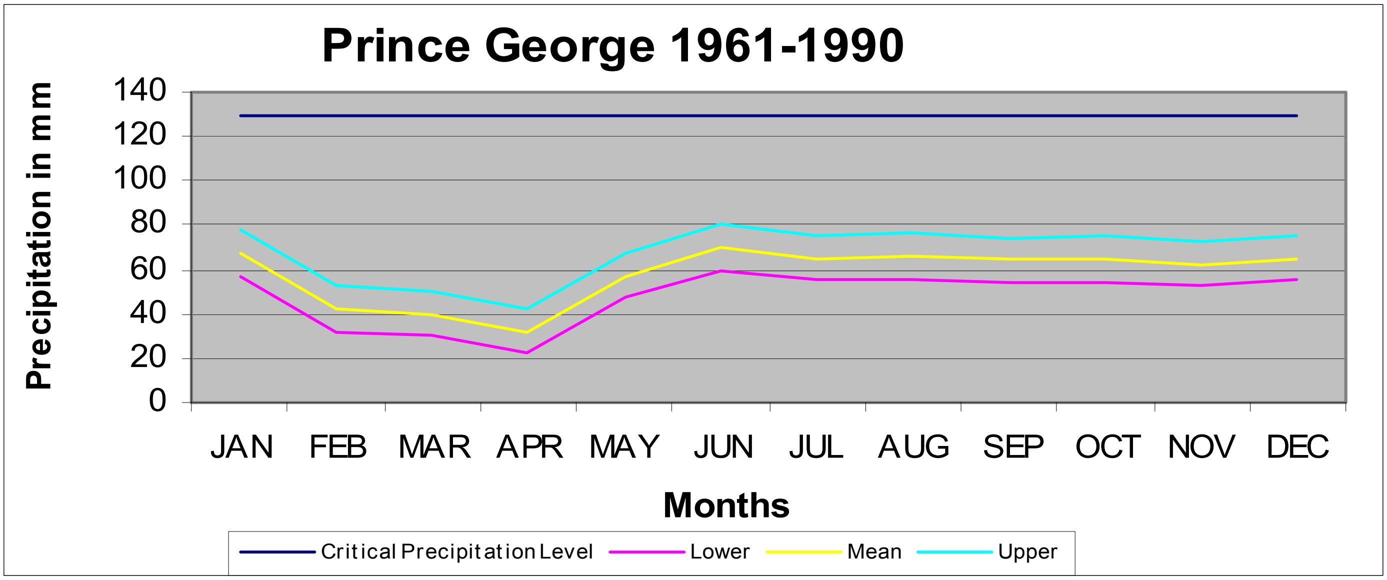


Figure 5.10.3: Results for Prince George (2010-2039)

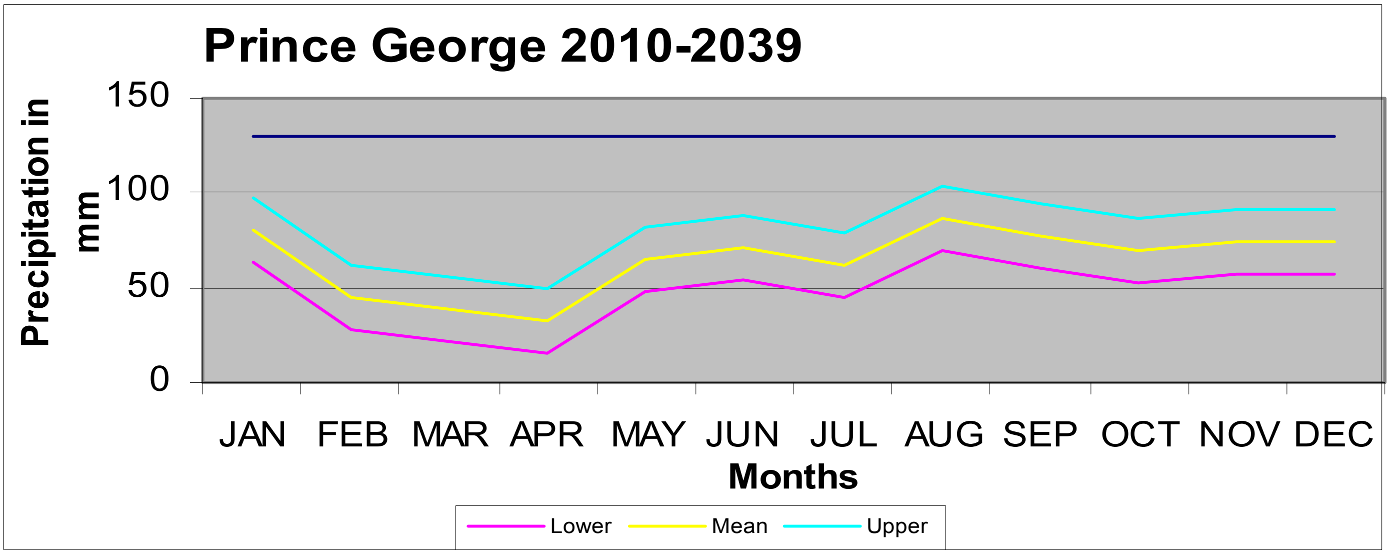


Figure 5.10.4: Results for Prince George (2040-2069)

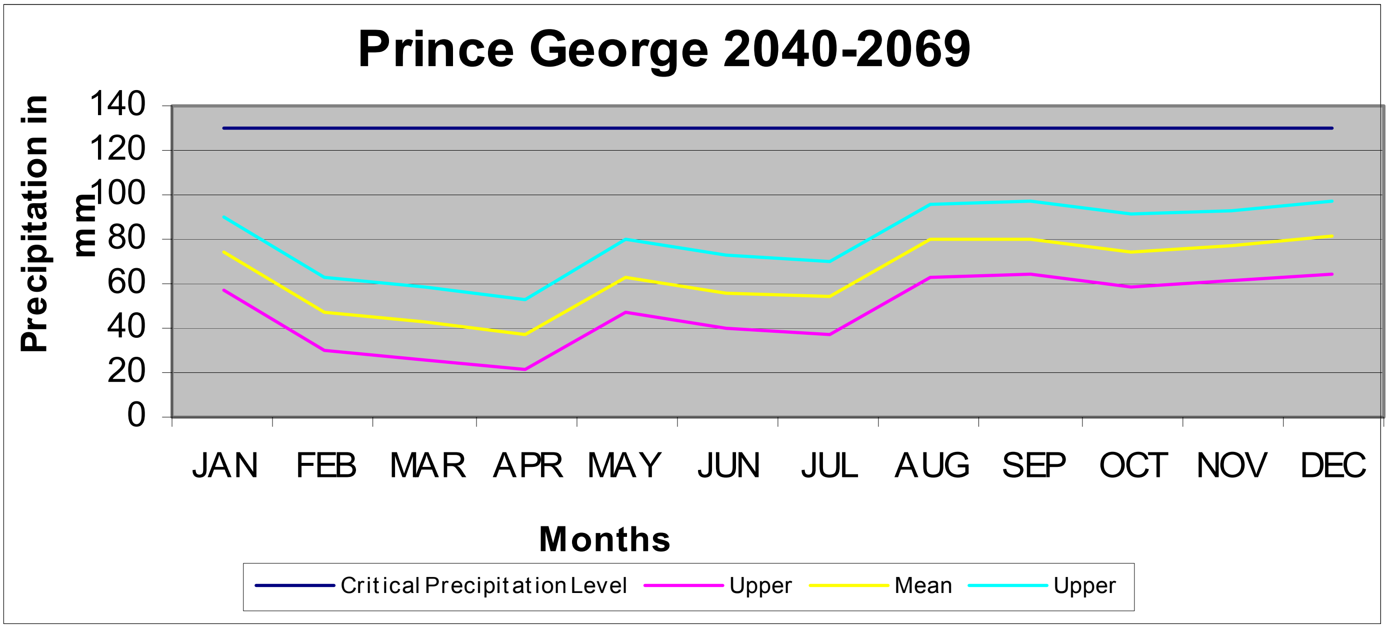
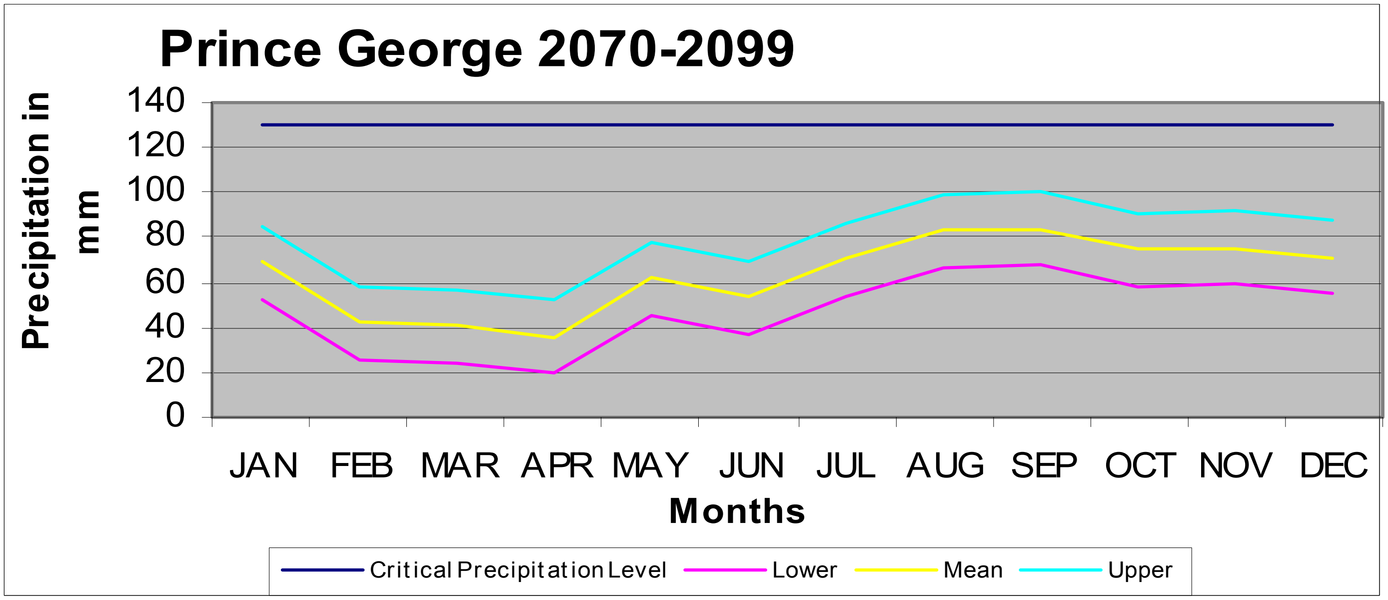


Figure 5.10.5: Results for Prince George (2070-2099)



The graphs indicate that the pattern of precipitation stays somewhat similar over the four time periods, but the amount of precipitation increases. We can see that the maximum upper confidence interval amount is 80 mm in the baseline but increases to 100 mm in the future scenarios.

5.10.4: Summary and Conclusions

The maximum capacity per day for wastewater treatment is 68.1 million litres per day and the average daily water flow is 30.3 million litres. Average daily flow divided by capacity rating is 44.5%. The mean precipitation in 1961 to 1990 is 58 mm. The precipitation level in a single month that will force the treatment plants to operate at 100% is 130 mm. Therefore, precipitation beyond 130 mm per month will force wastewater into the ecosystem.

The graphs indicate that existing wastewater treatment capacity will be sufficient. Neither the mean nor the upper confidence interval exceeds the capacity level in any scenario. Therefore, based on this analysis, there will be no adaptation costs associated with wastewater treatment due to climate change.

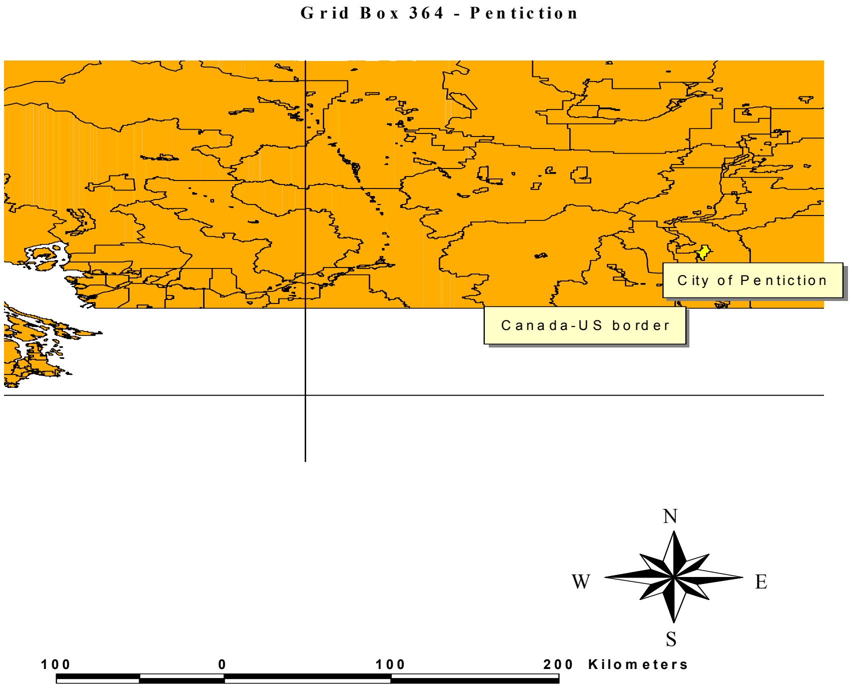
5.11: Penticton, BC

5.11.1: Drinking Water Supply

The City of Penticton has a population of 32,500 and produces treated water to meet the demand of the populace (see Figure 5.11.1). There is approximately 12 ML of storage in concrete reservoirs and the maximum plant production is 60 ML/d. Peak summer demand is 55 ML/d, but the demand for water is not increasing. The water is distributed through 180km of mains.

The source for drinking water is the Okanagan Lake and Penticton Creek. The Lake could provide water for a long period of drought but would impact on fish resources and downstream commitment of water. The Penticton Creek has 10,000-acre ft. of storage and Okanagan Lake is large, and so repeated droughts would not necessarily require the construction of a reservoir. Recently, the City of Penticton trimmed the flow of one of their 10,000 acre ft. storage reservoirs, due to the very low snow pack. The storage is now 3,500-acre ft., down from 5,000 for this time of year. There is a groundwater source but it is not used as the well water has high levels of iron and manganese.

Figure 5.11.1: Pentiction



Some statistics on daily consumption of water are given in Table 5.11.1.

Table 5.11.1: Daily Consumption of Water

Total	8003 million liters
Daily Average	21.87 million liters/day
Average Daily per Capita	683 liters/day
Maximum Daily per Capita	1636 liters/day
Minimum Daily per Capita	325 liters/day

Source: City of Penticton Water Treatment Plant Summary Report 2000

5.11.2: Wastewater Treatment

The City of Penticton has a separate sanitary sewer and storm water system, and storm water treatment is predicted to increase over time *(personal communication, B.Udala, City of Penticton)*. The wastewater treatment average is 405 litres per day per person.

Table 5.11.2 gives the average monthly flow of wastewater.

Table 5.11.2: Average Daily Flow (ML/Day)

Jan	12.008
Feb	11.969
Mar	11.893
Apr	12.732
May	13.784
Jun	13.883
Jul	15.092
Aug	15.718
Sep	13.967
Oct	13.043
Nov	12.224
Dec	11.889
Annual	13.183

Source: City of Penticton Advanced Wastewater Treatment Plant 2000 Operating Summary

Table 5.11.3 gives the Penticton precipitation statistics for the four time periods.

Table 5.11.3: Penticton Precipitation Descriptive Statistics

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	269.63	93.9	269.63	221.4	211.56
Minimum	0.87	1.3	1.05	0.96	0.87
Average	33.6	29.66	34.81	34.62	35.32
Stand. Dev.	28.42	17.23	32.45	30.72	30.38

The maximum precipitation increases 187% from the baseline period to the 2020 period. It remains 125% to 137% higher in subsequent periods. The standard deviation increases 88% from the baseline to the 2020 period.

5.11.3: Regression Results

The estimated regression for 1961 to 1990 is:

$$\mathbf{PPT}=\underset{(11.32)}{\mathbf{33.98}} - \underset{(-2.16)}{\mathbf{9.2D2}} - \underset{(-2.33)}{\mathbf{9.92D3}} - \underset{(-1.05)}{\mathbf{4.46D4}} + \underset{(0.73)}{\mathbf{3.14D5}} + \underset{(1.01)}{\mathbf{4.32D6}} - \underset{(-1.82)}{\mathbf{7.74D7}} - \underset{(-0.61)}{\mathbf{2.63D8}} -$$

$$\underset{(-1.9)}{\mathbf{8.08D9}} - \underset{(-3.58)}{\mathbf{15.22D10}} - \underset{(-1.34)}{\mathbf{5.69D11}} + \underset{(0.87)}{\mathbf{3.71D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT}=\underset{(7.02)}{\mathbf{40.54}} - \underset{(-1.75)}{\mathbf{14.35D2}} - \underset{(-2.4)}{\mathbf{19.59D3}} - \underset{(-1.19)}{\mathbf{9.71D4}} + \underset{(1.05)}{\mathbf{8.56D5}} + \underset{(1.05)}{\mathbf{8.6D6}} - \underset{(-1.48)}{\mathbf{12.12D7}} - \underset{(-0.28)}{\mathbf{2.28D8}} -$$

$$\underset{(-1.07)}{\mathbf{8.75D9}} - \underset{(-2.27)}{\mathbf{18.55D10}} - \underset{(-0.28)}{\mathbf{2.35D11}} + \underset{(0.22)}{\mathbf{1.85D12}}$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT}=\underset{(7.11)}{\mathbf{39.15}} - \underset{(-1.16)}{\mathbf{9.07D2}} - \underset{(-1.64)}{\mathbf{12.82D3}} - \underset{(-1.2)}{\mathbf{9.38D4}} + \underset{(0.93)}{\mathbf{7.31D5}} - \underset{(-0.29)}{\mathbf{2.3D6}} - \underset{(-1.62)}{\mathbf{12.68D7}} - \underset{(-0.85)}{\mathbf{6.66D8}} -$$

$$\underset{(-1.22)}{\mathbf{9.51D9}} - \underset{(-1.28)}{\mathbf{9.99D10}} - \underset{(-0.4)}{\mathbf{3.19D11}} + \underset{(1.78)}{\mathbf{13.9D12}}$$

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT}=\underset{(7.09)}{\mathbf{38.75}} - \underset{(-1.75)}{\mathbf{13.58D2}} - \underset{(-1.41)}{\mathbf{10.9D3}} - \underset{(-1.16)}{\mathbf{8.95D4}} + \underset{(0.86)}{\mathbf{6.7D5}} - \underset{(-0.75)}{\mathbf{5.83D6}} - \underset{(-1.3)}{\mathbf{10.09D7}} - \underset{(-0.29)}{\mathbf{2.24D8}} -$$

$$\underset{(-0.34)}{\mathbf{2.69D9}} - \underset{(-1.11)}{\mathbf{8.59D10}} + \underset{(0.34)}{\mathbf{2.65D11}} + \underset{(1.6)}{\mathbf{12.37D12}}$$

These regression results indicate the likely precipitation pattern for Penticton in the four time periods. The constant increases in the future scenarios from the baseline and is significant in every case. The results and 95% confidence intervals are graphed in figures 5.11.2 to 5.11.5.

Figure 5.11.2: Results for Penticton (1961-1990)

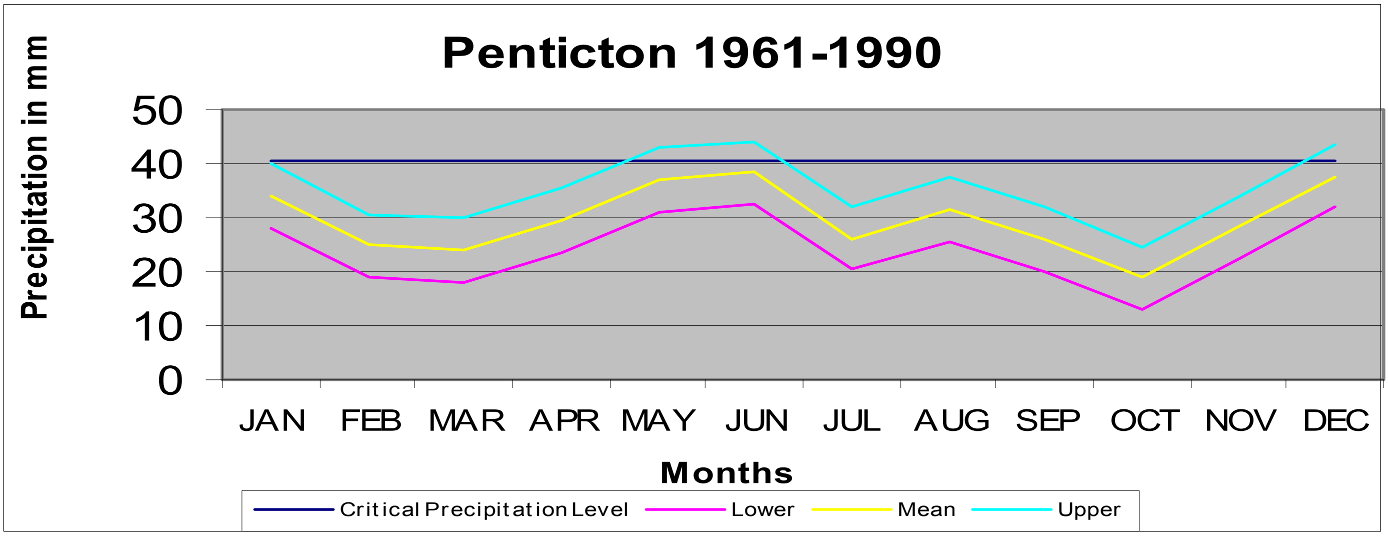


Figure 5.11.3: Results for Penticton (2010-2039)

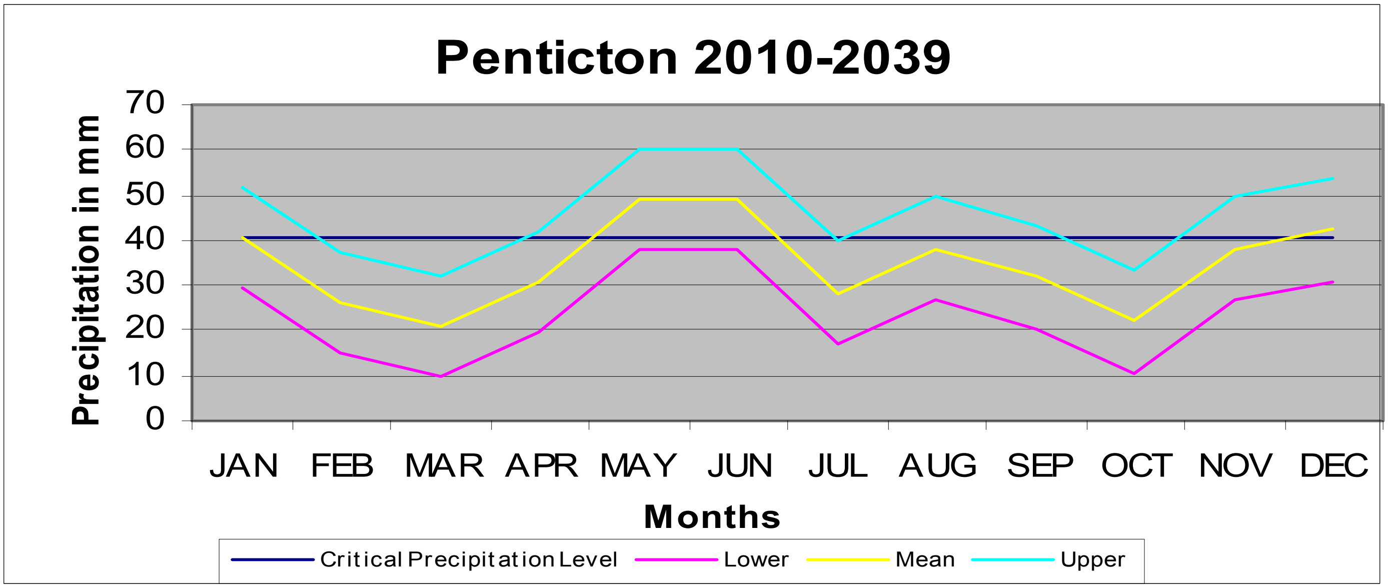


Figure 5.11.4: Results for Pentiction (2040-2069)

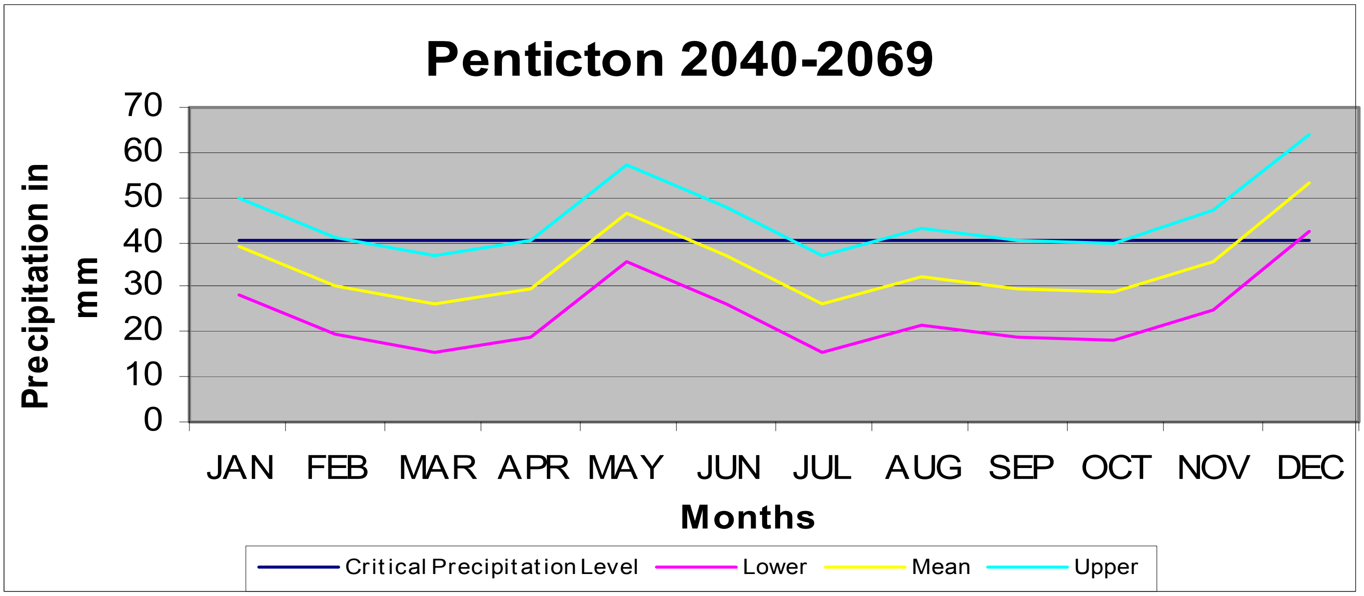
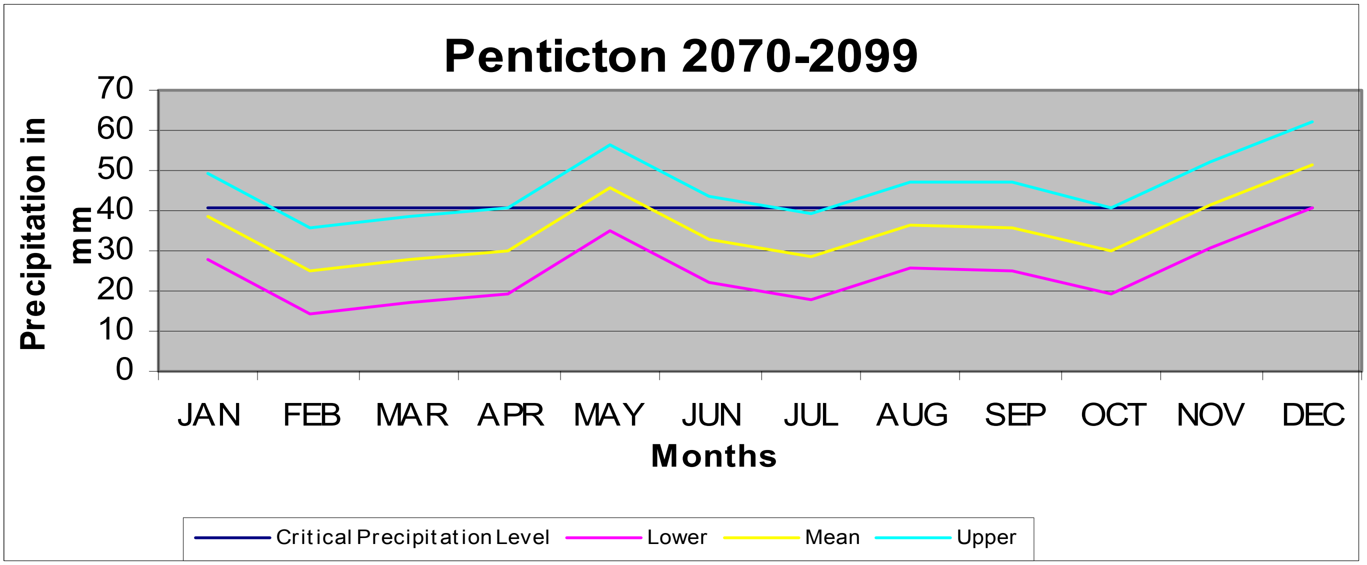


Figure 5.11.5: Results for Penticton (2070-2099)



The graphs indicate that precipitation peaks in spring and winter months. The upper confidence interval in the 2080 scenario is lower than that of the 2020 scenario.

The maximum capacity per day for wastewater treatment is 18 million litres per day and the average daily water flow is 13.138 million litres. Average daily flow divided by capacity rating is 73%. The mean precipitation in 1961 to 1990 is 29.66mm. The precipitation level in a single month that will force the treatment plants to operate at 100% is 40.6 mm. Therefore, precipitation beyond 40.6mm per month will force wastewater into the ecosystem.

Table 5.11.4: Precipitation Exceeding Penticton's Present Wastewater Capacity

	Precipitation Exceeding Penticton's Wastewater Capacity 1961 to 1990	Precipitation Exceeding Penticton's Wastewater Capacity 2010 to 2039	Precipitation Exceeding Penticton's Wastewater Capacity 2040 to 2069	Precipitation Exceeding Penticton's Wastewater Capacity 2070 to 2099
January	0	0	0	0
February	0	0	0	0
March	0	0	0	0
April	0	0	0	0
May	0	8.51	5.87	0
June	0	8.54	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	0	0	0	0
November	0	0	0	0.812
December	0	1.79	12.46	10.53
Totals	**0**	**18.84**	**18.33**	**11.34**

Table 5.11.5: Upper Confidence Interval Exceeding Penticton's Present Wastewater Capacity

	Upper C.I. Exceeding Penticton's Wastewater Capacity 1961 to 1990	Upper C.I. Exceeding Penticton's Wastewater Capacity 2010 to 2039	Upper C.I. Exceeding Penticton's Wastewater Capacity 2040 to 2069	Upper C.I. Exceeding Penticton's Wastewater Capacity 2070 to 2099
January	0	11.29	9.29	8.89
February	0	0	0.31	0
March	0	0	0	0
April	0	1.48	0	0
May	2.42	19.85	16.7	15.6
June	3.6	19.89	7.08	3
July	0	0	0	0
August	0	9	2.72	6.6
September	0	2.53	0	6.19
October	0	0	0	0.3
November	0	8.93	6.19	11.55
December	2.99	13.14	23.29	21.27
Totals	**9.01**	**77.11**	**65.58**	**70.4**

5.11.4: Costs of Adaptation

As shown in Table 5.11.5, precipitation exceeds the maximum treatment capacity of 40.6mm in the 2050 scenario by 23.29mm in December. In Table 5.11.4, the mean exceeds the capacity by 12.46 in the same month of the same scenario. This means that capacity needs to expand by a minimum of 30% to a maximum of 57%. Based on the costs of new treatment facilities for Prince George of $50 million (see Section 5.10.2), the costs of adaptation range from $15 million to $28.5 million.

5.11.5: Summary and Conclusions

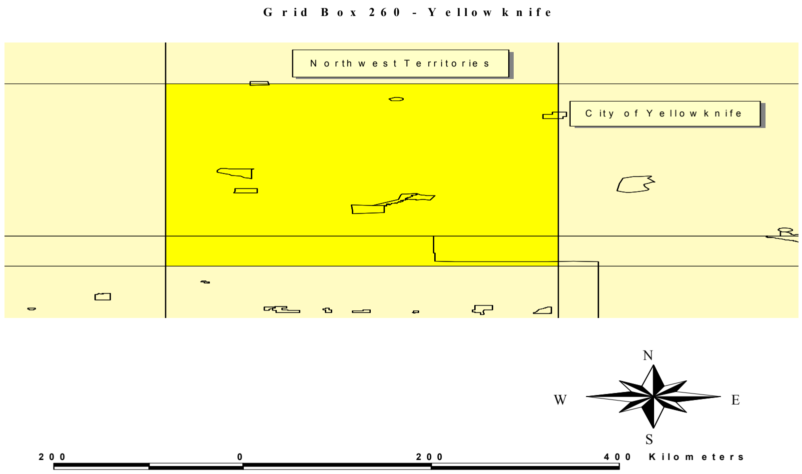
Penticton will face a wastewater treatment capacity shortfall, especially considering the upper 95% confidence interval where overflows occur in several months of the future scenarios. Overflows also occur when looking at the mean precipitation. The costs associated with climate change adaptation range from $15 million to $28.5 million.

5.12: Yellowknife, NT

5.12.1: Drinking Water Supply

The City of Yellowknife has a population of 18,000 and is in the discontinuous permafrost area (see Figure 5.12.1). In the past, Yellowknife used to draw its water from Great Slave Lake, but because of increased arsenic content, they now draw from the Yellowknife River. The draw down from the river is 2007 million cubic metres per year. The cost of production is $5.50/1000 gallons of drinking water. The water distribution pipes are insulated and buried below the permafrost. The temperature of water at the intake point is 33.3°C and it is heated to 35°C. Climate change will have the effect of reducing the heating costs of intake water because of the increase in temperature. These savings in heating costs could be more than offset by the increase in the breakage of pipes due to permafrost degradation.

Figure 5.12.1: Yellowknife



5.12.2: Permafrost and Climate Change

Mean air temperatures could rise several degrees over much of the Arctic if carbon dioxide concentrations double. It is possible that permafrost in the discontinuous region will disappear due to ground thermal changes. Where ground ice contents are high, soils have the potential for instability upon thaw, such as thaw settlement, creep or slope failure.

5.12.3: Wastewater Treatment

Yellowknife relies on a system of natural wastewater treatment where the sludge sits in lagoons and the treated water is discharged into Great Slave Lake. The lagoon system is a chain of small lakes and creeks covering a 13km course into Great Slave Lake. The current sewage lagoon has a retention capacity of 2.5 million cubic metres, which represents approximately 10 to 12 months worth of storage. In 8 to 10 years, a control dam will be constructed next to the lake, adding more storage capacity. Yellowknife will then have 9 million cubic metres of storage capacity.

Table 5.12.1 gives the descriptive statistics for precipitation for the four time periods.

Table 5.12.1: Yellowknife Descriptive Statistics

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	312.19	152.4	242.65	312.19	281.98
Minimum	0.59	1.7	1.25	0.59	0.68
Average	33.55	28.76	33.44	35.25	36.75
Stand. Dev.	35.44	20.45	36.53	40.69	39.86

In the three future scenarios, mean precipitation will increase by 16%, 22% and 27% respectively. Maximum precipitation increases in 2020 and 2050 and then decreases in 2080.

5.12.4: Regression Results

The estimated regression for 1961 to 1990 is as follows:

$$\mathbf{PPT} = \underset{(6.95)}{\mathbf{22.84}} - \underset{(-0.48)}{\mathbf{2.26D2}} - \underset{(-1.35)}{\mathbf{6.3D3}} - \underset{(-1.74)}{\mathbf{8.09D4}} - \underset{(-0.68)}{\mathbf{3.16D5}} + \underset{(0.84)}{\mathbf{3.91D6}} + \underset{(3.47)}{\mathbf{16.11D7}} + \underset{(4.96)}{\mathbf{23.03D8}} +$$

$$\underset{(2.06)}{\mathbf{9.6D9}} + \underset{(4.18)}{\mathbf{19.42D10}} + \underset{(3.59)}{\mathbf{16.67D11}} + \underset{(0.46)}{\mathbf{2.13D12}}$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT} = \underset{(4.56)}{\mathbf{28.9}} - \underset{(-0.76)}{\mathbf{6.82D2}} - \underset{(-1.4)}{\mathbf{12.54D3}} - \underset{(-1.58)}{\mathbf{14.14D4}} - \underset{(-0.83)}{\mathbf{7.43D5}} + \underset{(1.04)}{\mathbf{9.32D6}} + \underset{(2.19)}{\mathbf{19.66D7}} + \underset{(2.75)}{\mathbf{24.62D8}} +$$

$$\underset{(0.188)}{\mathbf{1.68D9}} + \underset{(2.37)}{\mathbf{21.27D10}} + \underset{(1.9)}{\mathbf{17.03D11}} + \underset{(0.2)}{\mathbf{1.79D12}}$$

The estimated regression for 2040 to 2069 is:

PPT= 23.2 – 5.41D2 –9.07D3 – 6.89D4 – 4.02D5 + 24.87D6 + 25.73D7 + 26.34D8 +
(3.32) (-0.54) (-0.91) (-0.69) (-0.4) (2.52) (2.6) (2.66)

19.88D9 + 32.45D10 + 29.7D11 + 11.01D12
(2.01) (3.28) (3) (1.11)

The estimated regression for 2070 to 2099 is:

PPT= 27.52 – 4.69D2 –12.7D3 – 10.1D4 – 7.51D5 + 12.05D6 + 30.96D7 + 26.37D8 +
(4.06) (-0.48) (-1.32) (-1.05) (-0.78) (1.25) (3.22) (2.75)

10.04D9 + 31.52D10 + 27.44D11 + 7.33D12
(1.04) (3.28) (2.86) (0.76)

The regression results indicate that the constant increases slightly from the baseline and is significant in all time periods. The 95% confidence intervals are graphed in Figures 5.12.2 to 5.12.5.

Figure 5.12.2: Results for Yellowknife (1961-1990)

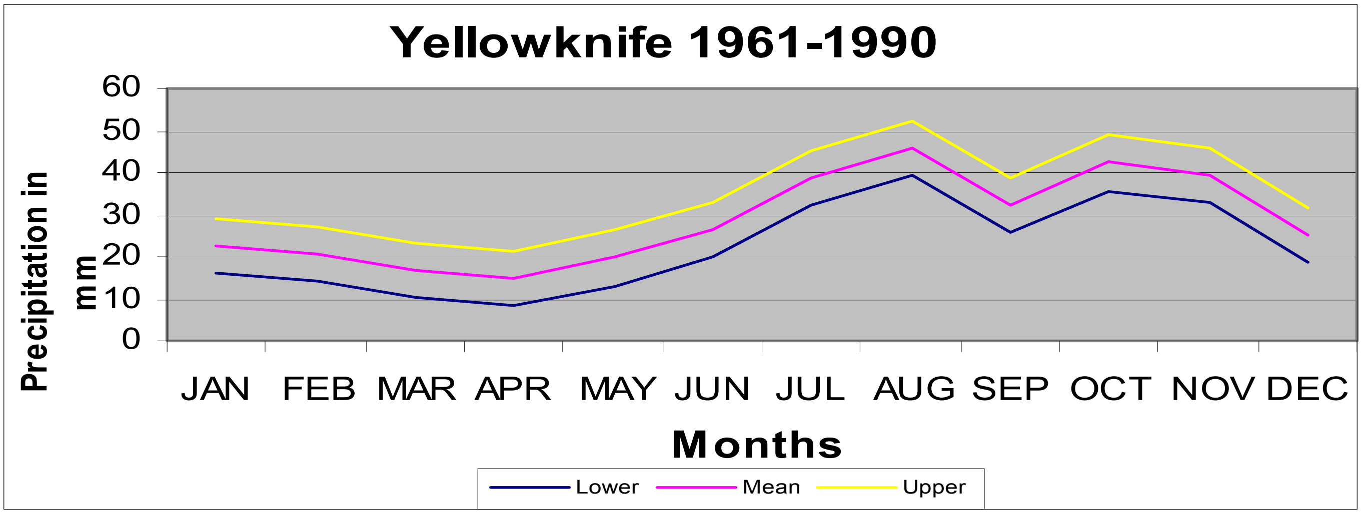


Figure 5.12.3: Results for Yellowknife (2010-2039)

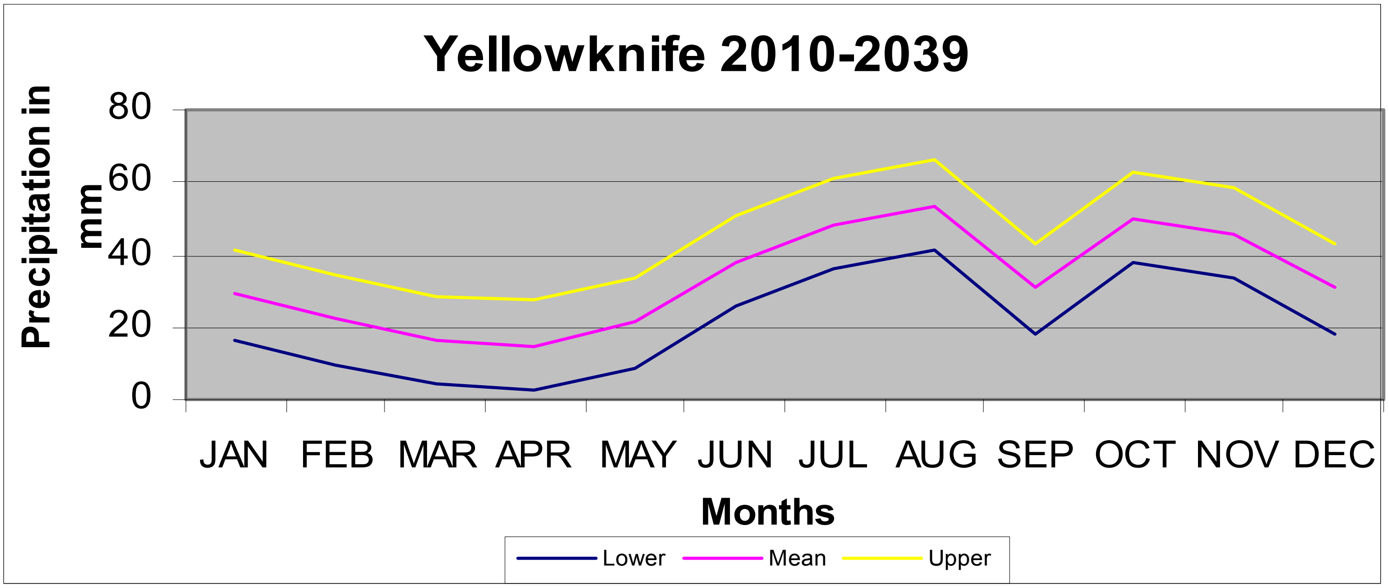


Figure 5.12.4: Results for Yellowknife (2040-2069)

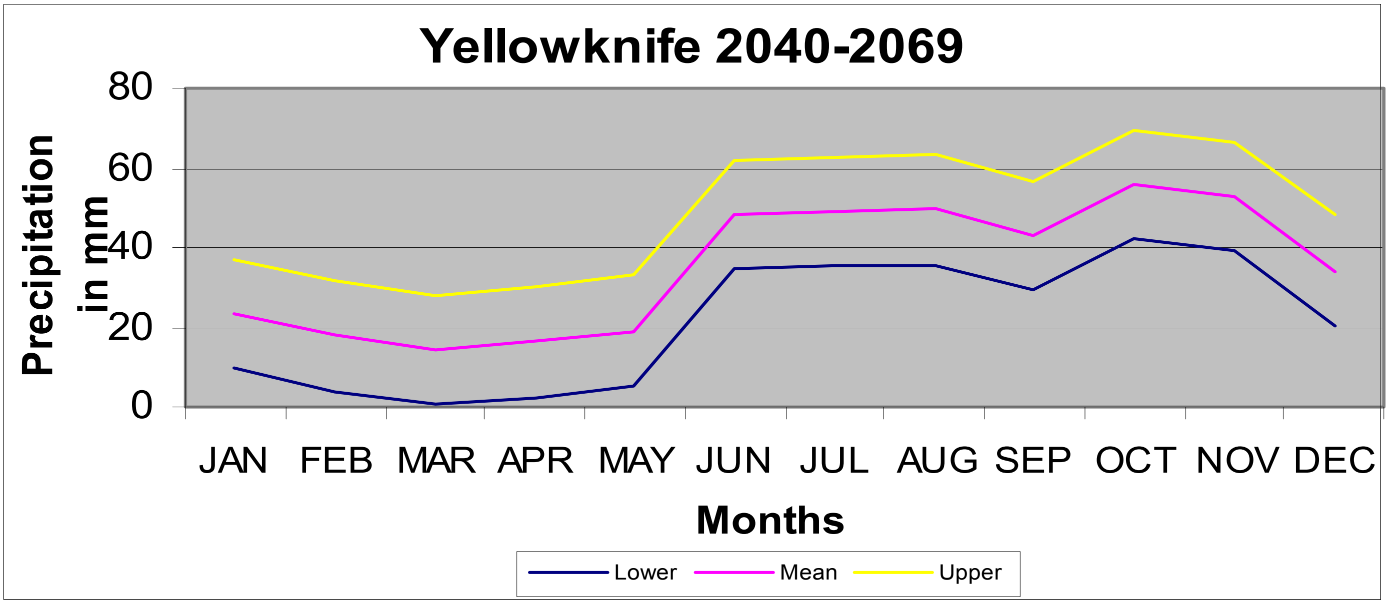
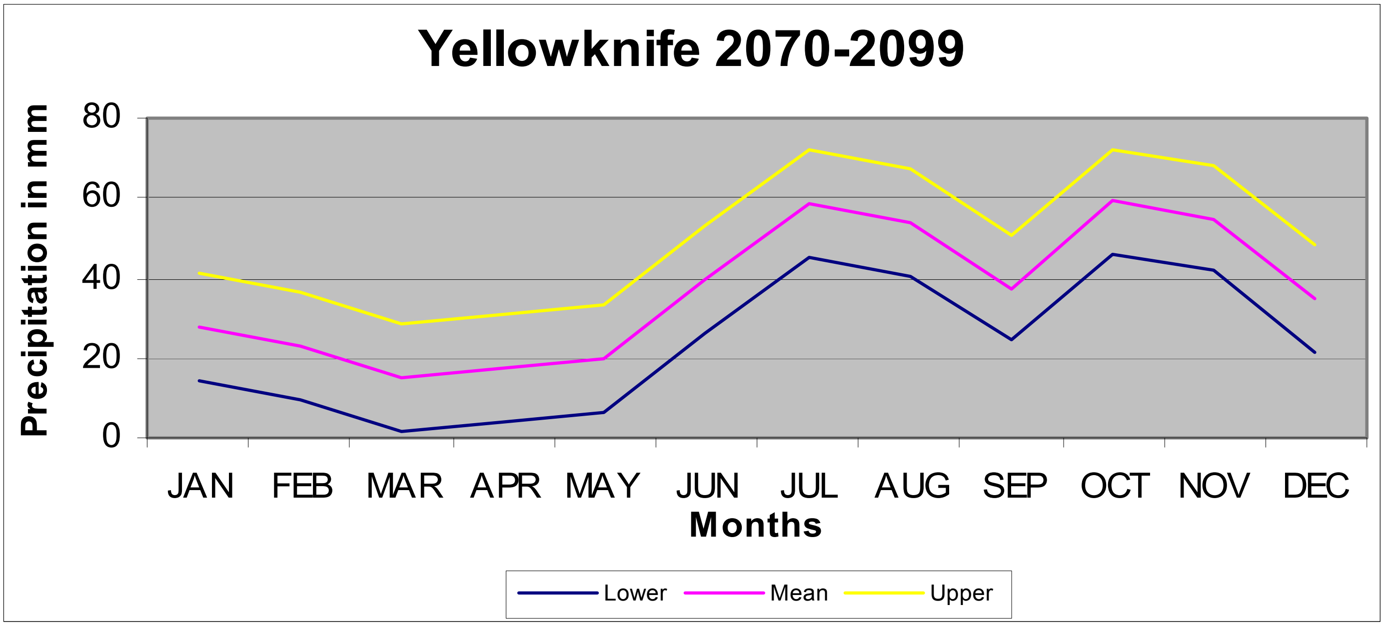


Figure 5.12.5: Results for Yellowknife (2070-2099)



The precipitation patterns depicted in the four time periods show that the upper confidence interval and the mean are increasing over time. There appears to be a double peak in July and October and a dramatic decrease in September.

5.12.5: Summary and Conclusion

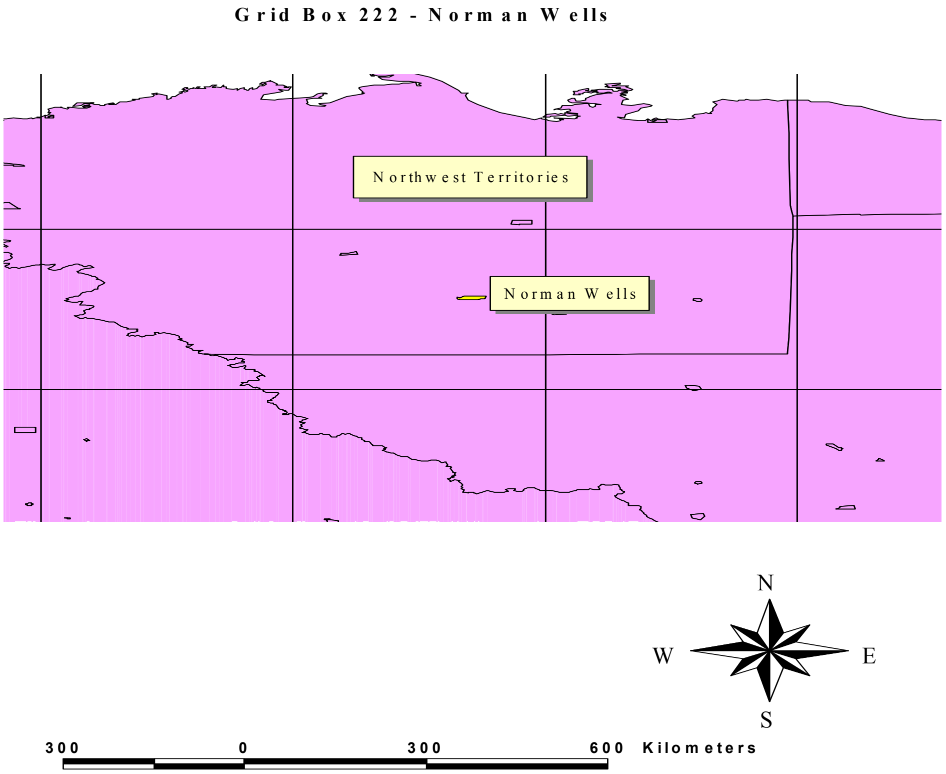
Because Yellowknife draws its water directly from the Yellowknife and the pipes are buried below the permafrost, there does not appear to be a water supply problem, nor a cost associated with damaged pipes due to disappearing permafrost. For wastewater treatment, Yellowknife has 10 to 12 months of wastewater storage, so an increase in precipitation is not expected to exceed treatment capacity.

5.13: Norman Wells, NT

5.13.1: Drinking Water Supply

Norman Wells is a town of 800 located in the discontinuous permafrost zone (see Figure 5.13.1). The water supply source is the Mackenzie River and the daily production of water is 300 cubic metres. Two-thirds of the town is on the utilidor system, where water is delivered in insulated above ground pipes supported on steel piles. The water is heated to 6-7° C. The remaining third of the town gets its water delivered by truck where it is stored in 500 to 1000 gallon water tanks. Water is priced at $12 cubic metre inclusive of sewage costs. Norman Wells does not have a large reservoir, and as a result, production of water is equal to demand. Demand for water never exceeds the 500L/M maximum capacity of water production and it is constant. The town has two km of watermain pipeline and raw water pumps in the river and distribution pumps in the water treatment plant. Because the town's water source is the Mackenzie River, a drastic reduction in rainfall would not have a huge impact on the river levels. However, if there were repeated droughts, and the water supply became unreliable, a reservoir would most likely be constructed.

Figure 5.13.1: Norman Wells



5.13.2: Wastewater Treatment

Sewage is treated at the primary level, where it goes to a lagoon and the sludge settles. The town has no storm water sewers and the total monthly volume of treated wastewater remains constant. Norman Wells has a natural wetland treatment facility, and as a result, there are no treatment costs, only pumping and trucking costs. According to local expert opinion, the wastewater that is stored in retention cells can be stored for at least two weeks *(personal communication with Murray Knox, Yellowknife Utilities Manager).* The wetland facility allows for years of retention after the wastewater is released from the cells *(personal communication with Murray Knox, Yellowknife Utilities Manager).* Because sewage production is based on water consumption, wastewater treatment flows are equal to water consumption. Table 5.13.1 gives water consumption and wastewater flows per month for Norman Wells.

Table 5.13.1: Water Consumption and Wastewater Flows, 2000 (m^3)

Jan	8,147
Feb	7,800
Mar	9,967
Apr	8,514
May	9,509
Jun	9,185
Jul	8,570
Aug	9,470
Sep	8,168
Oct	7,776
Nov	7,610
Dec	6,634
Total	101,350

Source: Norman Wells Utilities Department

5.13.3: Permafrost and Climate Change

In some areas of the discontinuous permafrost zone, permafrost will virtually disappear by 2100. This could possibly reduce the costs associated with heating the water. The ground will become unstable, especially adjacent to the rivers. However, this decrease in cost may be offset by the effects of a lower river level, in which case, intake pipes would have to be extended to a deeper part of the river.

Table 5.13.2 gives the descriptive statistics for precipitation.

Table 5.13.2: Norman Wells Descriptive Statistics

	1961-2099	1961-1990	2010-2039	2040-2069	2070-2099
Maximum	714.09	121	714.09	524.01	463.86
Minimum	0.49	2.3	1.31	0.49	1.71
Average	42.74	32.95	44.26	46.02	47.72
Stand. Dev.	49.91	22.79	57.93	57.56	51.6

The descriptive statistics for precipitation show that mean precipitation increases slightly in the future scenarios. However, maximum precipitation increases a dramatic 490% from the baseline to the 2020 scenario. The standard deviation increases by 159% from the baseline to the 2020 scenario.

5.13.4: Regression Results

The estimated regression for 1961 to 1990 is as follows:

$$\mathbf{PPT= 27.39 - 5.35D2 - 9.76D3 - 7.18D4 - 2.65D5 + 20.32D6 + 27.9D7 + 25.65D8 +}$$
$$(7.76)\quad(-1.07)\quad(-1.95)\quad(-1.44)\quad(-0.53)\quad(4.07)\quad(5.59)\quad(5.14)$$

$$\mathbf{8.46D9 +12.25D10 - 1.99D11 -0.97D12}$$
$$(1.69)\quad(2.45)\quad(-0.4)\quad(-0.19)$$

The estimated regression for 2010 to 2039 is:

$$\mathbf{PPT= 29.39 + 2.09D2 - 2.05D3 + 3.59D4 + 0.49D5 + 30D6 + 52.47D7 + 32.04D8 +}$$
$$(2.85)\quad(0.14)\quad(-0.14)\quad(0.27)\quad(0.03)\quad(2.06)\quad(3.6)\quad(2.2)$$

$$\mathbf{13.63D9 + 29.53D10 + 0.5D11 + 16.09D12}$$
$$(0.93)\quad(2.03)\quad(0.03)\quad(1.1)$$

The estimated regression for 2040 to 2069 is:

$$\mathbf{PPT} = \underset{(3.14)}{\mathbf{31.8}} - \underset{(-0.32)}{\mathbf{4.63D2}} - \underset{(-0.48)}{\mathbf{6.98D3}} + \underset{(0.36)}{\mathbf{5.24D4}} + \underset{(0.86)}{\mathbf{12.4D5}} + \underset{(1.91)}{\mathbf{27.45D6}} + \underset{(3.58)}{\mathbf{51.35D7}} + \underset{(3.23)}{\mathbf{46.31D8}} +$$

$$\underset{(1.01)}{\mathbf{14.49D9}} + \underset{(1.09)}{\mathbf{15.61D10}} - \underset{(-0.32)}{\mathbf{4.58D11}} + \underset{(0.97)}{\mathbf{13.96D12}}$$

The estimated regression for 2070 to 2099 is:

$$\mathbf{PPT} = \underset{(3.36)}{\mathbf{29.74}} - \underset{(-0.59)}{\mathbf{7.42D2}} - \underset{(-0.6)}{\mathbf{7.55D3}} + \underset{(1.04)}{\mathbf{13.02D4}} + \underset{(1.58)}{\mathbf{19.87D5}} + \underset{(3.15)}{\mathbf{39.48D6}} + \underset{(2.74)}{\mathbf{34.34D7}} + \underset{(4.59)}{\mathbf{57.47D8}}$$

$$+ \underset{(1.65)}{\mathbf{20.64D9}} + \underset{(2.91)}{\mathbf{36.46D10}} + \underset{(0.12)}{\mathbf{1.52D11}} + \underset{(0.63)}{\mathbf{7.89D12}}$$

These regressions show the likely precipitation pattern in the future scenarios and, as such, reveal that the constant stays practically the same. The regression results and 95% confidence intervals are graphed in Figures 5.13.2 to 5.13.5.

Figure 5.13.2: Results for Norman Wells (1961-1990)

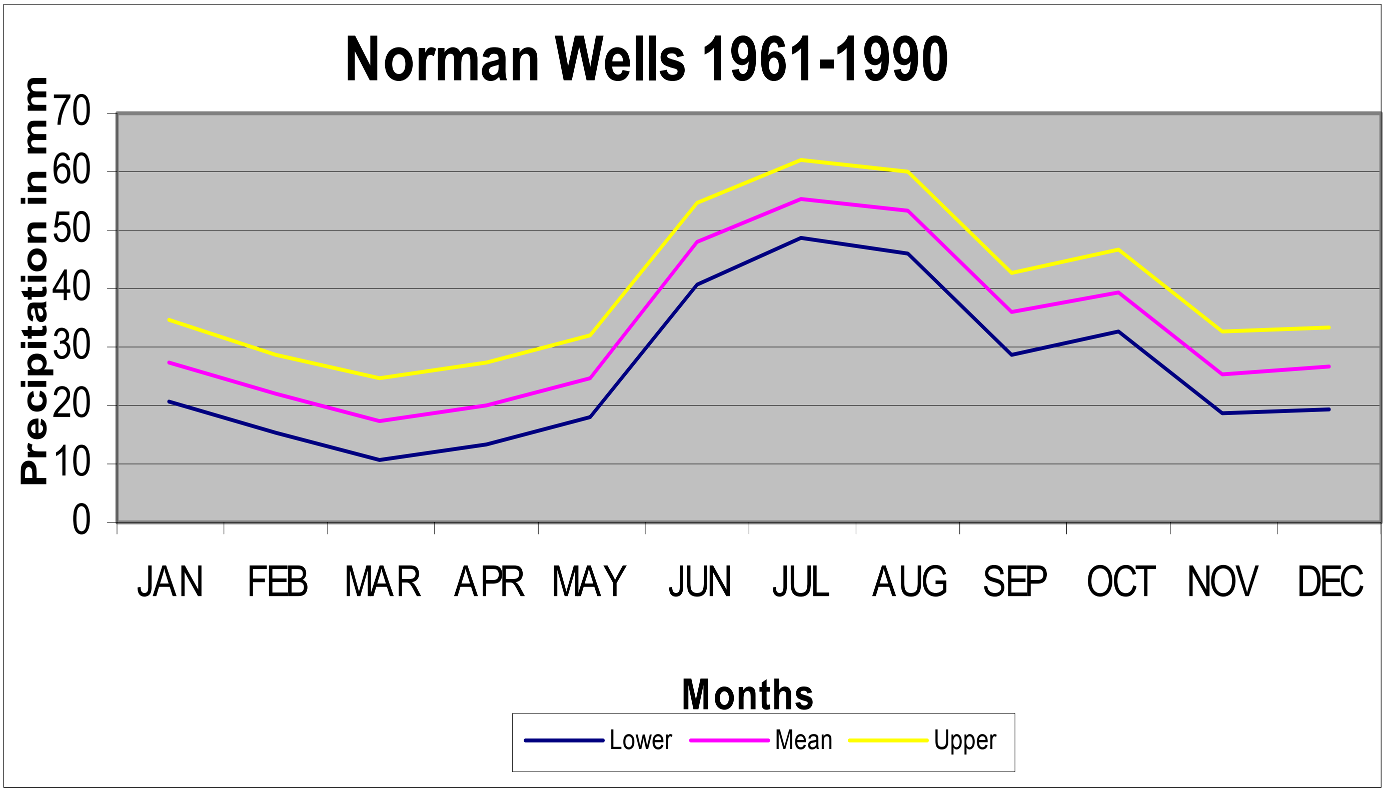


Figure 5.13.3: Results for Norman Wells (2010-2039)

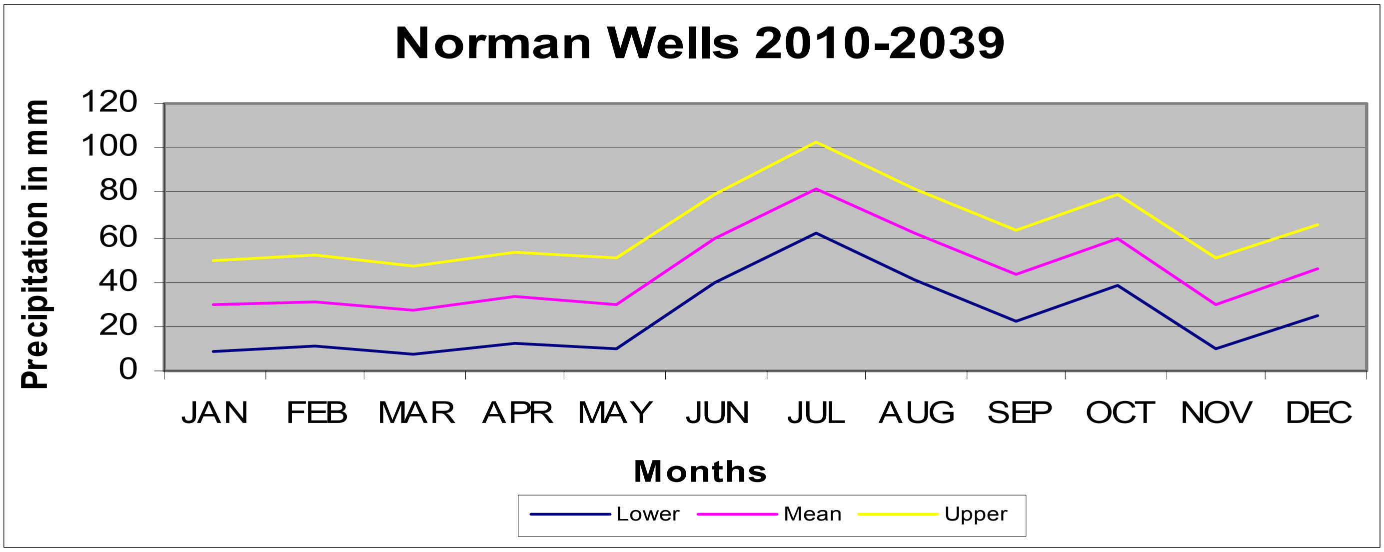


Figure 5.13.4: Results for Norman Wells (2040-2069)

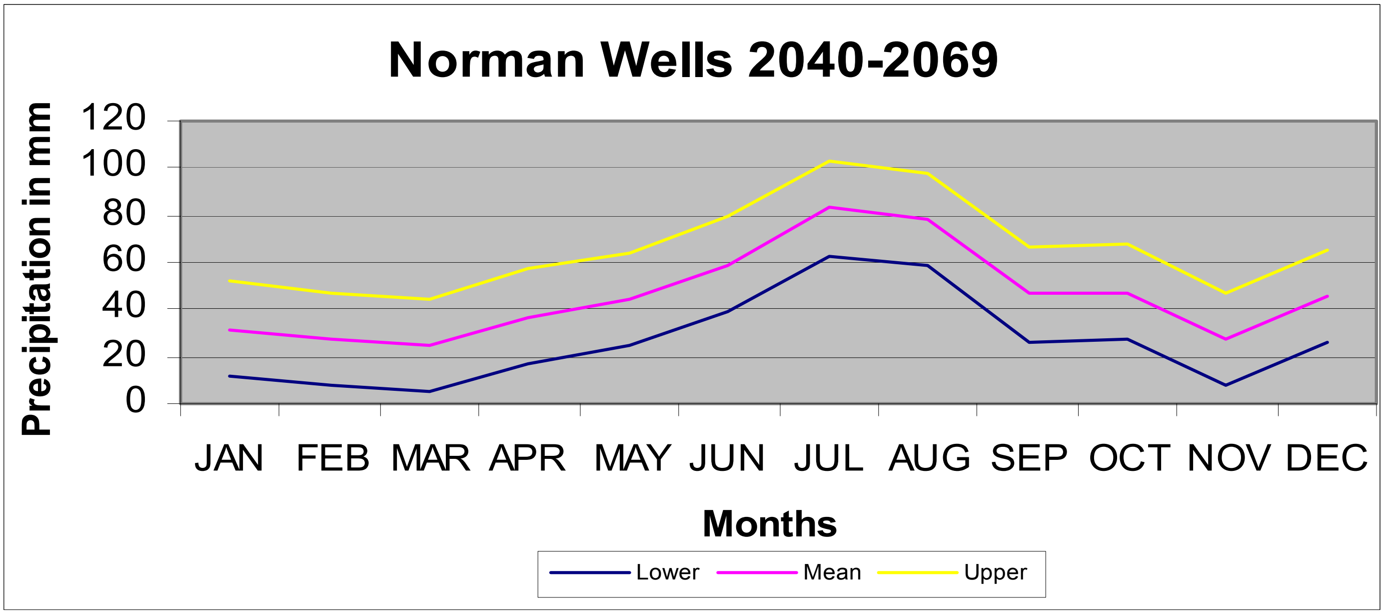
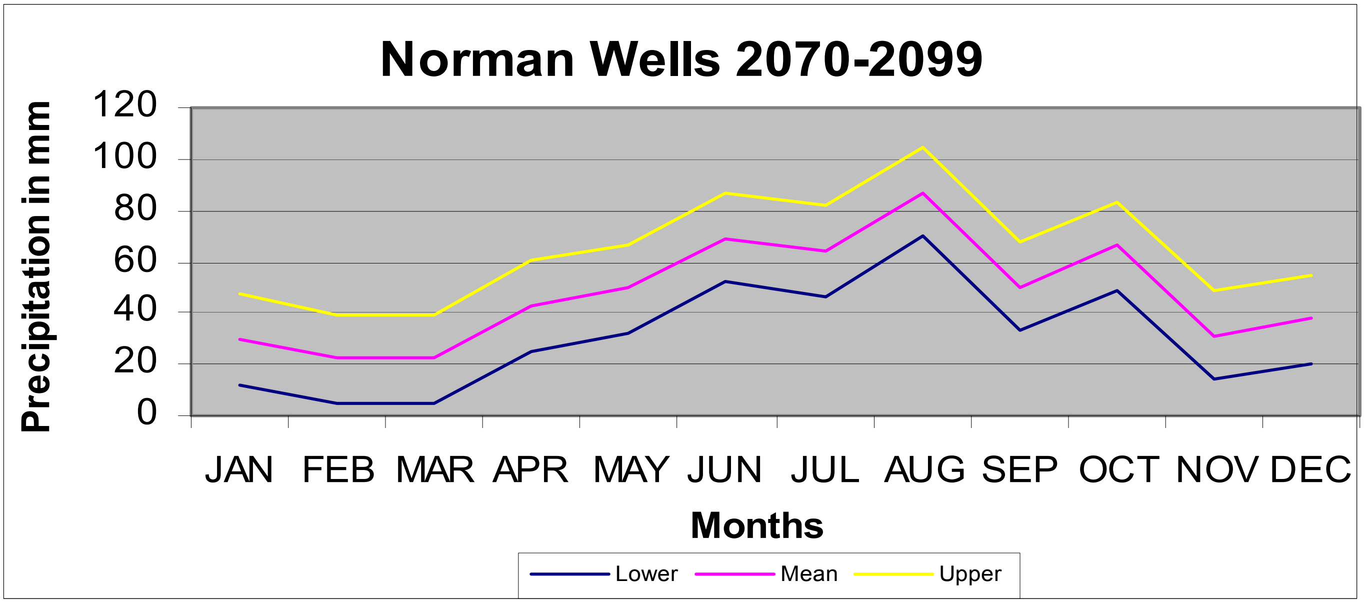


Figure 5.13.5: Results for Norman Wells (2070-2099)



Because Norman Wells is in the discontinuous permafrost zone, the main factor affecting possible climate change adaptation costs is the disappearance of the permafrost due to higher temperatures. The above graphs give an indication of the impact on precipitation. They show that the upper confidence level increases from a maximum of about 60mm in the baseline scenario to over 100mm in the future scenarios. Precipitation peaks in July and August in all scenarios.

5.13.5: Summary and Conclusions

Norman Wells will not be facing a water supply shortage as their water is supplied by the Mackenzie River, which is a large enough source for a small population. Wastewater treatment capacity also appears to be adequate as years of wastewater retention are provided by the natural wetlands.

5.14: Directions for Future Research

We have carried out a number of case studies in the various ecoclimatic zones of Canada. However, as a task for further research on drinking water supply, the coverage needs to be expanded to include more case studies in Quebec, northern Ontario, New Brunswick, Manitoba and Newfoundland. In this report we studied Montreal because of its large urban population and investment in infrastructure, but we need to include more rural locations in Quebec such as Sagard and St. Adolphe. Places like Val d'Or and Chicoutimi can be included based on geographic location.

Our Ontario case studies included Toronto and Niagara but should be extended to other communities in the northern and the eastern counties. The coverage should include a sample of First Nations Reserves in Ontario, Saskatchewan, B.C., and Quebec.

Furthermore, as indicated in Chapter 2, there is a need to carry out further experiments in downscaling using other methods mentioned in Chapter 2. With an ensemble of experiments, it might be possible to see if the various methods lead to convergent results or not. From the experiments reported here, we have excluded the implications of evaporation and evapotranspiration. That could also be investigated.
For the prairies, we need to explore the downscaled data on snow pack and ratio of rain to snow. Winter snow accumulation is a key surface water supply source for Canada, and much of the U.S. As part of the forecast of global climate warming, snow pack accumulations may vary substantially due to changes in long-term wintertime synoptic scale precipitation combined with regional warming that may increase the rain to snow ratio. Snowmelt contributes more effectively to stream flow than does rainfall. Hence conversion of winter snowfall to liquid precipitation will probably result in declining runoff. We are aware of research completed for an alpine watershed in southwestern Alberta that combined a wide area assessment of forecast changes in wintertime synoptic precipitation with the meso-scale alpine hydrometeorology to evaluate the impact(s) of

forecast climate change on mountain snow packs. The results show that modest increases in winter precipitation will not compensate for regional changes in the rain to snow ratios. The net result is a decline in winter accumulations of precipitation as snow; and we expect, a decline in surface water supply. In summer, higher volumes of water vapour in the atmosphere with a magnified greenhouse effect and warmer summer temperatures will probably result in greater occurrence and severity of thunderstorms. These storms could tax the capacity of existing storm water pipe networks; and will result in greater stress on water quality and treatment facilities, particularly in regions with combined sewer systems.

The cumulative effects of climate change on water resources may include an increase in urban floods, increasing groundwater recharge during winter, and a decline in average spring runoff. This means that there will be less riparian flow to dilute contaminants. Thus there is a need to study the effects of a change in rain to snow ratio for all prairie case studies that rely on rivers originating in the mountains. Changes in rain to snow ratios will impose additional adaptation costs. *For this reason, we believe that it would be unwise to assume that the CGCM1 projections of precipitation (which we relied on for this report) exhaust the research. On the contrary, all our Prairie and Western Canada case studies show a heavy dependence on snowpack as sources of water for rivers and basins. Therefore our results reported here should be seen only as a first experiment and that as soon as better and more reliable data on snowpack becomes available, the case studies reported here should be re-examined.* We know that vulnerability of water supply is likely to be most acute in the Prairie Provinces. Perhaps this can best be done by pooling resources and establishing research links with agencies such as the International Joint Commission and the National Water Resources Institute of Canada. The research on wastewater treatment can be expanded by gathering information on land prices for retention tanks and lagoons for major urban areas like Toronto. We also need to estimate the costs of adaptation in other parts of the country using location specific costs. In order to improve the estimates of the costs of adaptation, the costs of more efficient treatment technologies such as biological nutrient removal and UV disinfection techniques need to be included. Thus, much needs to be done to understand the costs of adaptation to climate change for water utilities, and this report should be seen as an important and, we hope, useful beginning.

5.15: Summary

1. The timing and regional patterns of precipitation will change, and more intense precipitation days are likely. General circulation models used to predict climate change suggest that a 1.5 to 4.5 degree C rise in global mean temperature would increase global mean precipitation about 3 to 15 percent. Some of this is due to the conversion of snow into precipitation.
2. Although the regional distribution is uncertain, precipitation is expected to increase in higher latitudes, particularly in winter. Potential evapotranspiration rises with air temperature. Consequently, even in areas with increased precipitation, higher rates may lead to reduced runoff, implying a possible reduction in renewable water supplies.
3. More annual runoff caused by increased precipitation is likely in the high latitudes. In contrast, some lower latitude basins may experience large reductions in runoff and increased water shortages as a result of a combination of increased evaporation and decreased precipitation. Flood frequencies are likely to increase

in many areas, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins. Floods may become less frequent in some areas.

4. The frequency and severity of droughts could increase in some areas as a result of a decrease in total rainfall and more frequent dry spells. The hydrology of arid land is particularly sensitive to climate variations. Relatively small changes in temperature and precipitation in these areas could result in large percentage changes in runoff, increasing the likelihood and severity of droughts and floods.
5. It seems reasonable to expect seasonal disruptions in the water supplies of mountainous areas if more precipitation falls as rain than snow and if the length of the snow storage season is reduced.
6. The Great Lakes impact assessments suggest global warming will result in a lowering of water supplies and lake levels and in a reduction of outflows from the Basin. Some projections show a lowering of lake levels by up to a meter or more by 2050. A one meter drop in the levels of Lakes Michigan and Huron in thirty years would have a severe impact on Lake St. Clair and Lake Erie, whose levels would drop by about 2 feet. A lake level drop of one meter in Lake Michigan could cause thousands of municipal water intakes and wells to be moved or extended.
7. We reported on several case studies of water utilities in the different ecoclimatic zones of Canada, focusing on the question of the impact of climate change on the availability of drinking water supply and capacity for treating wastewater. For Toronto, precipitation is expected to increase, and so it is unlikely that Toronto

will experience a water supply problem. The City draws its water supply from Lake Ontario, and even supposing that lake levels drop by a metre in the future time periods, intake pipes are deep enough, and far enough into the lake. Precipitation projections for Toronto are expected increase. Maximum precipitation is expected to increase from the baseline period to the 2020 period by a factor of 4. The standard deviation increases a factor of 1.7 from the baseline period to the 2020 period. We conclude that the City of Toronto will face adaptation costs for wastewater treatment from a low of $633 million to a high of $9.4 billion.

8. In the region of Niagara, our analysis shows a wet autumn, followed by a wetter winter. Wastewater treatment capacity will have to increase. We estimate the costs will be in the range of $8 million to $24 million.
9. We found that Montréal was an exception to the general eastern seaboard case studies. Montreal has a great deal of excess treatment capacity already built into the system. Based on our analysis, Montréal will not have climate change adaptation costs associated with drinking water supply and wastewater treatment. Its drinking water source is the St. Lawrence River, which of course relies on the Great Lakes for water supply.
10. In the case of Halifax, our projections show that maximum precipitation increases a dramatic 315% from the baseline period to the 2020 period. It remains 149% to 232% higher in the subsequent periods. The standard deviation also increases in the future time periods from the baseline. At present, Halifax discharges 16 mega gallons of untreated sewage per day into the Halifax Harbour. However,

new planned treatment capacity will come on stream in 2003. Based on this information and our regression analysis, it appears that Halifax will experience a wastewater treatment capacity shortfall in the future scenarios. The costs associated with climate change adaptation will include those that expand treatment capacity, and a rough estimate of this cost is $6.5 million.

11. We also did a sample of Prairie cities and towns. We considered Regina, Swift Current, Humboldt, and Lethbridge. For all these prairie studies there is a need to study the effects of a change in rain to snow ratio for all prairie settlements that rely on rivers originating in the mountains. Changes in rain to snow ratios will impose additional adaptation costs. We know that vulnerability of water supply is likely to most acute in the Prairie Provinces.
12. Our West coast case studies included Prince George, and Penticton. Our analysis indicates that existing wastewater treatment capacity in Prince George seems adequate for the near future. Therefore, based on this analysis, there will be no adaptation costs associated with wastewater treatment due to climate change.
13. However in the case of Penticton, we find that the city will face a wastewater treatment capacity shortfall. The costs associated with climate change adaptation range from $15 million to $28.5 million.
14. In Northern Canada, we included Yellowknife and Norman Wells. Because Yellowknife draws its water directly from the Yellowknife river and the pipes are buried below the permafrost, there does not appear to be a water supply problem, nor a cost associated with damaged pipes due to disappearing permafrost. For wastewater treatment, Yellowknife has 10 to 12 months of wastewater storage, so

an increase in precipitation is not expected to exceed treatment capacity.

15. The case of Norman Wells is more complicated. Because Norman Wells is in the discontinuous permafrost zone, the main factor affecting possible climate change adaptation costs is the disappearance of the permafrost due to higher temperatures. However, Norman Wells will not be facing a water supply shortage as its water is supplied by the Mackenzie River, which is a large enough source for a small population. Wastewater treatment capacity also appears to be adequate as years of wastewater retention are provided by the natural wetlands.

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Personal communications with the cities of Halifax, Regina, Humboldt, Lethbridge, Yellowknife, Norman Wells, Prince George, Penticton and the Regional Municipality of Niagara.