Climate Change and Winter Road Maintenance:
Planning for Change in the City of Prince George, British Columbia

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.
I understand that my thesis may be made electronically available to the public.

Abstract

Throughout Canada, significant resources are dedicated to winter road maintenance (WRM) activities. While changes in technology and materials are affecting WRM decisions, climate variability and change will also be of considerable importance in long-term decision making. This research explores how anticipated changes in winter weather may affect WRM activities in Prince George, British Columbia. The goal of this thesis is to contribute to our understanding of adaptation planning in the municipal transportation sector, and in particular to explore the ways in which empirical estimates of change may affect adaptation decisions. The link between weather and snow and ice control are analyzed using WRM data made available by the City of Prince George and meteorological observations from Environment Canada. The approach taken to document the association between winter weather and WRM expenditures is a winter severity index. Findings show that, notwithstanding changes in maintenance strategies, much of the historic variability in WRM can be attributed to weather. This winter severity index was applied to simulated climate data based on 65 global climate models from the Canadian Climate Change Scenarios Network. Based on the mid-range of the 65 projections, climate models indicate that the Prince George Region is expected to be 1.5°C to 2.4°C degrees warmer and have 3.7% to 10.6% more precipitation. The expected net effect for winter maintenance is reductions in expenditures by 15.3% to 22.7% by the 2050s. The empirical results of this thesis were presented to decision-makers in the City of Prince George using a semi-structured interview process to establish the extent to which site-specific climate change impact assessments could help to overcome the barrier of lack of local knowledge in climate change adaptation planning. Results indicate that the empirical analysis of projected changes in the demand for WRM activities led to the development of new knowledge; however, the degree to which this knowledge creates climate-change readiness remains unclear. Overall, the semi-structured interview process highlighted a number of barriers and enablers of adaptation planning action at the municipal level. Institutional inertial, path dependency, the role of governance structure, political timelines, resident influence, and uncertainty surrounding weather and climate information were all identified as being influential.

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1 Introduction

1.1 Research context

Human-induced global climate change is one of the greatest challenges facing society today. Greenhouse gas (GHG) forcing is likely to contribute to a variety of changes in the biophysical system resulting in plethora of impacts on communities globally, including impacts on health, food supply and infrastructure. While there is a clear consensus in the scientific community that there is a need for adaptations to take place, the processes through which adaptations are implemented are not well understood, especially in the transportation sector.

Canada's transportation sector is particularly vulnerable to the impacts of climate change. With over $150 billion in infrastructure assets, it is an economically critical sector. All amenities designed for the movement of people and resources, including railways, airports, ports, roads and bridges are considered transportation infrastructure (NRCan, 2007). Many of these assets and the ways in which they are built, maintained, and serviced will be affected by climate change (NRC, 2008). It is therefore critical to study the impacts of future climate change when planning transportation infrastructure and future services (Canadian Council of Professional Engineers, 2008). As such, policies will need to address how transportation infrastructure is designed, built and maintained because there are substantial costs that could be accrued through improper design and management of these assets (Hambly *et al.,* 2013; Koetse & Rietveld, 2009; Mills *et al.,* 2009; NRC, 2008; TAC, 2013).

While it has been established that there is a need to study the impacts of climate change on transportation infrastructure and services, concrete adaptations in this sector remain limited (Koetse & Rietveld, 2009). There is a variety of factors that are impeding the process of adaptation planning and the investment in planned adaptations in the transportation sector. Firstly, climate change impacts and adaptions research have not been a high priority for many levels of government in Canada (Picketts *et al.,* 2014; Burch, 2010). Secondly, with an aging infrastructure and increased growth, many Canadian communities are facing infrastructure deficits. As such, local governments are cautious to pursue adaptation initiatives that may result in short-term increased expenditures (TAC, 2013). Thirdly, transportation design, construction, and maintenance standards vary over time, but the protocols put in place to facilitate the decision-making frameworks that allow for changes in standards require data with high levels of certainty. As of yet, climate models have been unable to remove the uncertainty, especially at the local scale to a degree that would enable possible changes in standards (Jacobs *et al.,* 2013). As such, more research is needed that can work towards detailing the impacts of climate change in the transportation sector with relatively high levels of specificity that would allow for the implementation of planned adaptations in the transportation sector.

The City of Prince George presents an opportunity to contribute to this emerging body of research by detailing the impacts of climate change in the transportation sector. The City of Prince George is located in interior British Columbia and is a key road network center for the province. This network is, however, sensitive to weather and to future environmental change. In the future, precipitation in the City of Prince George is projected to increase by 3% to 10%, most of which is expected to occur during the winter months (Picketts *et al.,* 2009). With a changing climate, forecasting future winter road maintenance (WRM) needs and operational challenges becomes more difficult. These potential effects of climate change on Prince George's 630 km of roads include more frequent freeze-thaw cycles, icy roads, safety concerns, more salt use, pavement surface deterioration, and insufficient storage capacity for snow disposal sites. These could require improvements to road design and construction, as well as to ice and snow management.

The focus of this thesis is on the implications of climate change for WRM in the City of Prince George. Canadian road authorities have direct control on the methods and practices used for snow and ice control, and due to high expenditures on these activities, this is a topic of importance for virtually all Canadian municipalities, provinces and territories. Each year, approximately $1.5 billion is spent on WRM by road authorities in Canada (Suggett *et al.,* 2007), and in 2011 the City of Prince George spent $6.8 million (CAD) on such activities (CPG, 2012). Due to the high costs of WRM, assessing the impacts of climate change on transportation is a practical priority. From an academic perspective, the science and management of snow and ice control is evolving quickly (Suggett *et al.,* 2007), and changes in practices are being made continually in order to improve the efficiency and effectiveness of treatment and also reduce environmental impacts. Investigating long-term trends in a planning area that has a history of changes in practices provides a unique opportunity for researching climate change adaptation as it co-evolves with other intentional changes in practices.

The City of Prince George is not new to climate change planning research and initiatives. Since 2001, the City of Prince George has been proactive in addressing the need for adaptation to climate change. The City has partnered with the Pacific Climate Impacts Consortium (PCIC) and the Pacific Institute for Climate Solutions (PICS) to develop reports on past trends and future projections for Prince George, including consideration of municipal adaptation options. Prince George has also undergone an intensive community-based assessment (CBA) of climate change impacts that identified key vulnerabilities. After forestry and floodplain management, transportation was identified as a top priority with WRM emerging as a key concern in need of further attention (Picketts, 2013; Picketts, 2009).

Further investigation of the potential impacts of climate change on the transportation sector in the City of Prince George were explored through follow-up research that was completed in 2012. This research, led by Dr. Jean Andrey, investigated the historic relationship between WRM and weather as well as the historical relationship between road safety and weather. Work was then completed to project the future impacts and vulnerabilities for WRM and road safety in the City of Prince George. While these reports provided numerous insights into the current vulnerabilities and the potential impacts of climate change, questions remained as to the value of such sector-specific vulnerability assessments and the role they play in anticipatory adaptations at the municipal level. As such, the purpose of this thesis is to expand on the previously completed work, using new methods and a wider range of climate models, with the aim to explore the projected impact of climate change on WRM and how these site-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate change adaptation planning.

1.2 Research goal and objectives

The goal of this thesis is to contribute to our understanding of adaptation planning in the municipal transportation sector by exploring the ways in which empirical estimates of change affect how adaptation decisions would be made. This thesis uses a case study methodology and aims to achieve this goal through a combination of quantitative and qualitative methods. There are five research objectives:

1) The first objective is to develop a winter severity index (WSI) that explains the historical temporal variation in WRM expenditures using weather data as the explanatory variables.
2) The second objective is to compare two methods, the model output method and the change field method (CFM), of obtaining and using modeled climate data for climate change impact studies.
3) The third objective of this thesis is to apply this WSI to modeled climate data to determine the projected changes to WRM expenditures in the City of Prince George.
4) The fourth objective of this thesis is to explore how site-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate change adaptation planning through the use of semi-structured interviews.
5) The semi-structured interviews are also intended to explore whether decision makers are more likely to support climate change adaptation initiatives that involve the expenditure of resources rather than support those that involve the scaling back of resources.

The scholarly benefit of this research is its contribution to an understanding of the processes by which adaptation decisions are made and the degree to which local, site-specific impact assessments are beneficial for adaptation planning. The practical benefit of this research is that it is intended to increase the level of climate-change readiness in

Prince George and potentially inform decision making by focusing specifically on the issues of snow and ice control.

1.3 Thesis outline

This thesis comprises seven chapters. While a traditional thesis has separate chapters for methods and results, this thesis combines methods and results in chapters that are organized around the various objectives. More specifically, chapter two provides research context, and chapter three, information on the study area. Chapter four addresses the first objective, the development of the WSI. Chapter five addresses objectives two and three, the projections of climate change for WRM. Objectives five and six are achieved through a semi-structured interview process, and the results thereof are presented in chapter six. The content of the chapters is summarized below.

Chapter two of this thesis provides a review of the pertinent literature in the fields of climate change, climate change adaptation planning, and their relationship with the transportation sector. This chapter begins with an overview of the physical and human dimensions of global environmental change and is followed by a review of the possible responses: mitigation and adaptation. The focus of this chapter then evolves to a more in-depth discussion of climate change adaptation literature including the characterizations of adaptions and barriers to adaptation planning. There is then a detailed review of climate change and transportation in Canada with a focus on impacts and adaptation strategies.

Chapter three offers an overview of the value of case study methodology for researching adaptation planning and planned adaptations. This is followed by an overview of the study area, the City of Prince George. This includes a brief description of the location, geography, climate and economic composure of the City of Prince George. This is followed by a synopsis of the history of climate change planning and planned adaptations in the City of Prince George. The last section of this chapter is an overview of current WRM practices in the City of Prince George.

Chapter four involves an in-depth exploration of ways in which the City of Prince George currently handles snow and ice control in relation to winter weather. There is a review of possible techniques than can be employed to understand current practices and anticipate future needs in WRM. There is then a detailed discussion of the development of a WSI, which is a tool that can be used to benchmark WRM practices. The data requirements, steps taken in the development of the WSI, and associated empirical findings are then outlined.

Chapter five presents the methods and results of the climate change projection for WRM. In order to assess the impacts of climate change on WRM in the City of Prince George, this study applies the WSI to current and future climate simulations. By assessing the percent change in the WSI between the simulated baseline data and simulated future data for the mid-2050s, an estimate of future change is established. This chapter compares two methods of obtaining and applying climate projection data: model output method, and the CFM. Both of these techniques, their data requirements, and subsequent empirical results are presented and compared.

Chapter six explores the ways in which the climate change projections and current analysis of WRM activities are useful for decision makers in the City of Prince George. To explore how and in what way(s) site-specific Climate Change Impacts Adaptation and Vulnerability (CCIAV) assessments influence decisions making, semi-structured interviews were conducted with seven individuals who are involved with WRM operations and municipal planning in the City of Prince George. This chapter begins with an overview of the method of data collection including the interview script, interview recruitment and interview process. This is followed by a summary of the data analysis techniques employed, namely the thematic analysis. Interview findings are then presented by five themes followed by a synthesis section that aims to answer the objectives of this thesis. This chapter concludes with a discussion of the limitations and opportunities for future work.

The final chapter of this thesis, chapter seven, provides a synopsis of the key findings from chapters four, five, and six. This is followed by a discussion of the broader implications of these findings for both the scientific community and Canadian road authorities.

The appendices contain a copy of the information letter sent to potential research participants, a blank consent form, a list of the interview questions, and the one-page summary of the empirical analysis that was used as a discussion point during the semi-structured interviews.

In summary, this thesis offers:

- a new method for developing WSI models;
- an empirical estimate of projected impacts of climate change on WRM expenditures in the City of Prince George;
- and an exploration of the ways in which adaptation decisions are made with respect to site-specific empirical estimates of change for one aspect of the transportation sector.

2 Literature review

2.1 Physical dimensions of global environmental change

The past 25 years has realized a considerable amount of research devoted to understanding and quantifying global climate change. The international scientific community has reached agreement that, over the past century, an unprecedented rise in average global temperatures has occurred (IPCC, 2013). The rise in mean global temperature corresponds to increases in fossil fuel usage that has occurred since the industrial revolution, and there is a broad consensus that this warming trend has been caused by anthropogenic GHG emissions (IPCC, 2013; Hegerl *et al.,* 2007; Solomon *et al.,* 2007). Global mean surface temperatures have increased 0.85°C (±0.25°C) since 1880, and over the second half of the past century there has been a decadal increase in global mean surface temperatures of 0.12°C (±0.03°C) (IPCC, 2013). This rate of warming is nearly double what was seen in the first half of the 20th century. It is important to note that there is spatial heterogeneity in the amount of warming with the highest amounts of warming occurring in high-latitude areas, including much of Canada (IPCC, 2013).

The complexity of global atmospheric circulation and natural variability, coupled with the inability to predict future GHG and aerosol emissions, make global climate modeling incredibly complicated. There is uncertainty throughout all stages of the modeling process, but this uncertainty is not related to whether or not global mean temperatures are rising (Palmer *et al.,* 2005; Selten *et al.,* 2004; Solomon *et al.,* 2007). Instead, this uncertainty is with regards to the accuracy of timings and magnitudes of future changes (Solomon *et al.,* 2007; Murphy *et al.,* 2004). Identifying future levels of carbon dioxide and aerosol emissions is difficult, and understanding their impacts on radiative forcing is still developing (Deser *et al.,* 2012; IPCC, 2013). Additionally, there are sources of radiative forcing other than emissions, such as land use change and volcanic activity that are only recently being incorporated into global climate models (Deser *et al.,* 2012). Furthermore, aerosols and their offsetting effect on radiative forcing contributes to a high level of uncertainty (IPCC, 2013). Despite this complexity, improved computing power and more accurate computer simulations are continually reducing the uncertainty and improving the understanding of complex climate systems and the physical processes that drive them.

Global climate change will have a myriad of impacts on a variety of physical processes, some of which will have positive feedbacks on general atmospheric circulation and, in turn, global climate change. Climate change will affect biogeochemical cycles, the acidification of oceans, and thermohaline circulation (IPCC, 2013; Meehl *et al.,* 2007). Furthermore, changes in the cryosphere such as sea-ice extent and permafrost depletion will exacerbate the negative impacts of climate change. Reduced albedo from retreating sea ice and glaciers will result in higher levels of absorbed solar radiation. Melting permafrost will result in methane emissions, also further exacerbating climate change and resulting in increased global mean surface temperatures (IPCC, 2013; Meehl *et al.,* 2007).

While understanding the physical processes that underlie global climate models is of utmost importance, decision makers in a multitude of contexts rely on more tangible descriptions of climate change (Weber, 2006). Change in global mean surface temperature can be a deceptive descriptor because it does not encompass variability in daily and seasonal weather that will be observed and experienced by individuals and communities (Weber, 2006). Projections of future climates indicate that there will be changes in mean and extreme temperatures; changes in precipitation amounts, frequency, and intensity; changes in sea levels and changes in the frequency and severity of storm surges and flooding. All of these changes in weather variability and extremes will impact natural, built, and social systems.

2.2 Human dimensions of global environmental change

While the science and accuracy of global climate models has steadily improved, so too has the scientific understanding of the impacts and human dimensions of climate change. Analysis of local and regional impacts of climate change is highly dependent on atmospheric and oceanic climate models, which specify the ways in which local climatic factors and sea levels will change. It should be noted that regional climate models hold greater uncertainty than global climate models but are continually improving (IPCC-TGICA, 2007). Notwithstanding our partial knowledge emerging from modeling efforts, records of observed climate change provide reliable indications of where changes in are likely to occur (Murdock & Spittlehouse, 2011). Based on observed changes, and validated by climate models, the most warming is expected to occur over land, with northern latitudes being most affected (Meehl *et al.,* 2007). This is particularly relevant for Canada as the Arctic and sub-Arctic regions are at increased risk of experiencing the negative impacts of climate change.

As the literature on physical processes driving climate change has evolved, so too has the field of climate change impacts and vulnerability on natural, built and social systems. A variety of journals has emerged which are dedicated to disseminating climate change research. *Climatic Change, Mitigation and Adaptation Strategies to Global Change, Climate Policy, Global Environmental Change, Global Change Biology, Regional Environmental Change,* and *Nature Climate Change* are examples of journals that have risen to the forefront of climate change research. Tourism (Scott, 2011; Scott & Becken, 2010), agriculture (Piao *et al.,* 2010; Reidsma *et al.,* 2010; Seo, 2010), and construction (Hallegatte *et al.,* 2011; Measham *et al.,* 2011; Hayhoe *et al.,* 2010) are some of the sectors have begun to receive attention, but the most of climate change impacts, vulnerability and adaptation research has been focused on human settlements, with much attention on developing countries and regions (IPCC, 2014; Wilbanks *et al.,* 2007). While sector-specific studies have been popular, there has also been a focus in the scientific literature on groups of people who are particularly vulnerable, regardless of geographic location. Within communities globally, but especially in developing countries, the poor, women, children, and the elderly are more vulnerable to global environmental change (IPCC, 2014; Wilbanks *et al.,* 2007).

While much of the focus has been on developing countries, the impacts of climate change for natural, built and social systems in all regions are vast. Globally, coastal regions are at risk because of rising sea levels and the likelihood of more frequent and severe storms.

Islands, especially Small Island Developing States (SIDS), will be affected by drought and less reliable water supplies (IPCC, 2014). Changes in air and water quality will have an impact on food systems, as drought will be particularly problematic for arid and semi-arid regions. The increase in frequency and intensity of droughts will affect not only islands and SIDS, but also many areas in the Canadian Prairies. Changes in mean and extreme temperatures will also have impacts on settlements, particularly on health and infrastructure design standards that are traditionally based on a current range of climatic conditions (IPCC, 2014; Confalonieri *et al.,* 2007). All of these effects of climate change have profound implications for the global economy. Internationally, institutions are beginning to understand the importance of acting on climate change and there are a variety of initiatives that are beginning to gain traction (IPCC, 2014; Okereke *et al.,* 2009).

2.3 Responses to global environmental change

There are two broad ways that individuals and institutions respond to the challenges associated with climate change: mitigation or adaptation (Klein *et al.,* 2005). Policies related to mitigation and adaptations are often completed independent of one another (Füssel & Klein 2006). Even in the Intergovernmental Panel on Climate Change (IPCC) reports, mitigation is addressed by Working Group III, whereas adaptation is addressed by Working Group II (Füssel & Klein 2006). Historically, mitigation, which aims to reduce GHG emissions, has been the focus of climate change policy such as the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) treaty (Klein *et al.,* 2005). Mitigation is completed through measures such as technological advances in either the supply or demand for energy, or through the enhancement of carbon sinks. Supply-side measures include initiatives such as wind or solar power instead of fossil fuel based power. Demand-side technological mitigation strategies include, for example, improved fuel efficiency of vehicles and the design of infrastructure that reduces idling times and traffic delays. Other demand-side mitigation strategies involve behavioural changes such as taking part in active transportation or using public transit.

There has long been a policy focus on mitigation. This is in part because mitigation has global impacts and is easier to quantify than adaptation (Klein *et al.,* 2005). Additionally, a focus on mitigation ensures that those creating the emissions are the ones who are required to pay for reductions (Füssel & Klein 2006). However, the benefits of mitigation take years or decades to manifest, while the benefits from adaptations can be experienced on shorter timescales and at local or regional levels (Füssel & Klein 2006). As such, 25 years after the initiation of the UNFCCC treaty, there has been limited progress towards reducing GHG emissions. Furthermore, even if GHG emissions were to be drastically cut in the near future, climate change would not be prevented from happening (Warren, 2004). According to the Working Group III of the IPCC (Metz *et al.,* 2007) the world is already committed to an amount of climate change, but mitigation efforts can still be employed to help reduce even greater changes on longer time scales (Metz *et al.,* 2007; Klein *et al.,* 2005).

While mitigation efforts have not been as successful as some have hoped, the second way climate change can be tackled is through adaptation; a process by which nations, communities and individuals improve their ability to cope with the negative effects of climate change (UNFCCC, 2011; Klein *et al.,* 2005). If mitigation is seen as treating the cause of climate change, then adaptation can be seen as treating or preventing the symptoms. Similar to mitigation, adaptation can be achieved through technological advances and behavioural changes. Using the transportation sector as an example, improved road surface materials can be used to improve tracking in inclement weather. Behavioural changes, such as working from home during inclement weather, are adaptations that individuals already undertake. Other strategies could include changes in budgeting, financing, and insurance for transportation service (UNFCCC, 2011). While the aforementioned strategies aim to minimize the adverse effects of climate change, it is also possible to exploit possible opportunities that may arise (Biesbroek *et al.,* 2010).

Adaptation and mitigation are just two of the socio-economic processes that influence the impacts, or effects, of global climatic change. **Figure 1**, from the IPCC fifth assessment report, highlights other core concepts that have an influence on climate change impacts.

As defined by the IPCC (AR5), impacts are the effect or outcome that result from climatic stimuli. Impacts can refer to "effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system" (IPCC, 2014).

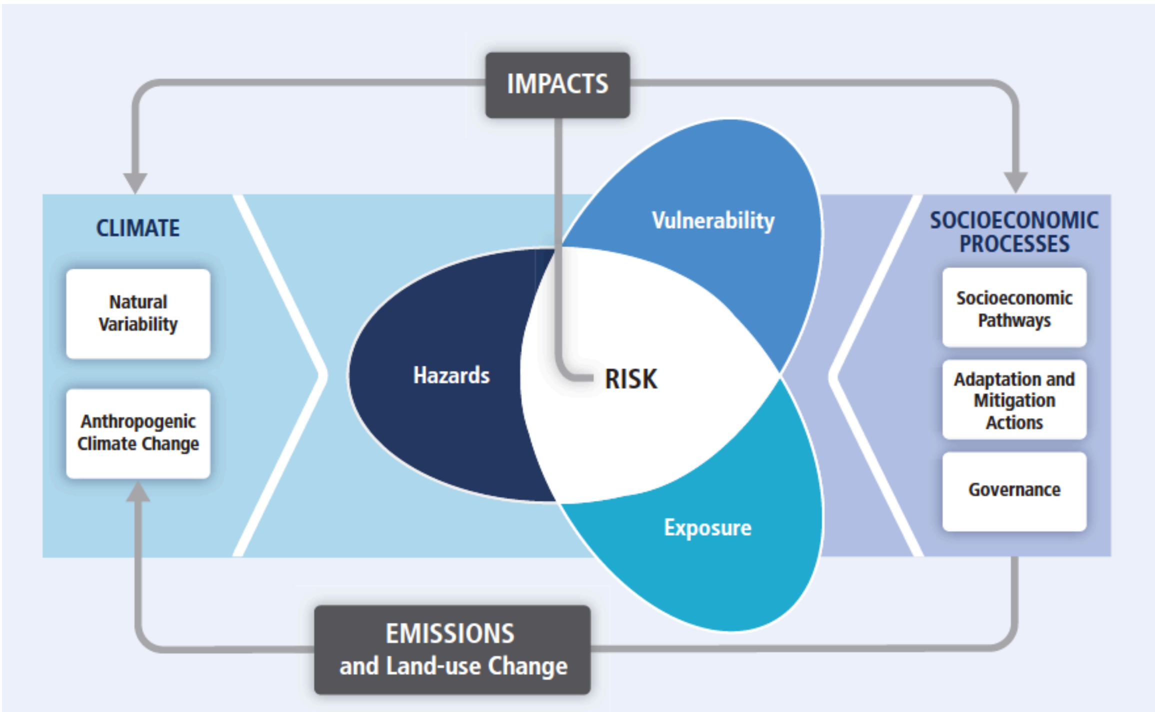

Figure 1: Core concepts of climate change impacts, vulnerability and adaptation research (reprinted from IPCC, 2014)

Both biophysical processes and socioeconomic processes influence the potential impacts that could be felt in a community. It should be noted that biophysical process are a function not only of anthropogenic climate change, but are can also result of natural variability. **Box 1**, below, outlines the definitions of other core concepts that will be used throughout this thesis. These definitions are from working group two of the IPCC fifth assessment report (IPCC, 2014).

Box 1. Key terms as defined by the IPCC (2014)

*"**Hazard:** The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.*

***Exposure:** The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.*

***Vulnerability:** The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.*

***Risk:** The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard."*

These concepts, their definitions and the relationship between these concepts affects the approaches adopted for vulnerability and adaptations research and their subsequent outcomes (O'Brien *et al.,* 2007). The concept of vulnerability is particularly relevant as there have been recent efforts to distinguish the ways in which this term is understood and used in the literature (O'Brien *et al.,* 2007). O'Brien *et al.* (2007) distinguishes between two frameworks for interpreting vulnerability as seen in **Figure 2**. The first is the 'outcome vulnerability' framework and the second is a 'contextual vulnerability' framework. Each of these frameworks results in a different type of knowledge and each framework is used by different types of scholars. Outcome vulnerability is a scientific framing of the concept whereby vulnerability is the outcome or endpoint. It is a linear process where the impact of climate change on an exposure unit can be measured or quantified (O'Brien *et al.,* 2007). Conversely, contextual vulnerability can be seen as a cyclical interaction between biophysical, social, economic and political influences that acknowledges the complex roles of different processes. With a contextual vulnerability depiction, vulnerability is the starting point (O'Brien *et al.,* 2007). These distinctions are directly linked with the two main types of adaptation research, top-down and bottom-up.

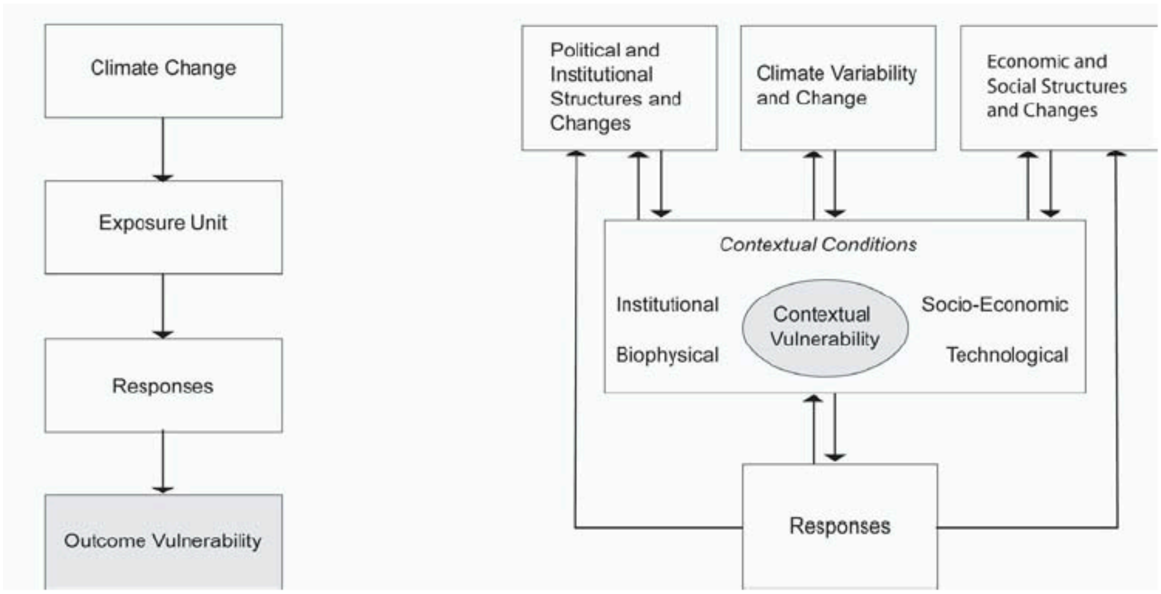

Figure 2: Interpretation of vulnerability frameworks (reprinted from O'Brien *et al.,* 2007)

2.4 Adaptation to climate change

Broadly, adaptations are ''adjustments in ecological-socio-economic systems in response to actual or expected climatic stimuli, their effects or impacts.'' (Smit *et al.,* 2000, p 225). The IPCC adds to this definition by highlighting that adaptions can take place both to reduce risk and to exploit possible benefits. According to the IPCC fifth assessment report (IPCC, 2014), adaptation is "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects" (IPCC, 2014).

Adaptations are considered for three broad categories of climatic conditions: 1) global climate change that results in long-term trends (e.g., warming, sea-level rise); 2) variability about the norms that results in shifts and/or changes in frequency and severity of climatic conditions (including anomalies); 3) extreme events such as storms, floods or droughts. Adaptation action may be motivated by various factors including safety and economic concerns (Duerden, 2004; Ford & Smit, 2004; Adger *et al.,* 2005). As Adger *et al*. (2005) indicates, sometimes it is difficult to establish whether adaptations are being triggered by climate change, or by other economic or social events (Adger *et al.,* 2005).

Adaptation literature is generally focused on four main themes: characterizing adaptations, assessing adaptations, impact assessments, and case studies of the adaptation planning process. Evaluating adaptations is essential for assessing the impacts of climate change and for developing policies to address these impacts (Smit *et al.,* 2000). There are many other benefits of adaptations; for example, they can help improve the current adaptive capacity of communities and reduce current vulnerabilities to stimuli. In addition to improving the ability to deal with climatic stimuli, systems need to be able to adapt to and handle current biophysical, social, and economic situations to which there are existing vulnerabilities. Adaptation research can help to identify these current vulnerabilities and help to towards creating more resilient communities.

2.4.1 Characterizing adaptations

Adaptation literature is replete with frameworks and typologies of the characterization of adaptation strategies that have been developed over the last twenty years. Early strategies have generally characterized adaptations based on when they occur in relation to the stimulus, stimulus being the climatic change, and the relation being either before or after the climate change has occurred (i.e., reactive or anticipatory adaptations) (Smit *et al.,* 2000). The greatest interest lies in anticipatory adaptation initiatives because these help to avoid and reduce negative impacts and allow for the possibility of exploiting opportunities (Smit *et al.,* 2000; Burton *et al.,* 1993; Bijlsma *et al.,* 1996). However, adaptation strategies also can be characterized based on its *relationship to hazards* (such as preventing, tolerating, or spreading the loss) or based on *when* they occur in relation to the stimulus (long range, tactical, contingency) (Stakhiv. 1993). Others (Carter *et al.,* 1994) characterize adaptations by *type* of adaptation measure (structural, financial, education *etc.).* As the field of climate change adaptation planning has progressed, frameworks for characterizing adaptation are becoming less simplified and are using multiple criteria for characterizing adaptations.

Literature in the last two decades has divided the field into two key types of adaptations: top-down or bottom-up (Carter *et al.,* 2007; Cohen & Waddell, 2009; Dessai & Hulme, 2004; Smit & Wandel, 2006; Wall *et al.,* 2007; Warren and Barrow, 2004). The top-down approach is the most common and is the approach that has been endorsed by the IPCC and focuses on the impacts of adaptation (Dessai & Hulme, 2004; Carter *et al.,* 2007). Top-down approaches are tied to the concept of 'outcome vulnerability' (O'Brien *et al.,* 2007) and focus on the use of climate models that are then applied to an exposure unit such as crop yields or insurance claims. These scenarios are usually limited to a few climate variables (*e.g.,* temperature, precipitation, wind) and therefore provide a somewhat simplified projection of impacts (van Aalst *et al.,* 2008). The top-down adaptation approach often focuses on physical vulnerabilities to structures and systems such as watersheds, floodplains or transportation networks (Dessai & Hulme, 2004). This type of analysis focuses on the local impacts on a sector or area to medium-long range climate scenarios. A top-down approach is 'predictive' in nature, lending itself to use in long-term adaptation-planning policy decisions, such as for infrastructure such as bridges that has longer lifespans (Dessai and Hulme, 2004). In the transportation literature, most of the adaptation research uses a top-down approach (TRB, 2008; van Aalst *et al.,* 2008). While these top-down approaches have contributed to a better understanding of potential impacts of climate change, and at times provided adaptation options, these studies have failed to explore how these projections and their respective adaptation options would be influenced by the economic, social and political situation in that community (van Aalst *et al.,* 2008).

In response to the limitations of a top-down approach, and in an effort to better understand the complicating factors that influence the ways in which adaptation decision are made, there was a transition towards a bottom-up approach. A bottom-up approach starts with an assessment of current vulnerabilities of a region or sector to climate factors along with an exploration of the economic, social and political landscape and then looks at the potential impacts of climate change (van Aalst *et al.,* 2008). In linking with the concept of vulnerability, the bottom-up approach to adaptation research explores 'contextual vulnerability' (O'Brien *et al.,* 2007), taking into account the contextual complexity of the social, economic, physical and political landscape. While both the top-down and bottom-up approaches to adaptation research lead to the development of new knowledge, they encompass fundamentally different methods, perspectives and outcomes.

Building on previous literature, the IPCC reports are now showing a trend towards interdisciplinary vulnerability assessments that use both top-down, or scenario-driven assessment and bottom-up, or contextual assessment approaches to climate change adaptation research (IPCC, 2014). Most recently, assessments have integrated these approaches. Also known as a hybrid approach (Carter *et al.,* 2007; Cohen & Waddell, 2009), these are second-generation studies that blend the top-down and bottom-up approaches to adaptation planning research. With increasing frequency these two approaches are being blended together, especially because there is now a common requirement for stakeholder engagement in community adaptation planning (Cohen & Waddell, 2009).

2.4.2 Barriers to adaptation planning

Assessing adaptation successes and challenges is important for understanding the barriers that have impeded adaptation planning and implementation. Studies suggest that adaptations are constrained by social, economic and technological conditions (Smit *et al.,* 2000). As such, it is important to identify which of these conditions are impeding adaptations. Adaptations are completed in response to multiple stimuli, not just climatic stimuli, and these adaptations are often specific to each situation or system (Smit *et al.,* 2000). In a Canadian context, the technological capacity is available in many Canadian communities; but the social, political and economic conditions have a greater influence whether adaptations occur or not. The five key barriers that have been cited in the literature are: 1) path dependency and inertia (institutions are invested and comfortable with the processes on which they currently depend) (Peters *et al.,* 2013; Burch, 2010); 2) political leadership (Burch, 2010; Wheeler 2008; Lee & Perl, 2003); 3) a lack of champions to promote climate change planning and initiatives (Picketts, 2013; Burch, 2010); 4) financial constraints (Schipper & Pelling, 2006; Burch, 2010); and 5) gaps in local knowledge of impacts, which are critical for informed decision-making and identifying feasible adaptations (Picketts, 2013; Burch, 2010).

Financial constraints are perhaps the most cited barrier to adaptation planning (IPCC, 2014; Moser & Ekstrom, 2010; Ford *et al.,* 2011; Schipper & Pelling, 2006; Burch, 2010). The IPCC fourth assessment report defines the costs of adaptation as "the costs of planning, preparing for, facilitating, and implementing adaptation measures, including transition costs" and the definition for the benefits of adaptation is "the avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures" (Adger *et al.,* 2007). If the monetary costs of adaptation are much greater than the risk they mitigate, that can possibly lead to maladaptation (UNFCCC, 2011).

While there are many definitions of maladaptation, the definition proposed by Barnett and O'Neill (2010) is perhaps the most comprehensive. According to Barnett and O'Neill (2010) maladaptation is "action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups" (Barnett & O'Neill, 2010, pg. 211). As such, in the context of transportation, maladaptation could occur in the event that financial resources allocated to reduce vulnerability (investment in infrastructure or services) were disproportionately high relative to the costs of the impacts (lost mobility and accessibility). This is especially true if resources were taken away from other groups or sectors that were in greater need (Barnett & O'Neill, 2010). However, it is difficult to assess what constitutes the 'greater need', especially the economic value of non-market sectors or attributes such as the cost of lost mobility (UNFCCC, 2011).

There are numerous instances where initiatives for both adaptation and mitigation have not been implemented because of the financial constraints (Picketts, 2013; Moser & Ekstrom, 2010; Schipper & Pelling, 2006). Burch (2010), however, found that it is not the resources that contribute to the success or failure of these projects, but instead it if the political will and direction of the institution that plays a larger role in exploring the success of an initiative. Despite these barriers, adaptation planning remains important for increasing the systematic resilience and reducing the vulnerability of the system or community (Walker & Salt, 2006).

2.4.3 Climate change adaptation assessments

The purpose of adaptation planning is to increase resilience and reduce vulnerability of a system (Walker & Salt, 2006; IPCC, 2014). The concepts of resilience, vulnerability and adaptive capacity were originally found in ecology and they strongly emphasized biophysical processes with little regard for anthropogenic dynamisms (Folke, 2006). Over time, however, resilience literature transitioned away from ecology towards other disciplines such as health, psychology, and engineering, all of which began to explore these concepts by including greater emphasis on human and natural systems (Folke, 2006; Adger, 2000). As these discourses around resilience, vulnerability and adaptive capacity matured, there grew an interest in researching the relationships between these biophysical and social systems, also know as social ecological systems (Folke, 2006). While social and economic aspects of a system respond in both reactive and proactive ways, biophysical aspects of a system respond in a purely reactive manner and this is also evident in **Figure 1** (Smithers & Smit, 1997). As such, communities have control over policies and processes that can evolve to absorb changes in the biophysical system. Given this complex relationship, urban communities are particularly interesting to investigate because of the feedbacks between the social, biophysical, and economic impacts in these systems (Pickett *et al.,* 2001).

The past two decades has seen a surge of peer-reviewed research that addresses the vulnerability of communities to different triggers, especially with a focus on the vulnerability to climate change (Adger, 2006; Smit & Wandel, 2006; Folke, 2006; Turner *et al.,* 2003). The vulnerability and adaptation literature has drawn on the resilience scholarship, but is distinct body of literature. A common framework for researching the vulnerability of urban communities is through vulnerability and risk assessments, most of which are completed on a regional or local scale. The goal of these assessments in the context of climate change adaptation is that they will lead to the development of a climate change adaptation plan. The first step in creating a climate change adaptation plan is to complete a climate impact assessment that provides aggregate estimates of the extent to which adaptation may reduce the impacts of climate change (Smit *et al.,* 1999, Burton *et al.,* 2002, Füssel & Klein, 2006). The most appropriate approach depends on the many factors including the urgency of the threats, the availability and quality of data, expertise and funding (Füssel & Klein, 2006).

Community-Based Assessments (CBA) including Vulnerability and Capacity Assessments (VCA), Community Risk Assessments (CRA), and Participatory Rapid Appraisals (PRA) are all examples of a blended approach and are used depending on the intended outcome of the research (van Aalst *et al*., 2008). CBAs are very resource-intensive initiatives and are best suited for addressing community vulnerability at the institutional level as opposed to the household level. One of the ways of assessing the current vulnerability of a community is through an exploration of past experiences the community has dealt with in relation to climatic risks (current exposure). One would then assess the adaptation options available to that community (current adaptive capacity) (Ford & Smit, 2004; van Aalst *et al.,* 2008). Despite a surge in the climate change adaptation literature, there are still a number of important barriers that need be overcome before climate change becomes mainstreamed into decision-making processes.

A critical component of vulnerability assessments is the identification of vulnerable areas or groups of people. Transportation infrastructure, as a part of the urban landscape, is an important aspect of community vulnerability (Cumming *et al.,* 2006; Grimm *et al.,* 2000). Assessments of vulnerability have been completed in many contexts, but transportation is often highlighted in these assessments because it is critical for the access to social functions, medical relief, food and employment (Cumming *et al.,* 2006; Grimm *et al.,* 2000). One key contributor to increased vulnerability is limited access to transportation; improving mobility and accessibility are important components of the resilience of urban communities (Janssen *et al.,* 2007). Within a country, region, or even at the community level, there will be areas of lower and higher vulnerability (O'Brien *et al.,* 2004, Füssel &

Klein, 2006). In addition to the heterogeneity of vulnerability, even within an area, differences in vulnerability across groups of people to different disturbances are evident (Gallopin, 2006). Furthermore, there can be a seasonal component to vulnerability of a transportation system, especially with respect to winter weather in Canada. The accessibility, or lack of accessibility, of the transportation system is a determinant of vulnerability. The accessibility and safety of a transportation system can be severely impeded during weather events such as flooding, heat waves, rain, snow events, and ice events (Berdica, 2002; Hambly *et al.,* 2013; Andersson & Chapman, 2011).

In this thesis, the focus is on the vulnerability of a community to transportation weather risks in the winter. Reducing vulnerability is achieved through improved adaptive capacity. Adaptive capacity is "the ability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (Burton *et al.,* 2002 pg. 150). Key determinants of adaptive capacity are dynamic (Vincent, 2007) and include technological, political, social, and financial mechanisms. Transportation is a fundamental component of the adaptive capacity of modern society and illustrates society's ability to adapt to biophysical conditions in ways that enable productive economies. Affordable and accessible transportation leads to reduced vulnerability for individuals, businesses, and communities (Berdica, 2002). The accessibility and mobility provided by a transportation system can be severely impeded in inclement weather such as snow and ice events. Actions are taken by road authorities to maintain roads to ensure that transportation systems continue to provide accessibility and mobility to stakeholders (Berdica, 2002). These actions, such as WRM are important aspects of the adaptive capacity of a community to weather risk in the transportation sector.

2.5 Climate change and transportation in Canada

2.5.1 Transport in Canada: mitigation and adaptation

In Canada, improved resilience and reduced vulnerability of the transportation system to climatic events is of utmost importance. Canada's transportation sector is an economically critical sector in that it constitutes over $150 billion in infrastructure assets, much of which is vulnerable to climate change (Canadian Council of Professional Engineers, 2008). All infrastructures designed for the movement of people and resources, including railways, airports, ports, roads and bridges are considered transportation infrastructure (NRCan, 2007). Many of these assets will be affected by climate change, and policies will need to address how transportation infrastructure is designed, built and maintained (NRC, 2008; TAC, 2013). It is critical to study the impacts of future climate change when planning transportation infrastructure and future services. Many of these infrastructures are built for longer lifespans that will be exposed to altered climates (NRC, 2008; Petersen *et al.,* 2008). As such, there are substantial costs that could be accrued through improper design and management of these assets (Hambly *et al.,* 2013; Koetse & Rietveld, 2009; Mills *et al.,* 2009).

As a socio-technical system, Canada's transportation system consists of networks of users, managers, designers, governments, and physical assets that interact in a variety of ways to provide mobility and accessibility services to residents (Markard *et al.,* 2012; Geels, 2005; Markard, 2011). Systems such as transportation are considered 'socio-technical' because they are comprised not only of social, cultural, and economic components, but also of technologies and infrastructures (Geels, 2004; Geels, 2010). It can be argued that Canada's transportation system is unsustainable from an economic, social, and environmental perspective and needs to transition towards a more sustainable and less carbon-intensive system (Glaeser & Kahn, 2010). With over a million kilometers of Canadian roadways, the transportation system is directly accountable for 24 per cent of Canada's total emissions with 166 Mt CO^2 emitted annually (Environment Canada, 2012).

Transitioning to a more sustainable and resilient system will entail a great deal of cooperation and coordination from multiple institutions. The complexity and path-dependency inherent in socio-technical systems such as transportation greatly inhibits the ability for sustainability transitions to take place (Geels, 2010). The existing infrastructure, behavioural norms, investment in vehicles, and preferential subsidies all impede a sustainability transition (Geels, 2010). Short election cycles and the attractiveness of windfall gains for municipalities from suburban land developers further complicates the sustainability of urban transportation systems.

2.5.2 Impacts of climate change and variability on transportation systems

In order to assess the future vulnerabilities of Canada's transportation system to climate change, it is first important to understand current vulnerabilities. Each mode (air, rail, marine, and road) has its own unique set of risks to different climatic stimuli. In recent years, there has been a growing body of grey literature that has examined the impacts that transportation networks will face in light of climate change. Much of this work focuses on flooding, sea level rise, and northern transportation. WRM in particular has received limited attention (Warren *et al.,* 2004; Mills *et al.,* 2007; Millerd, 2011). It is evident that the engineering community has taken the lead in assessing the impacts of climate change on transportation infrastructure, and this is true internationally as well (Rowan *et al.,* 2013).

For the majority of transportation vulnerability assessments, the focus has been on the physical attributes of the system with little attention paid to services and budgetary implications (Chapman, 2007; Koetse & Rietveld, 2009). One notable exception has been the recent focus on the impacts of climate change for road safety (Hambly *et al.,* 2013; Hambly, 2011; Jaroszweski *et al.,* 2013). Generally, for the engineering studies completed in Canada, the first stage of the vulnerability is to look at the relationship between transportation infrastructure and climate stressors, but these studies have not quantified the likelihood of various implications under a changed climate. Rowan *et al.* (2013) argue that services are more vulnerable to climate stressors than physical assets (Rowan *et al.,* 2013), while others assert that the opposite is true (van Aalst *et al.*, 2008).

2.5.3 Climate change adaptation research in Canada

The scholarship and practice of climate change vulnerability assessment and implementation has evolved, such that current, comprehensive assessments of vulnerability to climate change "… are conducted to estimate realistically the vulnerability of certain sectors or regions to climate change, in concert with other stress factors and considering the potential of feasible adaptations to reduce adverse impacts" (Füssel and Klein, 2006, 319). Community-based assessments endeavor to apply empirical knowledge and expertise to raise awareness and improve community adaptive capacity to climate change (van Aalst *et al.,* 2008). However, the rigor with which the knowledge and expertise is raised can be questionable, especially in grey literature. Research on implemented adaptations to climate change in a Canadian context is still limited, especially for transportation (Berrang-Ford *et al.,* 2011). However, in recent years Canadian municipalities have become increasingly engaged in climate change assessments; despite this increasing engagement, examples of adaptation actions remain limited.

Many communities across Canada have begun to understand the plethora of risks that they will face in association with climate change and variability. Many municipalities have developed climate change mitigation strategies over nearly two decades (Gore, 2010). It has been only in the past ten years that communities have begun to look at the impacts they will face and begin the process of planning for adaptation. These adaptation, risk, and vulnerability studies have been commonplace in arctic Canadian communities since the mid-1990s (Newton, 1995; Nuttall, 1998; Cohen, 1997) and have become a well-developed field over the past ten years (Berkes & Jolly, 2002; Ford *et al.,* 2006; Ford & Smit, 2004). It is only in recent years that research has focused on southern Canadian municipalities, and much of this work is very often in terms of food security, flooding, and sea level rise (Richardson, 2010). The majority of climate change adaptation work in Canada is completed through an outcome vulnerability perspective using a top-down approach to project impacts. While much the work in Arctic Canada takes a bottom-up approach, these studies are less common. Most of the studies in Canada are about the impacts of climate change, and very little is about the process of adaptation planning. One notable example of research that is starting to look at the adaptation process is that by Burch (2010).

2.5.4 Adaptation planning for the transportation sector in Canada

The Federation of Canadian Municipalities (FCM) has played a pivotal role in developing and disseminating resources to aid municipalities in identifying and assessing potential impacts of climate change on Canadian communities. Rarely, however, are transportation systems the focus of these studies. Even more rarely, have researchers and academics looked at climate change impacts for transportation in non-arctic Canadian communities. Planned adaptation means using our understanding of climate change to explore the suitability of planned and existing policies, practices, and infrastructure and seeking to reduce the risks associated with climate change and capitalize on the opportunities provided (Füssel, 2007). Adaptation planning for transportation lends itself especially well to the hybrid approach as both short-term and long-term policy decisions need to be made. The top-down scenario-driven work provides an understanding of the potential impacts, but the contextual aspect provides an understanding of the socio-economic and political constraints. There are short-term day-to-day decisions such as snow removal and road re-surfacing, and yet there are also long-term infrastructure decisions such as bridge construction and network planning that should account for possible impacts from climate change. On both these fronts, much is already known about climate sensitivities and vulnerabilities, but findings can be context-dependent and current vulnerabilities in a community should be assessed.

In addition to the academic literature, the Government of Canada has developed, and funded the development of a variety of guides to help municipalities create plans for local climate change adaptation initiatives. The focus on community or municipal planning is due to the tiered structure of government in Canada whereby most of the local decisions, especially infrastructure, are the responsibility of the local government. From forest management to water conservation, a variety of priority plans have been developed by Canadian municipalities and they typically follow a similar process. Many of these plans begin with the aim of building knowledge and capacity, and then identifying possible climate change impacts. This is followed by a process to determine adaptation priorities and a plan for the implementation of adaptation initiatives (Bizikova *et al.,* 2008; Bowron

& Davidson, 2012; CIP, 2011; ICLEI, 2010; Penney *et al.,* 2011; PIEVC, 2008; Richardson, 2010):

Canadian Institute of Planners (CIP) - The CIP has a *Model Standard of Practice for Climate Change Planning*. This model guides municipal decision makers in researching the core issues of climate change adaptation, and proposes a plan to deal with barriers to climate change adaptation. The steps of the plan are to create a road map; consult, communicate and educate; assess the impacts; assess the response; implement, and monitor and evaluate. The guide provides case studies and examples for communities to use. There are no case studies of adaptation plans that have been implemented (Bowron and Davidson, 2012; CIP, 2011).

Engineers Canada - *Protocol Tool for Guiding Climate Change Infrastructure Vulnerability Assessments* (Public Infrastructure Engineering Vulnerability Committee (PIEVC). Established by Engineers Canada, PIEVC conducted an assessment of the vulnerability of public infrastructure to changing climatic conditions in Canada (PIEVC 2008). This assessment used a scenario-driven approach to researching vulnerability. PIEVC (2008) created a protocol tool for guiding climate change infrastructure engineering vulnerability assessments. This protocol has been applied to case studies in four priority infrastructure categories: transportation infrastructure, buildings, stormwater systems and water resources infrastructure. PIEVC protocol case studies of roads and associated infrastructure has been completed in five communities.

Federation of Canadian Municipalities (FCM) – The FCM created a Protocol entitled 'Infrastructure Climate Risk Protocol Municipal Resources for Adapting to Climate Change'. This report profiles seven municipalities that are looking to implement adaptation in their communities, and the guide provides resources and tools that were used by other communities.

International Council for Local Environmental Initiatives (ICLEI) Canada - *Changing Climate, Changing Communities: Municipal Climate Adaptation Guide and*

Workbook. This ICLEI guide provides a framework to help municipalities develop adaptation plans that addresses the most significant climate risks for their community. The guide is a five-step process of adaptation planning: 1) initiate, 2) research, 3) plan,4) implement and 5) monitor. This is practical guide that has been used by communities such as Red Deer, AB and Windsor, ON (ICLE, 2010).

Clean Air Partnership – *Protecting your Community from Climate Change* – This training program for municipalities is a guide that was funded by Natural Resources Canada. This guide provides a step-by-step process for government looking to explore climate change vulnerability, develop and adaptation plan, and implement that plan (Penney *et al.,* 2011). As a follow up to the training program, the Clean Air Partnership developed another document, *Accelerating Adaptation in Canadian Communities*, which profiles case studies on what has been done in communities. There are no case studies of adaptation plans that have been implemented (Rodgers and Behan, 2012).

Natural Resources Canada developed a book *Adapting to Climate Change: An Introduction for Canadian Municipalities* which gives municipal decision makers the information to aid in understanding the need for climate change adaptation at the municipal level. This book also provides links to other guides that can help decision makers to identify and address risks, barriers and opportunities for adaptation planning and provides a series of case studies that serve as examples that could be followed by other municipalities (Richardson, 2010).

Many of these examples listed above provide a broad adaptation research framework (e.g., ICLEI 2010; CIP 2011). The PIEVC (2014) provides a more concrete set of tools for establishing adaptation research and action priorities that can be used in the transportation sector. This thesis can be seen as the sector-specific follow-up research that takes place between the prioritization and action components of a CCIAV assessment.

3 Study area

3.1 Case study methodology

This thesis uses a case study methodology to: 1) assess the current vulnerabilities of WRM practices to climate change; 2) project future changes in the need for WRM activities; and 3) assess the role and value of steps one and two for the climate change planning process. As such, the methods, analysis and results have been separated into three unique processes and are outlined in **Figure 3**. Steps one and two of this thesis were the scenario-driven approach to adaptation research, while step three provides the contextual, bottom-up analysis that is critical for framing the results of steps one and two.

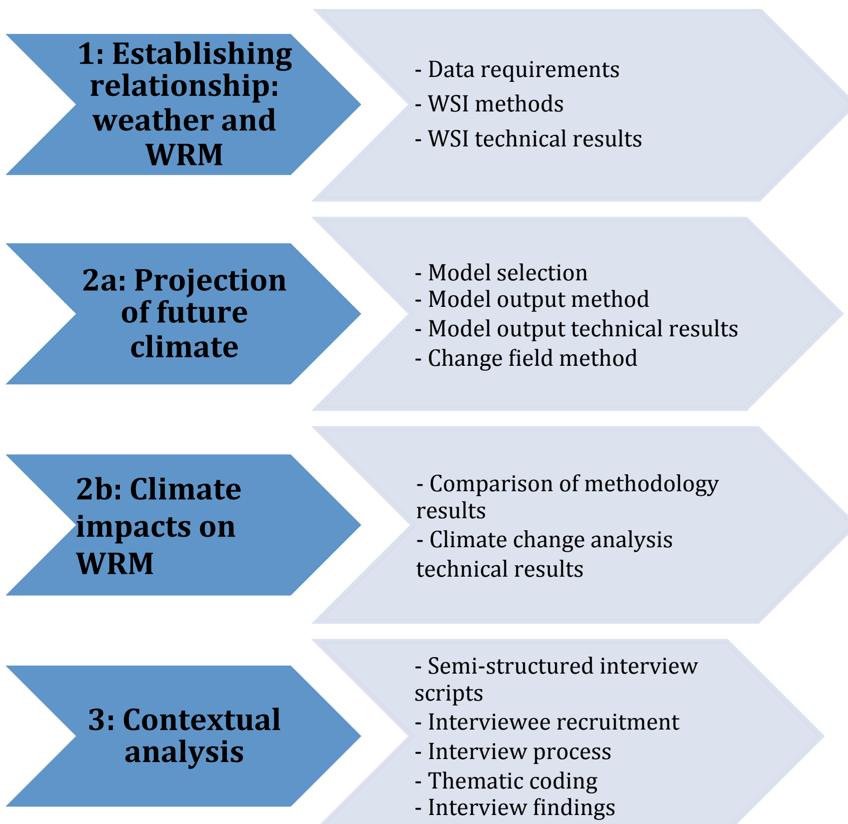

Figure 3: Process diagram of steps involved for this thesis

Adaptation literature is replete with case studies (Dessai & Hulme, 2007; Ford *et al.,* 2006; Nielsen & Reenberg, 2010), and single-unit analyses are almost exclusively used, with only few examples of cross-unit analysis (Hunt & Watkiss, 2011). Case studies have sometimes been criticized for being inconducive to generalizations from an individual case, thus limiting scientific development in that particular field. However, as Flyvbjerg (2001) argues, all research that involves human subjects or their action is incredibly context-dependent. Exploring an issue, such as climate change planning, through the means of a case study, however, is crucial for research and teaching. To become an expert in any field, researchers need experiential understanding, such as that which can be gained through case study research (Flyvbjerg, 2006; Stake, 1978). The discovery of knowledge is a key purpose of research, and context-dependent knowledge has considerable value. Context-dependent knowledge is important for the learning process as it allows a researcher to see all aspects of a problem in an isolated setting and the linkages between components can than be more clearly identified.

The choice of method is closely tied to individual circumstances and the problem under study (Flyvbjerg, 2006). This research in the City of Prince George is highly context-dependent, as is the field of adaptation research in general. Thus a case study method is well suited for this research (Dogan & Pelassy, 1990; Campbell & Stanley, 1966). This case study in the City of Prince George looks at the lessons learned from previous municipal climate change adaptation initiatives throughout the development of the approach for this research. While this is a single-unit research method, the value of this approach is that as the field of climate change adaptation research progresses, future researchers have a collection of reference to draw upon as they form new research projects. Furthermore, this case study illustrates municipal level decision making in the context of transportation with a focus on the barriers and enablers to planned adaptations.

3.2 The City of Prince George

With a population of approximately 77,000 residents, Prince George is a major city in the Fraser-Fort George Regional District of north-central British Columbia. Prince George encompasses a total land area of 316 km^2. At 739 km west of Edmonton and 786 km north of Vancouver, the City of Prince George is located near the geographical centre of British

Columbia, as seen in **Figure 4** (Picketts *et al.,* 2009). The elevation of Prince George is approximately 575 m in the city centre, but the City of Prince George is in a river valley and the elevation varies dramatically with the elevation of the Hart area being approximately 758m above sea level. Prince George is surrounded by a dense forested landscape, both in and around the city boundaries (Picketts *et al.,* 2009).

Natural resources drive the regional economy; there are three pulp mills and 12 sawmills in Prince George, and forestry is a major employer in the region. Prince George is also a staging centre for mining and prospecting. It is expected that the Liquefied Natural Gas (LNG) sector will expand over the next decade, and the Government of British Columbia has made commitments to create three LNG pipelines by 2020. These LNG pipelines are likely to route through or near Prince George ending at the ports of Kitimat, British Columbia. This will provide many economic opportunities for individuals and businesses involved with the construction, manufacturing, maintenance and operation of these facilities. Transportation is an integral part of Prince George's success as a central hub in the region. As such, the City of Prince George is a key road network center for the province. This network is, however, sensitive to weather and to future environmental change.

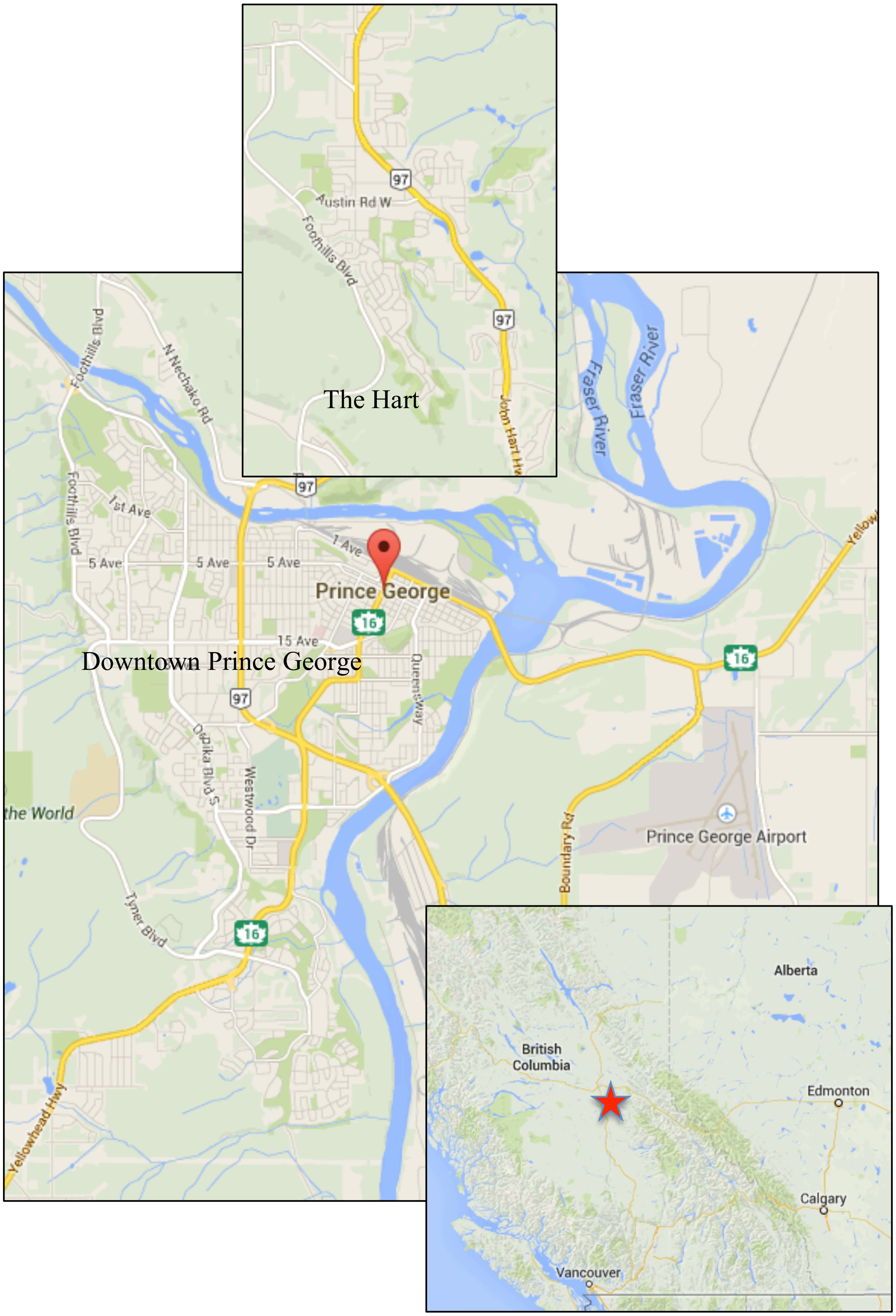

Figure 4: The City of Prince George (Prince George, 2014)

3.3 Climate

North-central British Columbia has a continental climate with short warm summers but long cold winters with snow cover from roughly November to March. Climate normal data (1961-1990) from the Prince George airport climate station (1096450 AHCCD) indicate that average summer (June, July, August) and winter (December, January, February) temperatures in Prince George were 14.3°C and -8.0°C, respectively. The station recorded an annual average precipitation of 687 mm with considerable inter-annual variability. Annually, the ratio of rain to snow was approximately 2:1 with an average of 456 mm of rain annually versus 231mm of liquid equivalent of snow (Picketts *et al.,* 2009). That said, winter weather remains a matter of concern for Prince George as considerable resources are devoted to snow and ice control, and winter storms create hazardous driving conditions. Also of relevance to the current study are changing weather patterns. Over the past 100 years, there has been a warming trend of 1.3°C, and the Prince George region is projected to experience further changes in temperature as well as more precipitation, especially in winter (Picketts *et al.,* 2009). This has potential implications for the transportation system in and around the City of Prince George.

3.4 Climate change planning

Since 2001, the City of Prince George has been proactive in addressing the need for adaptation to climate change. The City has partnered with the Pacific Climate Impacts Consortium (PCIC) and the Pacific Institute for Climate Solutions (PICS) to develop reports on past trends and future projections for Prince George, including a section on municipal adaptation options. Prince George has also undergone an intensive community-based assessment (CBA) of climate change impacts that resulted in the identification of key vulnerabilities. After forestry and floodplain management, transportation was identified as a top priority (Picketts, 2013).

To further explore the vulnerabilities of the transportation sector to climate change, a follow-up to the CBA was conducted in 2011. This follow-up work included a workshop for transportation professionals in Prince George and were led by researchers from the University of Northern British Columbia (Picketts, 2013). The City was interested in further exploring the specific nature of transportation vulnerabilities to better enable adaptation planning and the City invited a variety of transportation professionals, including researchers from the University of Waterloo to take part in a two-day workshop that outlined the key vulnerabilities of Prince George's transportation system. This project brought together community leaders, municipal planners, engineers, climatologists and academics from various institutions to deliberate adaptation-planning options for transportation infrastructure and maintenance in the community of Prince George. Road safety, pavement infrastructure, and WRM were priority areas that were identified at this workshop.

At the conclusion of this workshop, agreements were made between Dr. Jean Andrey, the City of Prince George, and myself to further explore the vulnerability of road safety and WRM to the impacts of climate change. In 2011-2012 a series of reports were completed for the City of Prince George that outlined current practices and vulnerabilities, as well as projections of future impacts and vulnerabilities for WRM and road safety in the City. While these reports provided numerous insights into the potential impacts of climate change, questions have remained as to the benefits of such sector-specific vulnerability assessments and the role they play in anticipatory adaptations at the municipal level. As such, the purpose of this thesis is to expand on the previously completed work, using new methods, with the aim to explore the projected impact of climate change on WRM and to explore how site-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate change adaptation planning.

3.5 Winter road maintenance

The City of Prince George has a continental climate with short warm summers and long cold winters. Snow cover extends from November to March in most years and winter weather is a matter of high concern for the City as considerable resources are devoted to snow and ice control. The City allocates a full 5% of its annual budget to snow and ice control activities, and these resources are collected through Snow Control Levy that appears on all municipal tax bills. Over the past two decades there has been a steady increase in the WRM budgets due to periodic annual deficits. After adjustment for inflation[1], annual[2] WRM expenditures since 1994 have ranged from between \$3.60 million and \$7.02 million. Any surplus resources are held in the Snow Control Reserve to be used for years in which there is a deficit. Since 1994 there have been six years with a recorded surplus and 13 years with a deficit. **Table 1** outlines the annual budgeted and actual expenditures from 1994 to 2012.

Table 1: Snow and ice control budgets in the City of Prince George (1994 – 2012)

Year	Budgeted expenditures (\$Millions)	Actual expenditures (\$Millions)	Difference from budget (\$Millions)	Expenditures (\$Millions adjusted to 2012 dollars)
1994	\$4.37	\$5.01	(\$0.64)	\$7.02
1995	\$2.83	\$3.31	(\$0.48)	\$4.61
1996	\$3.00	\$3.87	(\$0.87)	\$5.31
1997	\$4.19	\$3.78	\$0.41	\$5.01
1998	\$3.23	\$3.31	(\$0.08)	\$4.40
1999	\$3.73	\$4.81	(\$1.08)	\$6.35
2000	\$3.73	\$3.33	\$0.40	\$4.30
2001	\$3.66	\$3.29	\$0.37	\$4.12
2002	\$4.08	\$4.01	\$0.07	\$5.00
2003	\$3.93	\$4.24	(\$0.31)	\$5.02
2004	\$4.13	\$4.67	(\$0.55)	\$5.56
2005	\$4.13	\$3.36	\$0.77	\$3.85
2006	\$4.17	\$5.30	(\$1.13)	\$5.91
2007	\$4.02	\$4.42	(\$0.39)	\$4.88
2008	\$4.07	\$5.54	(\$1.47)	\$5.98
2009	\$4.25	\$6.25	(\$2.00)	\$6.68
2010	\$4.80	\$3.43	\$1.37	\$3.60
2011	\$4.84	\$6.74	(\$1.90)	\$6.90
2012	\$4.84	\$5.30	(\$0.46)	\$5.30

The City of Prince George has a thorough and well-defined program for dealing with WRM, and the City's *Snow Control Policy* has been in place since the early 1990s. This *Snow Control Policy* stipulates when and where WRM activities will occur in relation to a weather event. This policy dictates the meteorological circumstances that must occur before any snow and ice control activities are initiated. The City's *Snow Control Policy*,

[1] Inflation was calculated using the Bank of Canada Inflation Calculator found at: http://www.bankofcanada.ca/rates/related/inflation-calculator/
[2] The fiscal year in the City of Prince George runs from January to December and does not coincide with the winter season.

adopted by Council in 1991, has only been moderately amended in the past two decades but in essence has remained virtually unchanged.

There are two main aspects of *Snow Control Policy* in the City of Prince George. The first is snow removal, and the second is ice control. The *Snow Control Policy* relates mostly to snow control, and it identifies four priority levels to determine the order in which roads should be maintained (**Table 2** and **Figure 5**). Priority 1 roads, arterial and downtown roads, are cleared first and this maintenance occurs after 7.5cm of snow has accumulated. Once the priority 1 roads have been maintained then the priority 2 roads, collectors and bus routes, are cleared. Priority 3 roads, which are often the residential roads and sidewalks are cleared last and only after 12cm of snow has accumulated. The order in which the residential roads are cleared is based on the scheduled garbage routes. The City endeavours to ensure that residential roads are cleared the day before their designated garbage collection. The Ministry of Transportation maintains the two highways that run through the City of Prince George, as shown by the yellow-coloured roads in **Figure 5**.

Table 2: Priority routes for snow and ice control

Priority	Service Item	Cleared When
1	Arterial and Downtown Roads	Accum. > 7.5cm
2	Collectors and Bus Routes	Accum. > 7.5cm
3	Local Roads and Lanes	Accum. > 12cm[3]
4	Sidewalks	Accum. > 5cm

[3] In 2010 an amendment was made to change the threshold from 10cm to 12cm for priority 3 roads in an effort to reduce costs.

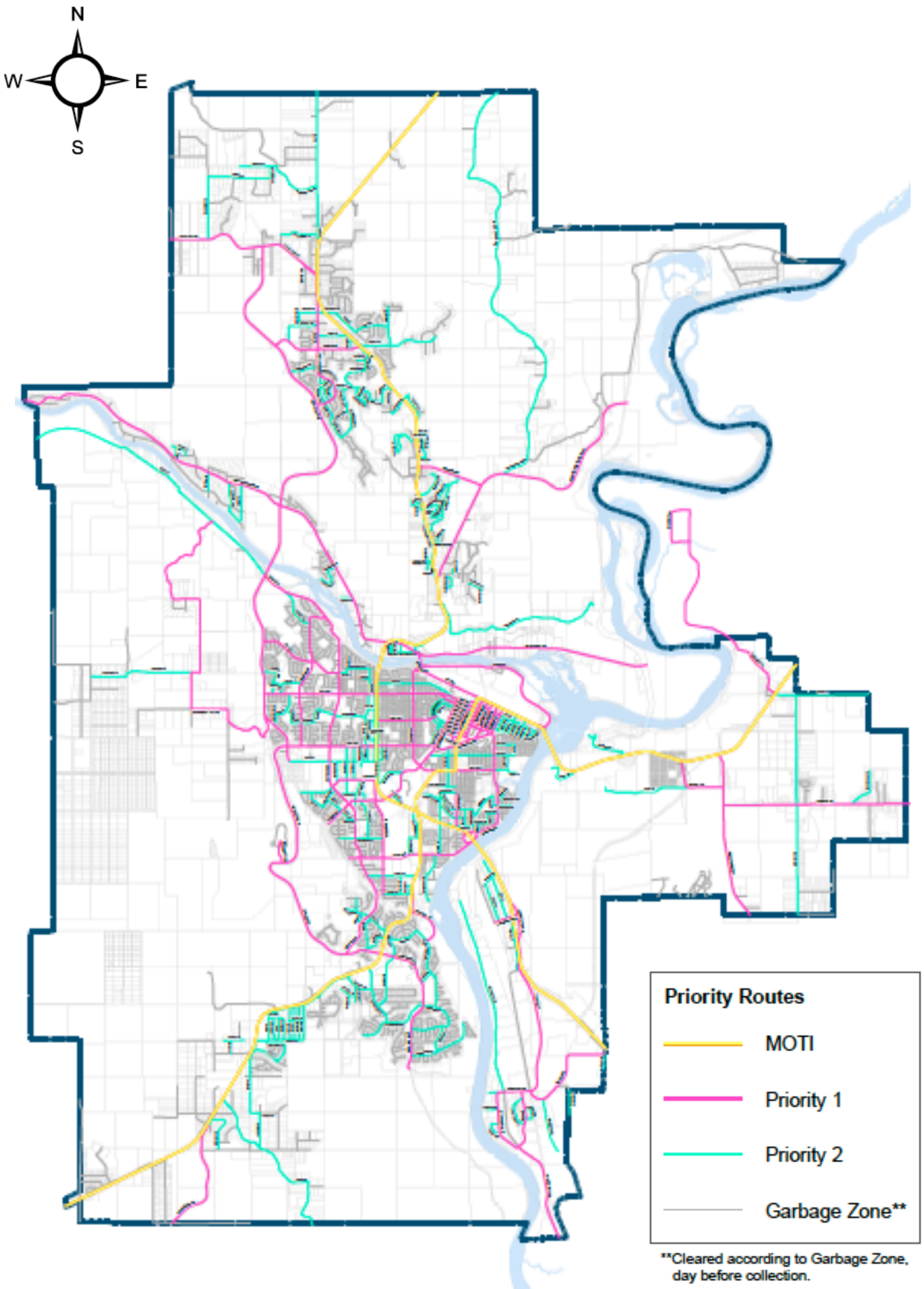

Figure 5: Snow removal priority routes (source: City of Prince George – Geographic Information Systems Group, 2014)

It is the goal of the City to complete post-snow event maintenance within five days of the storm. There are difficulties, however, in that the five-day schedule restarts at the end of each snow event (for example, if the City were to experience a 12 cm snowfall every three days for a week, the residential areas wouldn't be plowed until four days after the last snowfall, or 11 days after the first snow began). This is problematic in that the snow becomes compacted and the task of removing this snow and ice becomes more difficult. Part of the *Snow Control Policy* also stipulates that the City of Prince George is responsible for removing all snow from the downtown core due to parking constraints; this is at a cost of upwards of $100,000 per snow event. Another unique aspect of the City's winter maintenance program is its commitment to opening driveway aprons to all residential driveways at a cost of between $250,000 and $500,000 per winter (KPMG, 2012). Despite efforts to remove these practices from the *Snow Control Policy*, there is little resident and institutional appetite despite the high costs.

Ice control is the second key aspect of the WRM regime in the City of Prince George and is the feature of their program that has evolved the most over time. Through the use of materials such as sand, fracture, salt and anti-icing chemicals, along with the removal of snow from city streets, the City of Prince George tries to ensure a safe and efficient road network. Due to changes in technologies, practices, and possibly weather, the ways in which ice control is accomplished in the city has varied a great deal since 1994. **Figure 6** shows the annual variation in materials use. Over the years efforts have been made to reduce the environmental impact of their WRM materials usage, as seen by the implementation of AMEC's salt management plan (2006). Section 6.3.2 will provide a discussion of the reasons for these other changes in greater detail.

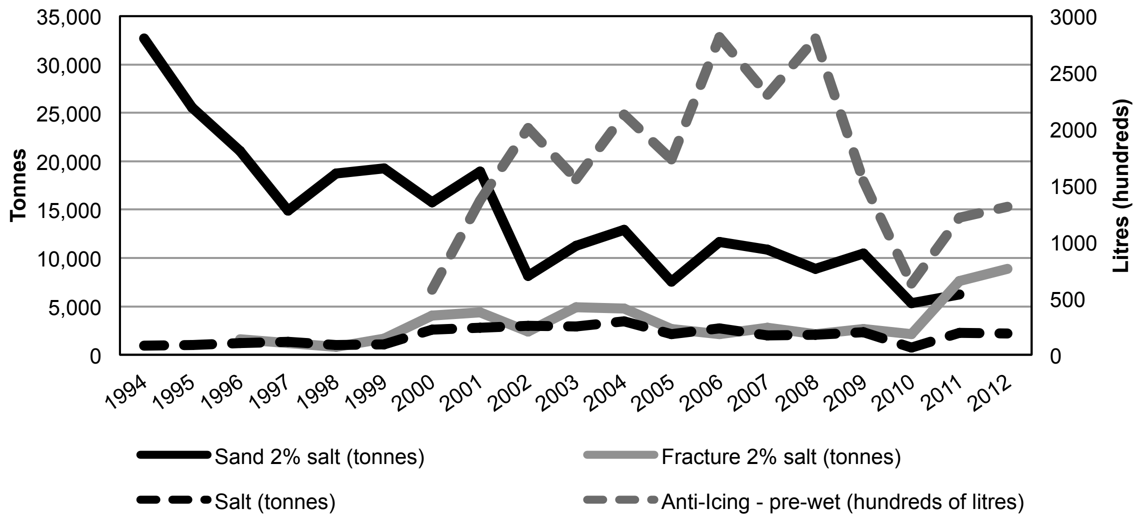

Figure 6: Materials use in the City of Prince George over time

While Council is responsible for making any amendments to the *Snow Control Policy*, it is within the purview of the managers and directors to determine the operations and procedures of snow and ice control in the City. For the most part, municipal staff are responsible for decisions about WRM in the City of Prince George. The total snow force is between 50 and 56 staff with five foremen and one supervisor. All materials application is completed by municipal staff but some of the snow removal is contracted out and equipment is also rented for snow events. **Table 3** provides an overview of the types and quantities of equipment used for the WRM in the City of Prince George.

Table 3: Equipment used in typical night shift (data from CPG, 2014)

Equipment	City owned	Rented	Total
Sander/Plow Trucks	7	0	7
Loaders	4	8	12
Graders	5	0	5
Sidewalk Machines	3	0	3
Dump Trucks	0	16	16
Bulldozer (snow dump)	0	2	2
Snow Blower/Loader	1	0	1
Loader Plows	1	0	1
Backhoe	1	0	1

A number of challenges face the Snow Operation Division in the City of Prince George. Through preliminary analysis of secondary sources, along with informal discussions with stakeholders in the City of Prince George, three key challenges were identified and these include: 1) micro-climatic conditions make prioritizing snow and ice control difficult, 2) there is a very high level of service expected by the residents of the City; and 3) the City has limited capacity to monitor and evaluate snow and ice control practices.

Figure 7: Snow accumulation in 'the Hart' – microclimate conditions are a challenge for the City *(photo taken March 25, 2014)*

Figure 8: Left over fracture material in downtown Prince George *(photo taken March 25, 2014)*

Figure 9: Three city owned graders used for WRM *(photo taken March 25, 2014)*

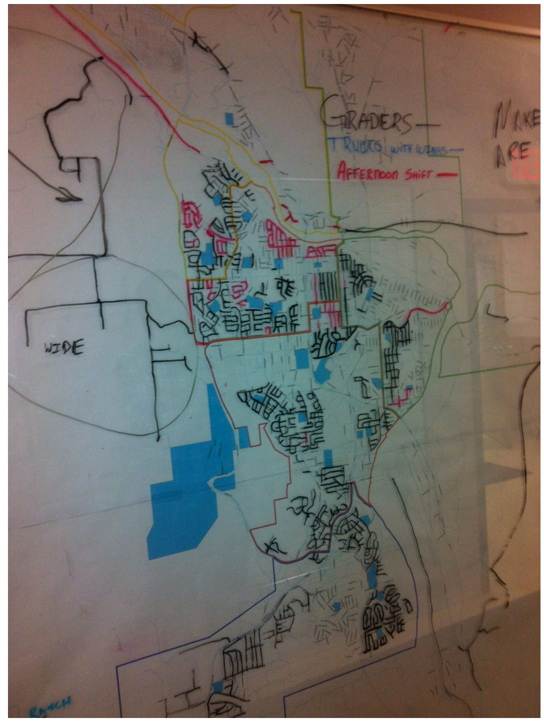

Figure 10: Map that employees use to record maintenance activities *(photo taken March 25, 2014)*

The first challenge for WRM in the City of Prince George is the micro-climatic conditions that are present. These micro-climatic conditions are present due mostly to the drastic elevation change between the downtown and core of the City of Prince George which is located in a valley, and the area known and the Hart, which is approximately 200m higher than the city centre. The Hart experiences much more snow than the downtown area, but there is not a weather station in the Hart area so these differences are not recorded. However, as seen in **Figure 7** and **Figure 8** there are very clear differences in the amount of snowfall experienced in the areas. **Figure 8** shows the downtown area of Prince George where it can be seen that there is no residual snow accumulation. **Figure 7**, however, shows substantial snow accumulation in a residential area of the Hart. These photos were taken on the same day and are illustrative of the substantial micro-climatic conditions.

The second challenge is that there is a very high level of service expected by the residents of the City. Ensuring that driveway aprons are cleared, snow banks are cut back, roadways are widened, and that there is no snow left in the downtown completes this service quality. This high level of service requires substantial investment in equipment and personnel. As seen in **Figure 9**, the three city-owned graders were purchased to ensure that ice and compacted snow could be completely removed from the road surface.

The third challenge is that the City has limited capacity to monitor and evaluate snow and ice control practices. All maintenance activities are recorded manually by hand and it the responsibility of each employee to record materials used and the roads that they have maintained. As seen in **Figure 10**, there is a map of the City at the service centre that is used by employees to mark their progress. While many other jurisdictions use a variety of new technologies such as GPS-enabled plows to record, evaluate and plan WRM activities, the City of Prince George still relies on manual documentation and there are currently no performance management tools in place.

4 Current relationship between weather and WRM practices

The City of Prince George has recently completed an intensive community-based assessment (CBA) that resulted in the identification and prioritization of vulnerable areas in the community (Picketts, 2013). After forestry and floodplain management, transportation was identified as a top priority (Picketts, 2013). Follow-up work was completed to further explore and prioritize aspects of the transportation system that could be vulnerable to climate change. WRM was identified as one of the possibly vulnerable features of the transportation system in the City of Prince George.

This thesis uses both a scenario-driven and contextual approach to impacts and adaptation research. This chapter of the thesis focuses on the scenario-driven approach whereby climate models are applied to an exposure unit and the outcome is quantified (van Aalst, 2008; Smit & Wandel, 2006; Ford & Smit, 2004). Therefore, in this case study, the first step has been to explore the ways in which the current climate influences snow and ice control practices and expenditures in the City of Prince George. Understanding the ways in which current weather influences the demand for WRM provides a baseline as to allow for future projections of WRM to be completed.

One way of establishing the relationship between weather and WRM is through the classification of weather days that reflect temporal variations in WRM. Classifying days according to weather as to reflect variations in WRM activity is a common approach taken but there are a variety of ways in which this classification can be completed. Three possible methods are: 1) cluster analysis, 2) classification and regression trees, and 3) the development of indices. All of these approaches can be used to classify weather days. In the 2011 and 2012 reports completed by the University of Waterloo researchers for the City of Prince George, the researchers explored all three methods.

The first method, cluster analysis is a multivariate statistical method that groups observations into a specified number of clusters. Observations, at the daily level, may be organized into clusters based on observed weather variables (e.g., temperature, amount of precipitation). Cluster analysis is a relatively simple calculation, but its disadvantage is that cluster analysis is not intended to link to a response variable such as salt use or WRM expenditures. To date, no examples could be found of research that has applied the cluster analysis method to WRM activities or expenditures.

The second possible method of classifying weather days is through classification and regression trees. Classification and regression trees identify explanatory variables and their thresholds (e.g., temperature, amount and duration of precipitation) and partitions days into groups, whereby groups each have days with a high probability of having the same value for a response variable (e.g., amount of salt use). The classification and regression tree approach was first applied to WRM by Andrey *et al.* (2008) and Brenning *et al.* (2011) and was explored in depth during the 2011 and 2012 research project for the City of Prince George. The for the 2011-2012 City of Prince George research project WRM materials use and snow dumping quantities were modeled as a function of daily weather variables. The results of that project provided a primarily a proof of concept that identified key explanatory variables and associated thresholds, however, the predictive accuracy of the models was low.

The third possible way of classifying weather days is through indices. For WRM, it is common to use WSIs. WSIs identify weather circumstances that trigger winter maintenance (e.g., certain amounts of snowfall or rain, wind combined with previous snowfall that may lead to blowing snow). Different weather conditions/events translate into different scores, which are then aggregated to monthly, seasonal, and yearly levels and subsequently correlated with maintenance activities or expenditures. Some studies have used individual weather variables such as daily temperatures (Andersson & Chapman, 2011), and others have used a combination of weather variables (Cornford & Thornes, 1996; Venäläinen & Kangas, 2003). In the 2011 and 2012 research project for the City of Prince George a WSI developed by Andrey & Matthews (2012) was used. This WSI had been developed for Environment Canada to explain temporal variations in salt use for Canadian municipalities. This WSI performed well in explaining the temporal variation in salt use ($R^2 = 0.30$) and snow dumping ($R^2 = 0.55$) as a function of weather in the City of Prince George at the annual level.

While this WSI developed by Andrey and Matthews (2012) is holding the most promise as a method for classifying weather days in the City of Prince George, there are some limitations. Firstly, the 2012 WSI by Andrey and Matthews was calibrated based on a national set of municipal salt use data. Given the high proportion of municipalities in Eastern Canada, there is a bias to the practices that are more common in Eastern Canada. Secondly, this WSI was developed specifically for salt use. The City of Prince George is concerned not only with the amount of salt use, but also with other materials use such as sand and gravel, but is also concerned with expenditures. As such, this thesis looked to improve on the findings from the 2011-2012 City of Prince George studies and developed a WSI that enhanced this previously completed work in ways that would allow for the WSI to be calibrated based on historic practices in the City of Prince George and that would have response variables of relevance.

4.1 Weather indices

An index is a measure that simplifies complex information for a particular application, typically representing this information as a single numeric value. Research on transportation-related weather indices has been ongoing for more than three decades (Thornes, 1993; Suggett *et al.,* 2006; Venäläinen & Kangas, 2003) and WSIs have gained increasing prominence over the past decade. WRM practices and expenditures vary both spatially and temporally for a multitude of reasons (Venäläinen & Kangas, 2003). Especially in light of recent technological advances, temporal changes have occurred, as there has been a phasing in of new technologies and improved materials. These technologies include changes in plow design, fuel efficiency, the use of GPS, anti-icing chemical development and improvements in communications. Spatial variations in WRM practices can be partially attributed to dissimilarities in road networks and infrastructure as well as differences in winter weather (Venäläinen & Kangas, 2003). As such there is a need for winter severity indices that can help to explain the temporal variability in WRM practices and associated costs.

A variety of existing WSIs have been developed in North America and Europe. The most widely cited is the WSI that was designed by the US Strategic Highway Research Program (SHRP) (Thornes, 1993) and this WSI has been used to benchmark winter maintenance activities in some jurisdictions (McCullouch *et al.,* 2004). In this original model, there were three weather variables that were used as inputs to the model: temperatures, snowfalls and ground frosts or freezing rain. However, this original WSI model did not perform very well when applied to jurisdictions in Canada (Andrey *et al.,* 2001).

Since 2001 there have been a variety of efforts to create an operational WSI for Canadian jurisdictions. In 2007 a Transportation Association of Canada Pooled Fund Project investigated spatial variations in salt use. However, the associated regression model was developed to explain inter-regional variations in salt use rather than within-region variability over time (Suggett *et al.,* 2006; Suggett *et al.,* 2007). Then, in 2009, Environment Canada contracted AMEC Earth & Environmental Consultants to develop a method for characterizing winter severity in Ontario at the daily level (AMEC, 2009). This method assigned a point value to each day, and the points were then aggregated at coarser temporal resolutions and correlated to materials use. While the model fit was only moderate, this study did validate the use of snowfall and freezing rain as important components of a WSI. This study also introduced the use of blowing snow as another important components for a WSI in the Canadian context.

Recently in 2012, Environment Canada contracted University of Waterloo researchers to conduct a study to develop a WSI that could be used to explain temporal variations in salt use within a region (Andrey & Matthews, 2012). This study took a similar approach to the AMEC (2009) study in developing two different WSI models, depending on the availability of weather data. In both cases, the WSI provided good fit with the salt use as a response variable.

While there has been a steady improvement in development of WSIs over the past 15 years, most of these models provide only moderate fit to their response variables and as such are of limited practical use for road authorities to use as a management tool. In efforts to remedy this limitation, most recently in 2014, University of Waterloo researchers developed a more promising WSI by incorporating optimization (Andrey *et al.,* 2014). The current study proceeds in a similar way to develop an improved WSI that reflects WRM in the City of Prince George.

4.2 Data

For this study, detailed daily weather data were required for two timeframes. The first timeframe was from 1994-2013, as this was the study period for the evaluation of WRM activities in the City of Prince George. The second timeframe was from 1971-2000 as this represents the climatological normal period of climate models and was required in order to assess the ability of the climate models to simulate the 20C modeled climate data.

Table 4: Environment Canada daily-level weather data availability

Location	*Climate ID*	*Data availability*	*Latitude*	*Longitude*	*Surface elevation*	*Days in dataset*
Prince George STP	1096468	1976-2013	53°52' N	122°46' W	579 m	13,880
Prince George A	1096450	1970-2009	53°53' N	122°40' W	691 m	14,539
Prince George Airport	1096453	2009-2013	53°53' N	122°40' W	691 m	1,475

The weather data used in this thesis were obtained from Environment Canada’s digital archives. Detailed daily weather data were obtained from three weather stations located in Prince George. The first weather station was the “Prince George A” (Climate Identifier: 1096450) which has daily data available dating back to 1942. This station was replaced by the “Prince George Airport” station (Climate Identifier 1096453) in November 2009. The third weather station used was “Prince George STP” (Climate Identifier: 1096468), which is located closer to the centre of Prince George than the airport stations. **Table 5**, below, provides a summary of the weather data and its completeness for the study period (1994-2013).

Table 5: Summary of weather data completeness for the study period (1994-2013)

Weather variable	***PG A and Airport (1096450 and 1096453)***		***PG STP (1096468)***	
	% Complete	Annual mean	% Complete	Annual mean
Min Temp °C	99.00%	-1.04	98.28%	-0.03
Mean Temp °C	98.81%	4.37	98.25%	5.29
Max Temp °C	99.06%	9.75	98.82%	10.66
Total Precipitation (mm)	98.60%	579.3	98.84%	596.8
Rain (mm)	80.63%	346.1	98.84%	435
Snow (cm)	78.95%	162.0	98.84%	161.9

While the temperature data are more complete for the airport weather stations, the precipitation data are more complete for the Prince George STP station. Furthermore, at the airport weather stations, there is an average of 80mm of precipitation a year that is identified as neither rain nor snow. Given the improved data completeness for precipitation, which is crucial for the development of a WSI, as well as the proximity of the STP station to the city centre, the Prince George STP station was used for the calibration and calculation of the WSI. It should be noted, however, that there was similar amount of snowfall accumulation recorded at the two stations, although the STP station is one degree warmer, on average. **Figure 11**, below, illustrates the monthly variation in temperatures and precipitation for the 1994-2013 study period using data from the STP station.

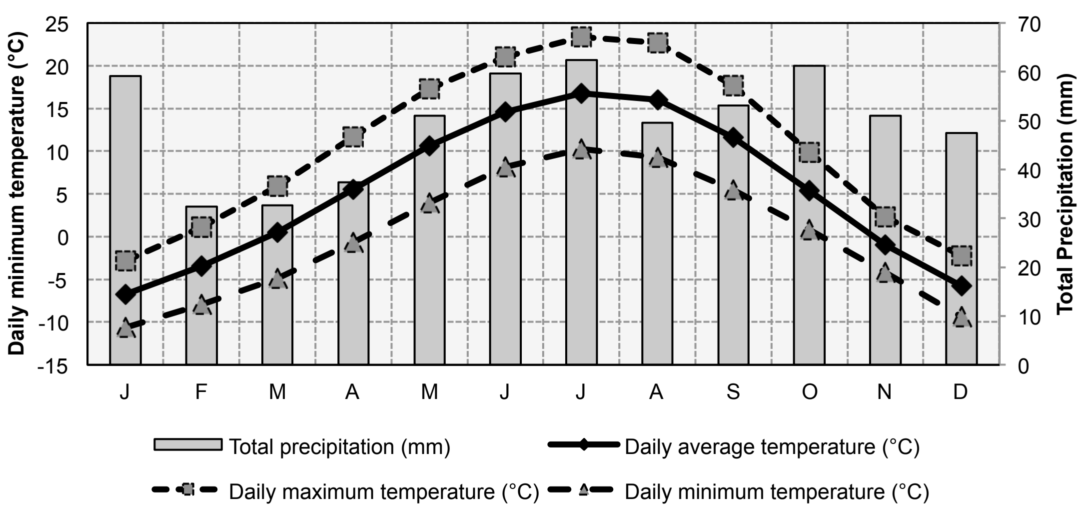

Figure 11: Temperature and precipitation in Prince George for the study period (1994-2013)

Seeing as the data for the Prince George STP station were more complete for the study period (1994-2013), it was decided to use the same station for the climatological normal period to ensure consistency. One issue with the use of the STP station is that the first five years of data for the climatological normal period were not available (1971-1976) and as such it is important to investigate whether the 25-year record is representative of the climatological normal period. Accordingly, the 1971-2000 data from the airport station were compared to the 1976-2000 time period (**Table 6**).

Table 6: Summary of weather data completeness for the climatological normal period

Weather variable	***PG A (1096450)***		***PG A (1096450)***		***PG STP (1096468)***	
	1971-2000 (30 years)		***1976-2000 (25 years)***		***1976-2000 (25 years)***	
	% Complete	Annual mean	% Complete	Annual mean	% Complete	Annual mean
Min Temp °C	99.82%	-1.44	99.78%	-1.22	99.85%	-0.15
Mean Temp °C	99.82%	4.00	99.78%	4.21	99.81%	5.18
Max Temp °C	99.83%	9.43	99.79%	9.61	99.93%	10.49
Total Precipitation (mm)	99.88%	601.28	99.86%	595.88	100.00%	554.59
Rain (mm)	99.88%	421.11	99.86%	427.28	100.00%	407.02
Snow (cm)	99.88%	213.60	99.86%	200.24	100.00%	147.57

It is important that the data for the 1971-1975 period are not too different from the proceeding 25 years. As such, using the Airport station, the five years were removed from the 30-year time series and the annual averages were recalculated. The removal of the data for the 1971-1975 time period changed the average annual temperature by approximately 0.22°C as the first five years were upwards of 1°C cooler on average than the following 25 years. Thus, any projections that are not inclusive of the 1971-1975 time period in their observed data are slightly conservative in nature in that the observed baseline is actually slightly cooler than what is presented in this thesis. When working with annual averages over decadal timescales, this slight discrepancy in time period is negligible and as such, the STP station was used for the climatological normal period. **Figure 12,** below, illustrates the monthly variation in temperatures and precipitation for the 1976-2000 climatological normal period.

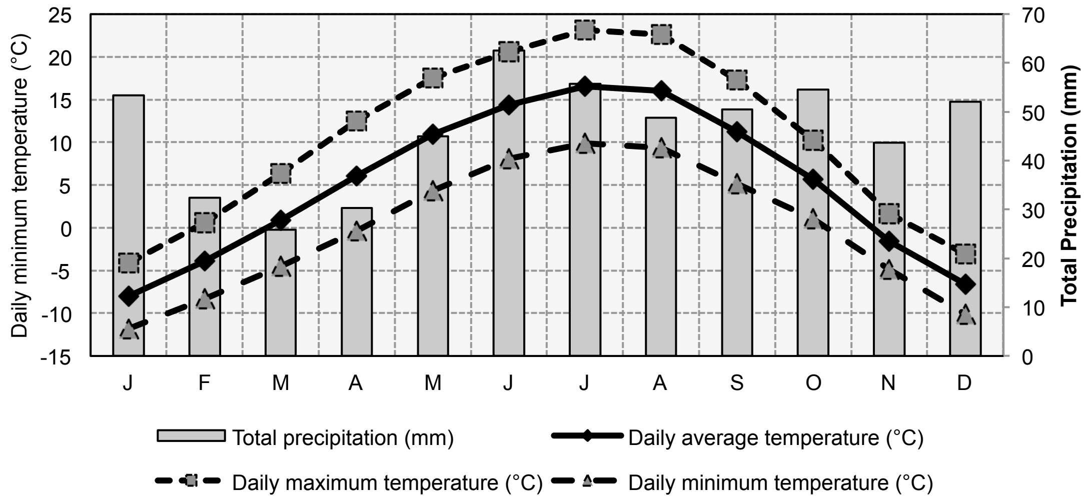

Figure 12: Temperature and precipitation in Prince George for the climatological normal period (1976-2000)

4.3 Winter severity index development

In order for the WSI to be of operational relevance to decision makers, the WSI must be easy to interpret and communicate. Calculating the WSI at the daily level allows for clear links between observed maintenance activities and observed weather. This model was therefore designed to be of practical relevance where days were assigned a score between zero (no maintenance) and 0.75 (an upper limit that emerged from the optimization process). It should be noted that it is common practice for the City of Prince George to allocate three days of clean-up for any winter weather event in which more than 5cm of snowfall accumulated. Accounting for an extended clean-up time that may occur in response to more severe winter weather events is difficult to incorporate at the daily level and as such it is appropriate to work at monthly, seasonal, or yearly levels for model testing.

Previous research has indicated that the amount of snowfall affects the practices and duration of WRM activity (Suggett *et al.,* 2006; Suggett *et al.,* 2007; Venäläinen & Kangas, 2003). In addition to snowfall, icing that happens when rainfall occurs with or before freezing temperatures can also lead to the need for snow and ice control. Although other variables such as blowing snow, freezing rain, prolonged periods of cold temperature, and pavement conditions may also necessitate WRM activities, there were limitations in data availability for related variables.

Furthermore, there was the need for a WSI that could be applied to modeled climate data and, as such, this WSI was limited to two weather conditions: 1) the number of days of snowfall, and 2) the number of days with the potential for icing during or after rainfall (rain occurring on days where temperature are within the freezing range). **Table 7**, below, outlines the explanatory variables that were used in the development of this WSI that was calibrated to annual WRM expenditures in the City of Prince George. Index calibration involved the determination of eight constants (A though H) using an optimization routine (related to model fit). These constants are shown in **Table 7**.

Table 7: WSI Constants (A through H)

Index Component	***Component Variables***	***Daily Score***
Snowfall (low)	Low Amount of Snow (0.4 to A cm)	Daily score E
Snowfall (moderate)	Moderate Amount of Snow (A to B cm)	Daily score F
Snowfall (high)	High Amount of Snow (> B cm)	Daily score G
Potential Icing	< 0.4 cm daily snowfall, > C mm of rainfall, ≤D°C minimum daily temperature	Daily score H

Most of the existing WSIs use salt/deicing use, snowplow hours, or other materials use (sand, gravel, fracture) as a response variable. For this study, the WSI scores were correlated to actual snow and ice control expenses (by calendar year) from 1994 to 2012. The decision to use annual WRM expenditures as a response variable for the WSI development was chosen because of its practical relevance for decision makers. Data limitations prevented extension of the WSI to other variables. WRM materials use and snow dumping data were provided by the City of Prince George in the form of daily records. In addition to materials use data, snow dumping (m^3) was also provided at the daily level. However, there were a number of quality control issues associated with these data in that there were a number of months missing and data from 2004-2005 and the 2007-2008 seasons were missing in their entirety. Furthermore, there had been a number of technological advances and changes in practices that have occurred over the past two decades in the City of Prince George, and as such, it was decided that annual expenditures (adjusted for inflation) were the most appropriate indicator of maintenance activities.

For each of the constants (**Table 7**), an optimization routine in *Microsoft Excel* was used to define thresholds values while simultaneously assigning scores. This optimization routine uses the Generalized Reduced Gradient (GRG2) Algorithm that is included in *Microsoft Excel*. The values for these constants are provided in the third column of **Table 8**, and are specific to the City of Prince George maintenance area and to annual maintenance expenditures as a measure of maintenance activity.

Table 8: Snowfall Constants and Days Meeting Criteria

Index Component	***Component Variables***	***Daily Score***
Snowfall (low)	Low Amount of Snow (0.4 to 2 cm)	0.1
Snowfall (moderate)	Moderate Amount of Snow (2.1 to 5.1 cm)	0.2
Snowfall (high)	High Amount of Snow (> 5.2 cm)	0.75
Potential Icing	< 0.4 cm daily snowfall, rainfall > ≤0°C minimum daily temperature	0.25

Each day with measurable snowfall (i.e., ≥ 0.4 cm of snowfall or ≥ 0.4 mm liquid precipitation equivalent) was assigned to one of three categories: low accumulation, moderate accumulation, and high accumulation. Previous studies, based on expert judgment and goodness of fit (Andrey & Matthews, 2012) used the following three categories: 0.4 to 1.9 cm, 2.0 to 4.9 cm, and 5.0 cm or more. Interestingly, as shown above (**Table 8**), the threshold values determined by the *Microsoft Excel* optimization algorithm are very similar to what has been used in previous WSI development studies, but are different in small ways because of the site-specific calibration.

4.4 Winter severity index technical results

A WSI has been created to explain year-to-year variations in WRM expenditures in the City of Prince George. This index illustrates a clear relationship between the weather of a given year and the millions of dollars spent on WRM activities. **Figure 13** illustrates the annual variation in both WSI and expenditure, and **Figure 14** shows the very strong correlation between these two. As shown in **Figure 14**, the coefficient of determination (R^2) between annual WSI and annual expenditures is 0.93, which represents a very good fit.

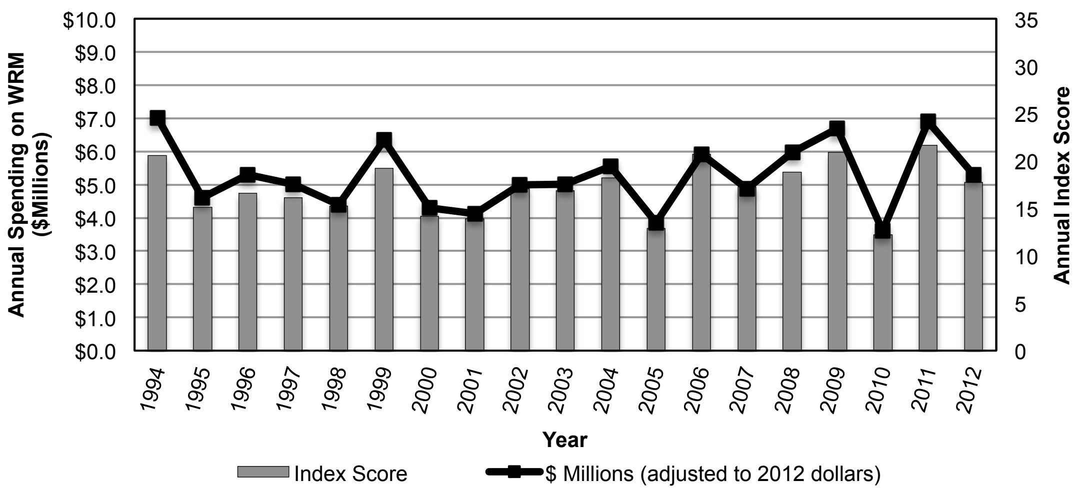

Figure 13: Winter Severity and Winter Maintenance in Prince George, BC over the past 18 years

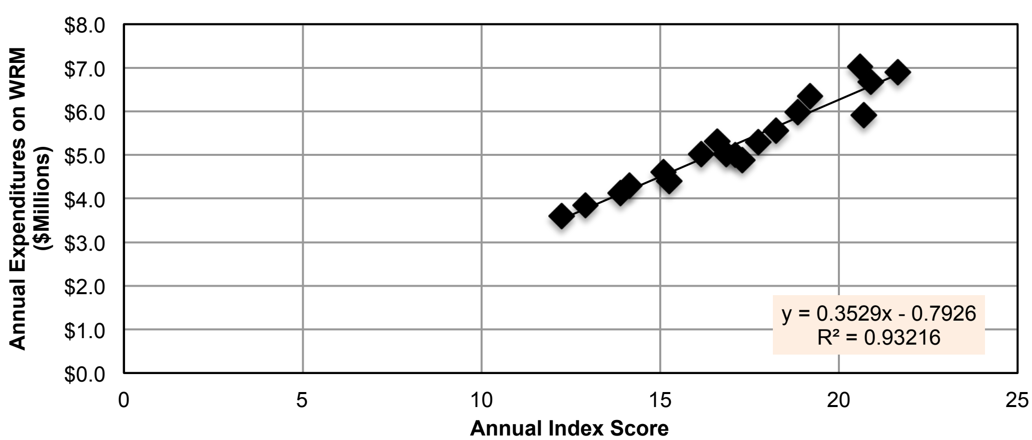

Figure 14: Correlation between WSI and expenditures on WRM in Prince George, BC from 1994-2012

This index has two main components: the number of days of snowfall and the number of days with the potential for icing during or after rainfall (rain occurring on days where temperatures are within the freezing range). Daily scores were calculated for each day during the 18-year study period. Altogether, there were 6575 days during the study period, 1213 of which met the criteria for one of the conditions considered as potential maintenance triggers. The daily scores were then aggregated to the yearly level (simple addition), with yearly values ranging from 12.05 (2010) to 21.65 (2011). The average annual WSI score was 17.2 and average annual expenditures on snow and ice control were $5.4 million annually from 1994-2012 (adjusted to 2012 dollars).

Table 9: Snowfall Constants and Days Meeting Criteria for 1994-2013

Index Component	***Component Variables***	***Daily Score***	***Number of Days (annual mean)***	***Contribution to WSI (annual mean)***
Snowfall (low)	Low Amount of Snow (0.4 to 2 cm)	0.1	386 (20.3)	36.60 (2.0)
Snowfall (moderate)	Moderate Amount of Snow (2.1 to 5.1 cm)	0.2	248 (13.1)	49.60 (2.6)
Snowfall (high)	High Amount of Snow (> 5.2 cm)	0.75	185 (9.7)	138.75 (7.3)
Potential Icing	< 0.4 cm daily snowfall, rainfall > 0.4cm ≤0°C minimum daily temperature	0.25	394 (20.7)	98.50 (5.2)
Total			1213 (63.8)	325.45 (17.1)

One limitation of this method is that the use of the *Microsoft Excel* optimization algorithm has likely led to over-fitting of the data. This is especially a concern when working with small datasets. In order to test the predictive accuracy of the model, and therefore the degree of over-fitting that has occurred, the results from the original WSI developed by Andrey and Matthews (2012) relative to the new calibrated WSI presented in this thesis are compared. There are two simple ways to calculate the predictive accuracy of the model. The first method is through the use of test-set cross-validation. This is done through the use of training (model calibration) and testing datasets. The second method is through use of the leave-one-out cross-validation method. Both of these methods use the MSE (mean squared error or the sum of squared residuals) as an indicator of predictive accuracy. The model with the lowest MSE is considered the best model.

To use the leave-one-out cross validation method, one data point (year) is excluded and the line of best fit is computed. Then the residual for the left-out data point is computed (the residual is the difference between the expenditures point and the model-estimated expenditures). This process is repeated for each of the data points in the model. These residuals are then squared and added together to obtain the MSE. The model with the lowest MSE is considered to have the best predictive accuracy and as **Table 10** shows, the calibrated WSI developed for this thesis has the better predictive accuracy than the model developed for Environment Canada.

In future studies, a longer time period, or a finer resolution response variable (*e.g.,* monthly expenditures) would allow for the partitioning of the observations into a training (model calibration) data set and a testing data set. This would provide a more realistic assessment of the robustness of the model. However, 18 years of WRM expenditures provides a adequate dataset for the purposes of this study. Now that a clear relationship between WRM practices (as a function of expenditures) and weather has been established, it is possible to project the impact of changing climate and weather on WRM in the City of Prince George.

Table 10: Comparison of model performance

Year	*Expenditures ($Millions)*	*Calibrated WSI Index Scores*	*Residuals for Calibrated WSI*	*Residuals^2 Calibrated WSI*	*EC WSI Index Score*	*Residuals for EC WSI*	*Residuals^2 for EC WSI*
1994	$7.02	20.60	0.56	0.32	30.50	1.16	1.35
1995	$4.61	15.85	-0.20	0.04	27.20	-0.71	0.51
1996	$5.31	16.05	0.43	0.19	24.30	0.46	0.21
1997	$5.01	15.95	0.17	0.03	22.20	0.50	0.25
1998	$4.40	15.45	-0.27	0.07	24.90	-0.55	0.30
1999	$6.35	19.75	0.19	0.04	30.40	0.51	0.26
2000	$4.30	13.40	0.34	0.12	20.70	0.04	0.00
2001	$4.12	14.00	-0.05	0.00	19.60	0.03	0.00
2002	$5.00	17.10	-0.24	0.06	27.20	-0.32	0.10
2003	$5.02	16.75	-0.10	0.01	27.50	-0.35	0.12
2004	$5.56	18.25	-0.08	0.01	30.20	-0.25	0.06
2005	$3.85	13.15	-0.02	0.00	18.00	0.02	0.00
2006	$5.91	20.45	-0.49	0.24	29.50	0.21	0.05
2007	$4.88	17.40	-0.47	0.22	31.10	-1.08	1.16
2008	$5.98	18.95	0.10	0.01	28.10	0.51	0.26
2009	$6.68	20.90	0.12	0.01	35.60	-0.01	0.00
2010	$3.60	12.05	0.11	0.01	17.00	-0.06	0.00
2011	$6.90	21.65	0.08	0.01	34.60	0.37	0.14
2012	$5.30	17.75	-0.17	0.03	30.00	-0.48	0.23
MSE				**0.088**			**0.313**

5 Climate change analysis of demand for WRM

In order to assess the implications of climate change for WRM in the City of Prince George, this study applies the WSI to current and future climate simulations. The percent change in WSI scores between the simulated current and future periods is used to provide an indication as to how climate change could impact WRM needs in Prince George. The first stage of the climate change analysis is the selection of climate data; it is important that thoughtful consideration is paid to choosing climate scenarios and data.

5.1 Climate scenario selection

Climate scenarios are projections of future climates based on emissions scenarios that have been applied to global climate models (GCMs). Emissions scenarios are divided into groups of storylines. These storylines, developed by the IPCC, are known as the SRES series (Special Report on Emissions Scenarios) (Nakićenović & Swart, 2000). These storylines provide a range of possible futures regarding economic, demographic, and technological states that would influence anthropogenic GHG and aerosol emissions. The main storylines (A1, A2, B1, B2) are then further divided into scenario groups. These storylines were used to develop scenarios for IPCC's third and fourth assessment reports, as seen in **Figure 15**. While the fifth assessment reports use relative concentration pathways (RCPs) instead of the SRES series (IPCC, 2013), the RCP model data were not publicly available at the time of analysis.

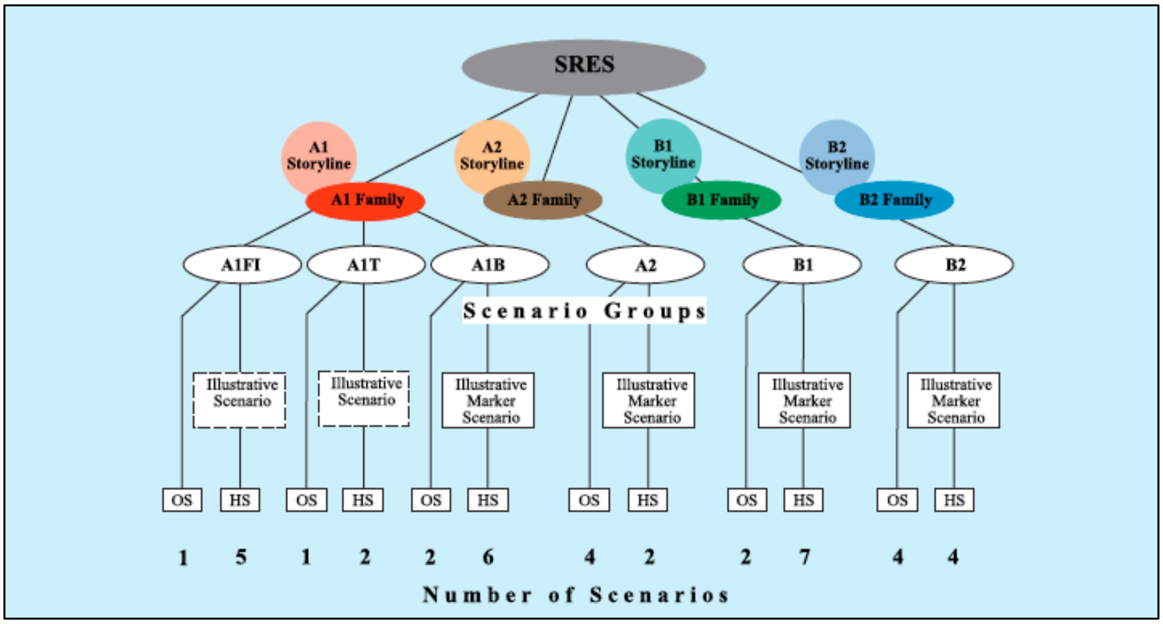

Figure 15: Diagram of SRES storylines and scenarios (reprinted from Nakićenović & Swart, 2000)

This thesis focuses of scenario groups A1B, A2 and B1, as these are seen to be the mid-range of projections. The A1 storyline projects a future that involves rapid economic growth along with a rapid adoption of efficient technologies. In this storyline, world population peaks in the 2050s and then declines (Nakićenović & Swart, 2000). There are three groups in the A1 storyline and these are differentiated by the dominant projected energy sources. The A1B scenario group is based on a balance between fossil intensive and non-fossil intensive energy sources. In the A2 storyline, there is a focus on slower growth and technological change, but also slower, but consistently increasing projections of population growth (Nakićenović & Swart, 2000). The A1B storyline also has a focus on regional development and growth rather than a homogeneous global growth present in the A1 and B1 storylines. The B1 storyline is very similar to the A1 storyline except that there is a greater emphasis on a service, knowledge, and information economy that would result in reduced demand for material resources and energy (Nakićenović & Swart, 2000). The B1 storyline emphasises a global solution to reducing fossil-fuel dependency and improved global equity, but this storyline assumes that additional climate initiatives would not be implemented (Nakićenović & Swart, 2000).

These scenarios, when applied to the variety of GCMs, result in hundreds of GCM experiments. Deciding which of these experiments to use for impacts and adaptations research can be difficult. Metrics and performance measures have been developed to assess these experiments (Gleckler *et al.,* 2008; Moore *et al.,* 2010), but assigning weights of likelihoods to one future over another should be avoided (Murdock & Spittlehouse, 2011). Still, while all scenarios in the IPCC fourth assessment should be seen as equally plausible on the global scale, it is suggested that a range of GCM experiments should be used for impacts and adaptation research to illustrate the range of possible change to a system (CCCSN, 2014; Murdock & Spittlehouse, 2011).

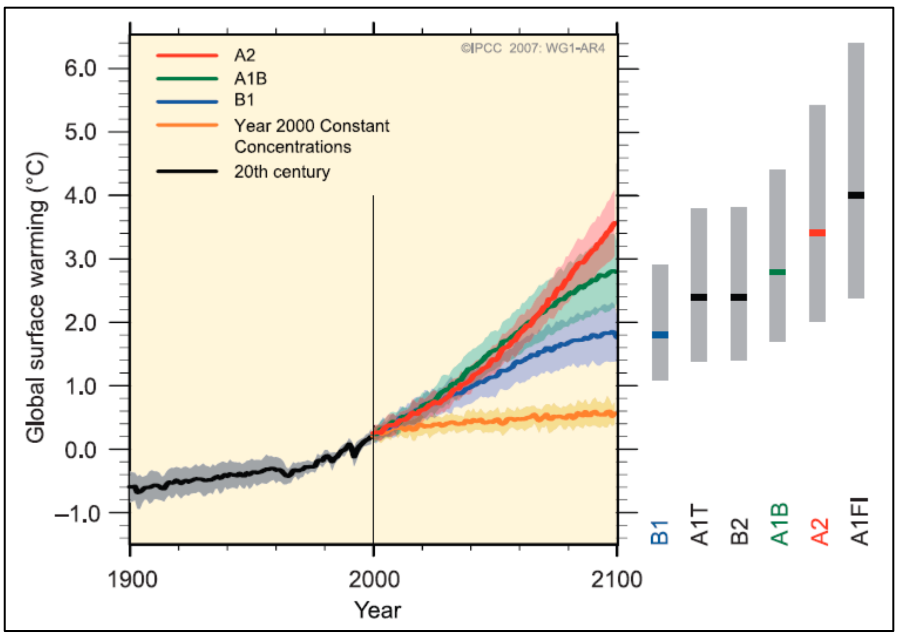

Figure 16: Multi-model averages and assessed ranges for surface warming (reprinted from IPCC, 2007)

5.2 Climate change projections for CCIAV research

There are three main approaches for obtaining modeled climate scenario data: 1) model-based (either GCM or RCM), 2) synthetic or statistically downscaled, and 3) analogue. Model-based data can be derived either directly from the climate model, or through the Change Factor Methodology (CFM) which is a manipulation of the observed weather data for a given location (Anandhi *et al*., 2011). Synthetic and statistically downscaled data are computationally more cumbersome and can be achieved through various methods such as weather generators, and weather classification methods (Anandhi *et al.,* 2008; Brinkmann, 1999). The analogue methodology uses existing weather data from different climatic areas, and has been used in CCIAV studies (Ford *et al.,* 2010; Hellegatte *et al.,* 2007; Dawson *et al.,* 2009). This thesis focuses on the first approach and uses direct model output as well as the CFM.

GCMs are performing increasingly well in modeling the climate system on global and continental scales. However, as the spatial scale of interest decreases, so too does the certainty of the projections. Furthermore, the intended purpose of the research needs to be considered when choosing which type of modeled data would be best suited for the research project. Given the need for local-scale data, it is important to have high-resolution time series data. As such, there are a few ways to obtain data high-resolution data that is well suited for CCIAV research on regional or municipal scales. There is a variety of online data centers that store and distribute GCM output data. The Canadian Climate Change Scenarios Network (CCCSN), the National Aeronautics and Space Administration (NASA) and the IPCC's Data Distribution Centre all make output data available. The IPCC stipulates that for GCMs to be included in these data centres, they must have been peer-reviewed and participated in model inter-comparison studies (IPCC-TGICA, 2007).

While it is important to select a range of GCM experiments, it is equally important to assess and compare the climate scenario data from a suite of approaches (Teutschbein & Seibert, 2012). While RCMs are considered better than GCMs as simulating temperature and precipitation, they still hold substantial bias and should be used with caution. It is recommended to use an ensemble of projections together with bias correction because there is inherent uncertainty in climate models (Teutschbein & Seibert, 2012) and it is therefore good practice to apply a variety of approaches and models to the same problem as to provide a more comprehensive estimate and increase the confidence and range of the projections (CCCSN, 2014; Barrow *et al.,* 2004). As such, this thesis compares the results from the model output method of RCMs and GCMs as well as a comprehensive examination of the CFM process for 65 scenarios.

5.3 Model output method

Model output data have been used in in a variety of studies, some of which have used GCM data (Wilby *et al.,* 2002; Ines & Hansen, 2006), some have used RCM data (Hambly *et al.,* 2013), and others a combination (Fronzek & Carter, 2007). The use RCMs has been cited as the preferable option as they are thought to perform better for regional analyses than GCMs (Fronzek & Carter, 2007). While the RCMs use a higher resolution grid cell of 50km by 50km, the GCMs use lower resolution grid cells of 150-200km and as such may be less valuable in CCIAV research (Teutschbein & Seibert, 2012; Murdock & Spittlehouse, 2011). However, it has been cited that it is best to use a range of scenarios and included both RCMs and GCMs (Murdock & Spittlehouse, 2011). As such, this thesis uses three RCMs and two GCMs.

The three RCMs, based on the SRES-A2, represent the mid-range of future climate for Prince George and data are from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP is a program that develops regional climate change simulations that are appropriate for use by impacts and adaptation researchers (Mearns *et al.,* 2009). The two other models (GCMs), are also based on the SRES-A2 scenario, and are the driving GCMs for the RCMs used in this study. The first model, CCCMA_cgcm3_1, is from the Canadian Climate Change Scenarios Network (CCCSN) and the second model, GFDL_cm2_1, is from the Geophysical Fluid Dynamics Laboratory (GFDL) developed by the National Oceanic and Atmospheric Administration (NOAA) in the USA. **Table 11** lists the models used in this portion of the analysis along with the location of their grid centers and their distance from the Prince George STP weather station. All three RCMs use 1971-2000 as the baseline climate period (20C), and the simulated future period is 2041-2070 (21C). The two GCMs use the same 20C period of 1971-2000, but they have a shorter 21C future period of 2046-2065 as its mid-2050s scenario.

Table 11: Location of model grid centers relative to Prince George STP weather station

Location/model	*Latitude*	*Longitude*	*Elevation*	*Distance from STP*	*20C*	*21C*
Prince George STP	53°52' N	122°46' W	616 m	--	1976-2000	NA
CCCMA_cgcm3_1	53°5' N	123°45' W	947 m	87.4 km	1971-2000	2045-2064
CRCM_cgcm3	54°3' N	122°44' W	689 m	20.5 km	1971-2000	2041-2070
RCM3_cgcm3	54°1' N	122°30' W	722 m	24.1 km	1971-2000	2041-2070
GFDL_cm2_1	53°0' N	123°45' W	1083 m	116.3 km	1971-2000	2045-2064
RCM3_gfdl	54°1' N	122°30' W	722 m	49.8 km	1971-2000	2041-2070

In the past decade the use of model-based data has been popular in the climate change impacts field (Barrow *et al.,* 2004). These data can be obtained directly from the climate modeling providers; however, there are four key limitations of using the modeled data. The first limitation is that only a limited number of GCM runs have made daily level data available because of storage constraints. A second limitation is that most of these climate models have temperature and precipitation biases that need to be rectified before being used in CCIAV studies. A third limitation of these data sets and this is the presence of the 'drizzle effect' and a fourth limitation is that the modeled data do not differentiate between snow and rain. Overcoming the first limitation is straightforward in that only simulations that have daily level data are selected for this research. Overcoming the other thee limitations requires a little more investigation.

Modeled climate data biases are evident by comparing the difference between the observed weather data and the current period in the modeled data. Difference in temperature and precipitation between observed data and the modeled data then needs to be corrected for both the current and future modeled data before the analysis can take place (Anandhi *et al.,* 2011; Jakob Themeßl *et al.,* 2011). A temperature bias is particularly important because a small change in temperature will determine whether precipitation falls as rain or snow. Seeing as the modeled data do not differentiate between rain and snow, temperature is used to identify precipitation days as either snow days or rain days. As such, any bias must be corrected before further analysis can take place.

As seen in **Table 12**, there is a substantial wet bias across all five models. The models in this research over-represent observed total precipitation by up to 156%. Furthermore, there is also a strong cold bias in the models. Observed minimum and maximum temperatures are also both underrepresented in these models (**Table 12**).

Table 12: Model bias relative to observed climate (20C) for the Prince George area (1976-2000) – before adjustment

Experiment	*Annual precip bias (%)*	*Annual Tmean bias (°C)*	*Annual Tmin bias (°C)*	*Annual Tmax bias (°C)*
CCCMA_cgcm3_1	+156%	-6.6	-5.9	-7.3
CRCM_cgcm3	+100%	-6.8	-6.2	-6.5
RCM3_cgcm3	+87%	-4.7	-2.7	-5.9
GFDL_cm2_1	+101%	-6.5	-5.0	-7.9
RCM3_gfdl	+70%	-6.4	-4.6	-7.3

Seeing as it is expected that both the 20C and 21C period have the same bias, a comparison of the difference between the two periods could still be seen as accurate. It is precisely for this reason, however, that comparisons between the observed data and projections of future climate should not be made and instead projections should be based on the relative change between the modeled 20C and 21C datasets.

The bias in the modeled data can be corrected to ensure that the datasets are comparable. As such, the 20C and 21C time period were adjusted in to remove the temperature and wet biases. For example, the RCM3_gfdl model underrepresented daily minimum temperatures by 4.6°C (RCM3_gfdl was on average 4.6°C colder during the 20C period relative to the observed weather). Therefore, to complete the adjustment, 4.6°C was added to the minimum temperature in everyday of the 20C and 21C period. This process was repeated for each model and each temperature variable (Tmin, Tmean, and Tmax). **Figure 17** illustrates that all five models represent observed monthly daily minimum temperatures well for the 20C period after the adjustment was completed.

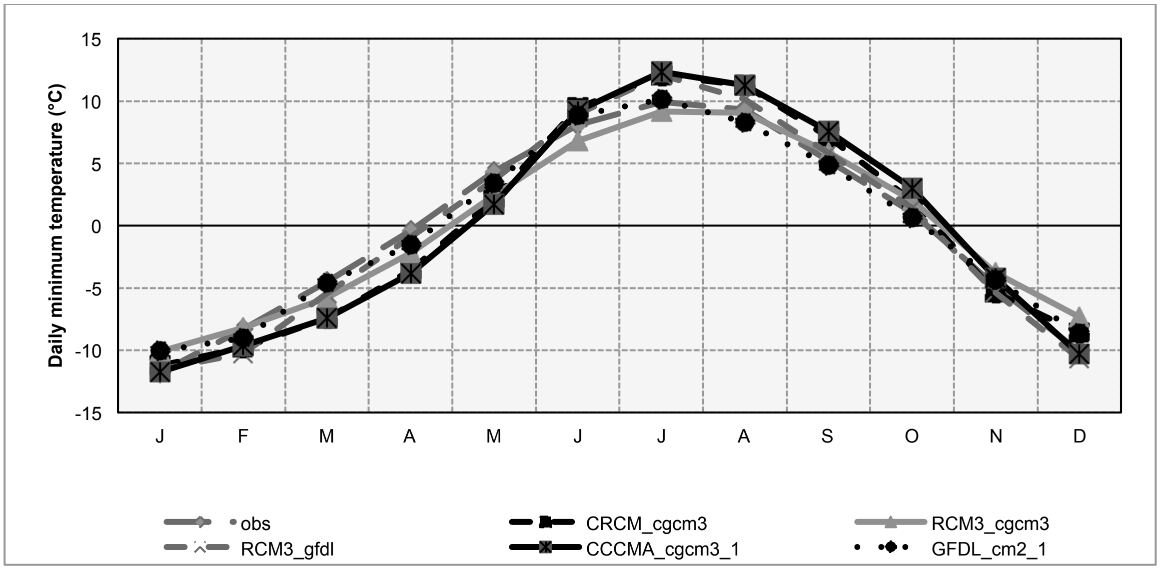

Figure 17: Model ability to reproduce Prince George STP observed minimum monthly minimum temperature (after adjustment by mean annual difference), 1971-2000

Adjusting for the wet bias was not as straightforward. Using the RCM3_gfdl model again as an example, the limitation of using modeled output data becomes increasingly evident. The RCM3_gfdl model overrepresented precipitation by 101% (20C=1120mm of precipitation compared to 555mm of precipitation for the observed). This bias was partially rectified by subtracting 101% from the precipitation amount in everyday of the 20C and 21C datasets. However, there is a limitation to this approach because it is not possible to have a negative amount of precipitation in a given day. As such, any day that had 0mm of precipitation remains at 0mm of precipitation, while all the other days were adjusted. This means that a bias still exists in the modeled precipitation data. However, seeing as it is the difference between the 20C and 21C periods that is important in this research, this bias will have little impact on the percent change between the time periods (Fronzek & Carter, 2007).

Table 13: Model bias relative to observed climate (20C) for the Prince George area (1971-2000) after adjustment

Experiment	*Annual precipitation bias (%)*	*Average annual Tmean bias (°C)*	*Average annual Tmin bias (°C)*	*Average annual Tmax bias (°C)*
CCCMA_cgcm3_1	56%	0	0	0
CRCM_cgcm3	49%	0	0	0
RCM3_cgcm3	80%	0	0	0
GFDL_cm2_1	42%	0	0	0
RCM3_gfdl	53%	0	0	0

A third limitation of these data relates to the presence of the 'drizzle effect', generally displayed as an over-representation of low-accumulation precipitation events and an underrepresentation of high-accumulation events (Denis *et al.,* 2002; Maraun, 2013). This 'drizzle effect' occurs due to the coarse resolution of the models.The precipitation is evenly dispersed throughout the grid cell, which is substantially different from how precipitation occurs. The topography and micro-climatic conditions are not evident in these models, especially with GCMs that have grid cells of 150km by 200km (Maraun, 2013). While RCMs continue to be developed, a grid cell of 50km by 50km is still quite large to encompass micro-climatic conditions (Teutschbein & Seibert, 2012; Jakob Themeßl *et al.,* 2011; Maraun, 2013).

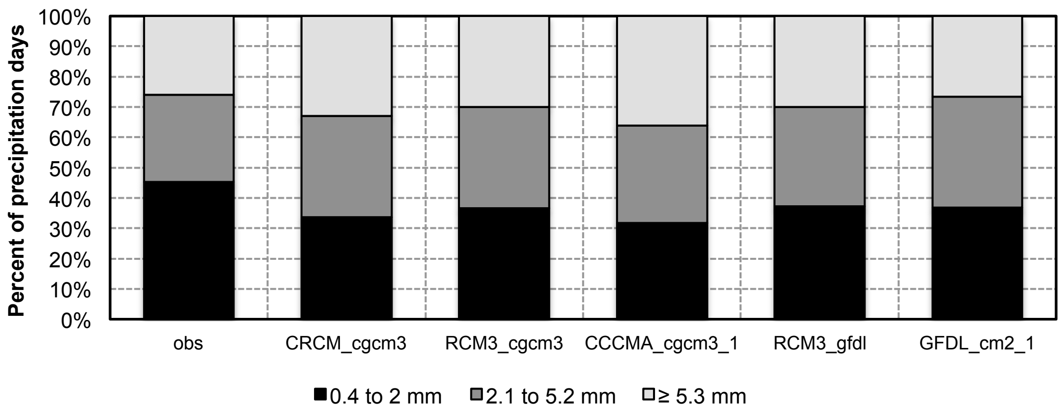

Figure 18: Model ability to reproduce Prince George STP observed distribution of precipitation days after adjustment

Despite these concerns, as seen in **Figure 18** there is little difference in the distribution of precipitation days between the RCMs and the GCMs. Generally the modeled data for Prince George underrepresent the low precipitation days (0.4 – 2.0 mm precipitation) and overrepresent the medium and high precipitation days (2.1 to 5.2 mm and ≥5.3 mm of precipitation). These three categories of precipitation amounts were chosen in order to be consistent with the precipitation categories used in the calculation of the WSI. While the distribution of precipitation days is quite similar between the two time periods, the discrepancy in the total amount of precipitation and the number of days of precipitation between the observed and modeled data exists despite attempts to remove the bias. This further reiterates the importance of making relative comparisons between 20C and 21C of the modeled data and not directly with the observed or study period data when using modeled output data.

The fourth limitation is that modeled climate data do not differentiate between snow and rain, but the WSI models rely heavily on such differentiation. As such, a temperature threshold was used to partition the modeled daily data in order to assign a day as either a day with snowfall or a day with only rainfall. In order to determine which temperature threshold should be used, an investigation of the observed data took place. For the observed period, 64.7% of the precipitation fell as rain, and 35.3% fell as snow. *Excel* solver was employed to determine the cutoff point for the daily mean temperature that resulted in the same proportion of rain and snowfall when partitioning total precipitation based on temperature. A daily mean temperature value of 1.5 was assigned as the threshold point. All days where the mean temperature was >1.5°C was assigned as rainfall. All days with a mean temperature of ≤ 1.5°C was assigned as snowfall. This resulted in 64.6% of the precipitation being assigned to rainfall and 35.4% as snowfall. There is a limitation of this approach in that each day with precipitation is only assigned as either snow or rain, whereas in reality there are days with both snow and rain. However, seeing as the WSI will only count a single weather component on a given day, this classification of precipitation days should not change the results.

Table 14: Identifying rain and snowfall days (1976-2000)

	Total precip (mm)	*Total rain (mm)*	*Total snow (cm)*	*$\bar{x}$ WSI (20C)*	*St.dev WSI*	*10th percentile WSI*	*90th percentile WSI*
Observed – snow and rain data	13930	9015	4914	19.46	4.74	12.72	25.80
Observed – after 1.5°C threshold was used	13930	8998	4931	20.00	5.08	13.18	27.05

5.3.1 Model output method: technical results

This section outlines the future climate change for the City of Prince George. Although the five climate simulations are not the same with regards to their magnitude, they all suggest that, by the mid-century, the area is expected to be warmer and wetter. **Figure 19** and **Figure 20**, show the projected changes in precipitation and temperature for the 2050s in the City of Prince George

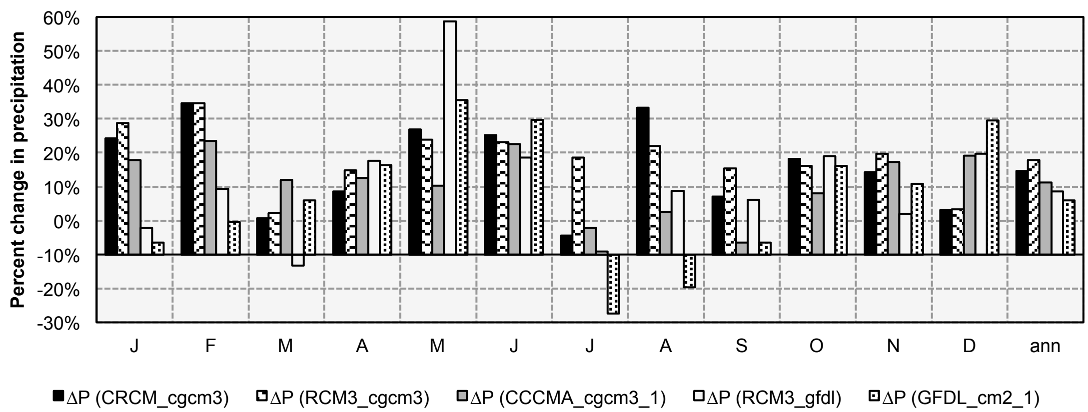

Figure 19: Projected monthly changes in precipitation for the City of Prince George for the 2050s

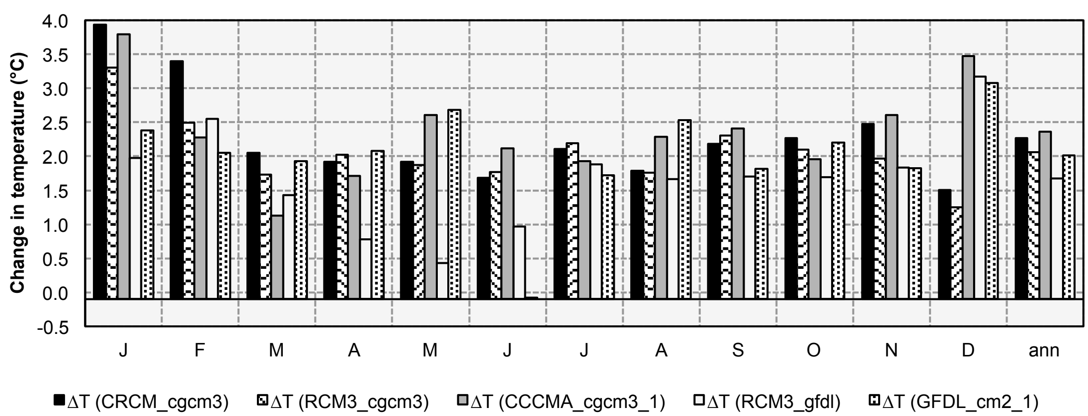

Figure 20: Projected monthly changes in mean temperature for the City of Prince George for the 2050s

By applying these model output data to the WSI calculator, the percent change in the WSI between 20C and 21C can be established. **Table 15**, below, outlines the WSI scores for all five models in both the 20C and 21C time periods. The 20C WSI scores are lower for the modeled data than for the observed weather data because of the presence of the drizzle effect combined with fewer precipitation days. For the observed time period, there was an average annual WSI of 20. The modeled data generally underestimated the WSI score for the current period relative to the observed data; however, as stated above, it is the relative difference between the 20C and 21C time periods that is of interest.

Table 15: WSI scores for modeled data (20C and 21C)

Experiment	*20C*				*21C*			
	$\bar{x}$WSI (20C)	*St.Dev.*	*10^{th} percentile*	*90^{th} percentile*	*$\bar{x}$WSI (21C)*	*St.Dev.*	*10^{th} percentile*	*90^{th} percentile*
CCCMA_cgcm3_1	22.67	4.52	16.96	28.55	15.89	4.03	9.34	20.65
CRCM_cgcm3	18.11	4.44	12.97	21.60	13.17	3.13	9.58	18.20
RCM3_cgcm3	16.67	3.69	11.63	21.35	12.34	3.09	7.93	16.80
GFDL_cm2_1	15.94	3.89	10.67	22.80	12.21	3.06	8.07	16.85
RCM3_gfdl	13.68	2.81	9.65	16.90	10.70	3.01	7.58	14.60

Based on the model output method, these results indicate that, on average, there will be a net decrease in the severity of winter weather, and therefore a decrease in the amount of resources needed for WRM into the mid-century. Overall the projected decrease is between 21.8% and 29.9%, largely because of warmer winter temperatures (**Figure 22**).

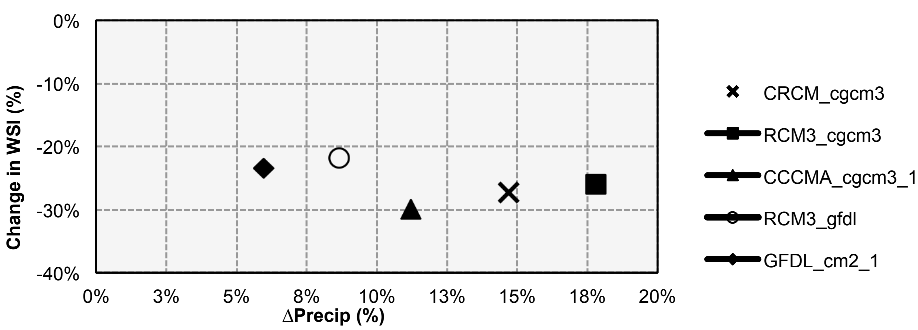

Figure 21: Projected changes to precipitation and winter severity in Prince George for the 2050s

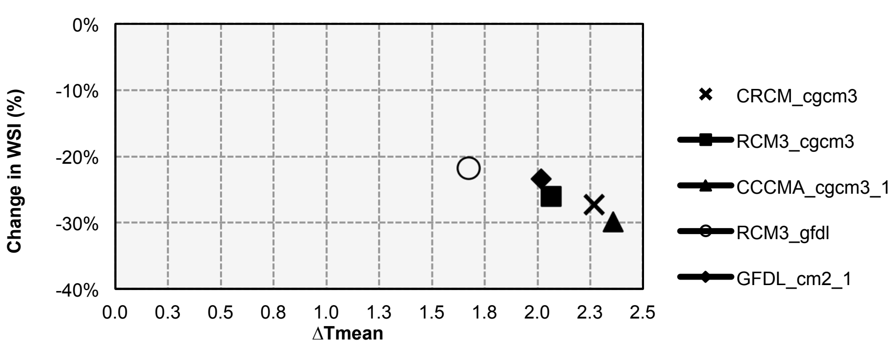

Figure 22: Projected changes to temperature and winter severity in Prince George for the 2050s

5.4 Change factor method

The CFM, also referred to as the delta method in some literature, has some advantages over the use of model output data or statistically downscaling techniques (Anandhi *et al.,* 2011). The first main advantage is its ease of implementation. There is only a need for two pieces of information: 1) complete daily level observed data for the research area and 2) access to climate anomalies (or delta) for the variables of interest. These anomalies can be obtained through downloading the daily level model output data and calculating the difference between 20C and 21C, but there are also a number of readily available products that provide these anomalies for a specified location. The Canadian Climate Change Scenarios Network (CCCSN) provides a suite of model output data, mostly in the form of climate anomalies that can then be applied to observed whether data to obtain future climate projections for a given location. Through the CCCSN website, as well as the PCIC website, it is possible to view and download a wide range of climate anomalies for hundreds of climate experiments specific to a region of interest. These anomalies can then be applied to observed weather data for that area. Using the CFM approach, one is able to assess a wide range of possible futures.

There are two main methods of applying the CFM approach, additive and multiplicative. For the additive approach, the mean difference between 20C and 21C for a given location is computed. This difference (also referred to as delta or climate anomaly) is then added to the observed data. The additive approach is usually used for temperature variables. A multiplicative approach, however, is best used for precipitation variables where it is the ratio (or percent) difference between 20C and 21C that is important. The observed precipitation data are then multiplied by the percent change in projected precipitation (Kilsby *et al.,* 2007; Anandhi *et al.,* 2011; Hay *et al.,* 2000; Akhtar *et al.,* 2008). Anandhi *et al*. (2011) have assessed various additional CFM methodologies, all of which are more computationally complex, and they found that the use of the additive and multiplicative approach is most appropriate when looking at projected trends in climate impacts. However, if the purpose of the research was to investigate the impact of changing extremes and variability, then other CFM approaches would be more appropriate. For the purposes of this study, the additive and multiplicative CFM approaches are used.

Table 16: Projections of climate change (21C-20C after adjustment)

Model/simulation	*Annual Δ Tmean (°C)*	*Annual Δ Tmin (°C)*	*Annual Δ Tmax (°C)*	*Annual Δ Precip (mm)*	*Annual Δ Precip (%)*
CCCMA_cgcm3_1*	2.4	2.7	2.0	158.1	15.9%
CRCM_cgcm3	2.3	2.6	1.9	155.7	18.0%
RCM3_cgcm3	2.1	2.3	1.8	180.2	21.9%
GFDL_cm2_1*	2.0	2.1	1.9	67.3	8.0%
RCM3_gfdl	1.7	1.9	1.5	78.3	10.0%

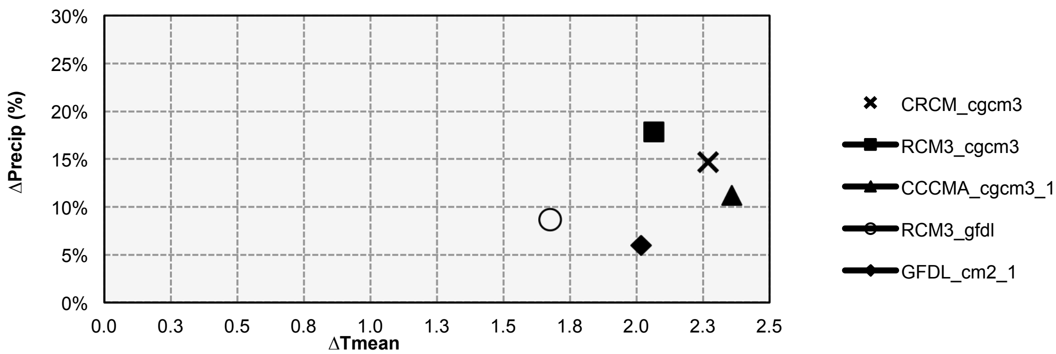

Figure 23: Projected changes to precipitation and temperature in Prince George for the 2050s

The main disadvantage of the CFM approach is that it assumes that the variability in weather will remain constant, but the means in temperatures and precipitation will change. The CFM approach applies the climate anomalies (ΔTmin, ΔTmax, ΔTmean and ΔPrecip) to observed whether data. It is important to note that the climate anomalies should only be applied to observed whether data that are consistent with the current period in the climate models; usually this period is 1960-1990 or 1970-2000. For this research, the climate anomalies were applied to observed weather data in the City of Prince George for the period of 1975-2000.

Table 17: Comparison of model output method and CFM approach when applied to WSI

Experiment	*Model output method*				*CFM approach*			
	x̄WSI (21C)	*10th percentile*	*90th percentile*	*%ΔWSI 20C/21 C*	*x̄WSI (21C)*	*10th percentile*	*90th percentile*	*%ΔWSI 20C/21 C*
CCCMA_cgcm3_1	15.89	9.34	20.65	-29.9%	15.64	8.41	23.70	-21.8%
CRCM_cgcm3	13.17	9.58	18.20	-27.3%	15.94	8.89	24.05	-20.3%
RCM3_cgcm3	12.34	7.93	16.80	-26.0%	16.84	10.60	24.05	-15.8%
GFDL_cm2_1	12.21	8.07	16.85	-23.4%	16.21	9.43	23.65	-19.0%
RCM3_gfdl	10.70	7.58	14.60	-21.8%	16.76	10.57	25.15	-16.2%

As seen in **Table 17**, there is little difference between the use of the model output and the CFM approach. While this analysis has only been completed for five models, it is possible to scale up the CFM for use with more models. The CCCSN website provides climate anomalies for a given location. These anomalies, however, are only for mean temperature and precipitation. As such, it is important to see if there are any differences between applying the CFM on one temperature variable versus three. **Table 18**, below, shows that using one temperature variable instead of three leads to slightly more conservative estimates of change.

Table 18: Comparison of CFM using Tmean anomaly vs. Tmean, Tmin and Tmax anomalies

Experiment	*Use of 3 temp variables*				*Use of 1 temp variable*			
	$\bar{x}$ WSI (21C)	*10th percentile*	*90th percentile*	*%ΔWSI 20C/21 C*	*$\bar{x}$ WSI (21C)*	*10th percentile*	*90th percentile*	*%ΔWSI 20C/21 C*
CCCMA_cgcm3_1	15.64	8.41	23.70	-21.8%	16.10	9.79	24.05	-19.5%
CRCM_cgcm3	15.94	8.89	24.05	-20.3%	16.52	9.88	24.65	-17.4%
RCM3_cgcm3	16.84	10.60	24.05	-15.8%	17.29	10.69	24.55	-13.5%
GFDL_cm2_1	16.21	9.43	23.65	-19.0%	16.29	9.46	23.65	-18.5%
RCM3_gfdl	16.76	10.57	25.15	-16.2%	17.18	10.97	25.40	-14.1%

5.4.1 CFM: technical results

Given the ease of implementation of the CFM approach relative to the model output method, combined with the need to project a range of possible futures, the CFM approach was used to project the percent change in the WSI into the mid-2050s. In order to do this, climate anomalies were downloaded from the CCCSN website for the Prince George region for 65 GCMs, spanning three scenario groups (**Table 19** and **Figure 24** provided the projected climate anomalies from the CCCSN website). The CFM additive approach was used for the temperature variable, and the multiplicative approach was used for the precipitation variable. Only the mean temperature climate anomaly was available for the majority of the models, and as such this was applied to all temperature variables. For example, if the mean temperature anomaly was 1.9°C, then 1.9°C was added to each of the daily temperature variables (Tmean, Tmin, Tmax). Thus, the analysis is most likely conservative in its estimates of future change because the daily minimum temperatures is expected to warm more than maximum daily temperatures. Annual precipitation in the City of Prince George is projected to increase by 3.7% to 10.6% for the 2050s based on the mid-range of the ensemble of 65 GCM projections. Annual temperatures are projected to increase by 1.5°C to 2.4°C for the 2050s based on the mid-range. Although the 65 climate simulations are not identical in terms of magnitude, they all project that by the 2050s, the City of Prince George is expected to be warmer and wetter.

Table 19: Annual climate anomalies downloaded from the CCCSN website for the Prince George area

	B1 runs		*A2 runs*		*A1B runs*	
Simulation	***ΔTmean (°C)***	***ΔPrecip (%)***	***ΔTmean (°C)***	***ΔPrecip (%)***	***ΔTmean (°C)***	***ΔPrecip (%)***
BCM2.0(Run 1)	0.48	7.64	0.87	8.18	1.31	10.72
CGCM3T47(Mean)	1.62	8.63	2.20	13.66	2.08	13.39
CGCM3T63(Run 1)	2.39	12.06	3.14	18.92	2.63	17.28
CNRMCM3(Run 1)	1.19	2.70	1.23	4.78	1.25	4.32
CSIROMk3.0(Run 1)	1.23	4.92	1.75	2.96	1.23	6.15
CSIROMk3.5(Run 1)	1.67	3.16	2.23	0.34	2.44	1.86
ECHAM5OM(Mean)	1.68	11.40	1.78	11.97	2.12	16.01
ECHO-G(Mean)	1.60	4.07	1.63	6.21	1.81	5.28
FGOALS-g1.0(Mean)	1.93	3.64	-	-	2.66	1.78
GFDLCM2.0(Run 1)	1.99	6.01	2.12	5.65	2.09	8.26
GFDLCM2.1(Run 1)	1.59	5.39	1.86	4.04	2.27	6.25
GISS-AOM(Mean)	1.31	6.18	-	-	1.79	10.55
GISS-EH(Mean)	-	-	-	-	1.12	-1.50
GISS-ER(Run 1)	1.42	-6.07	1.39	-11.37	1.48	-4.26
HADCM3(Run 1)	1.39	13.18	1.62	6.90	2.30	9.59
HADGEM1(Run 1)	-	-	3.21	-1.48	3.37	-3.17
INGV-SXG(Run 1)	-	-	2.26	3.84	2.19	4.04
INMCM3.0(Run 1)	1.72	12.44	2.17	11.14	2.12	5.94
IPSLCM4(Run 1)	2.41	6.04	2.80	7.50	2.82	7.79
MIROC3.2 hires(Run 1)	3.26	10.81	-	-	3.92	12.42
MIROC3.2 medres(Mean)	2.50	9.47	2.54	11.67	2.96	10.94
MRI CGCM2.3.2a(Mean)	1.06	1.21	1.29	-0.17	1.56	3.22
NCARCCSM3(Mean)	1.71	4.78	2.50	7.00	2.64	7.75
NCARPCM(Mean)	1.49	9.28	1.93	5.96	2.16	7.83

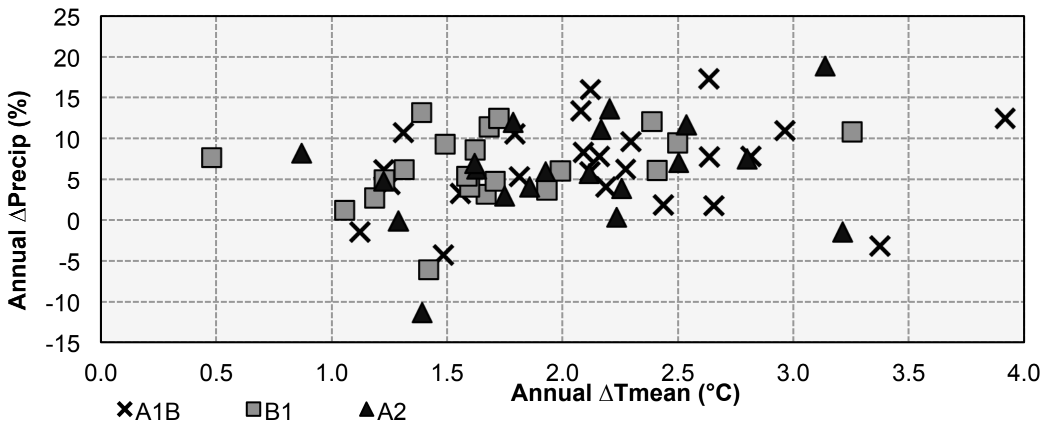

Figure 24: Projected annual changes to temperature and precipitation in Prince George for the 2050s

The WSI calculator was applied to the modeled climate data for 65 scenarios to project changes in expected budget for snow and ice control into the 2050s. Consistently, all models project a net decrease in the need for WRM activities. The average annual WSI score for the 2050s is 16.3 in comparison to 19.5 for the baseline period. The lowest annual index score for the 2050s is 3.6 and the highest is 25.1. Of the 65 models that were run, there was an average of five years out of 30 that would have WSI scores higher than 19.5. **Figure 25** and **Figure 26**, below illustrate the projected changes for the demand for WRM. Each point on these figures represents a 30-year average change in the need for WRM.

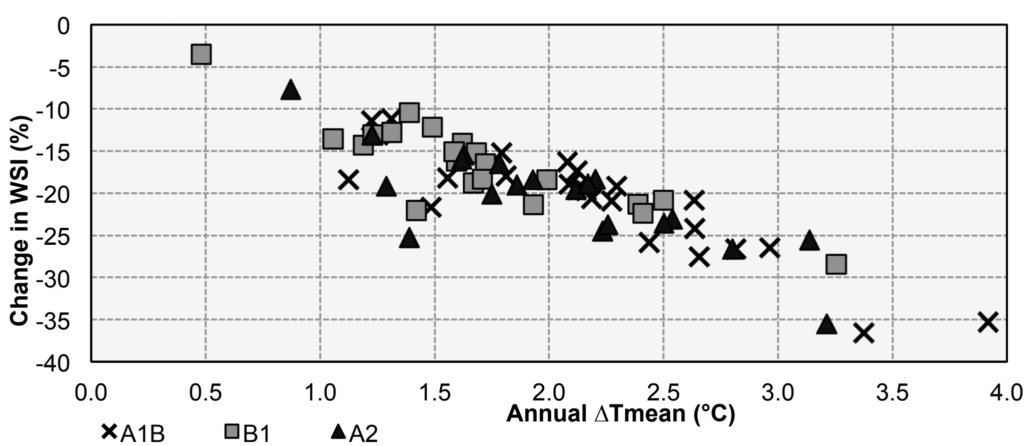

Figure 25: Projected annual changes to temperature and winter severity in Prince George for the 2050s

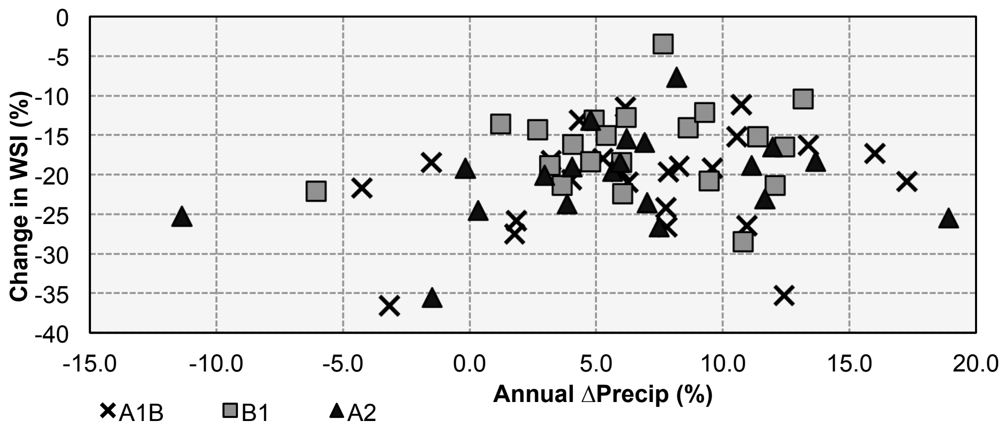

Figure 26: Projected Annual Changes to Precipitation and Winter Severity in Prince George for the 2050s

These empirical estimates of the projected change in demand for WRM expenditures in the City of Prince George addresses Objective three of the research as outlined on page four. When these modeled data were applied to the 65 scenarios, there is an indication that there will be a net benefit for the City of Prince George. Despite increasing precipitation, the warmer temperatures are projected to result in more precipitation falling as rain rather than snow. Seeing as a substantial portion of WRM expenditures is allocated to snow removal, it is estimated that there will be a net benefit for the City. Based on the mid-range (25th to 75th percentiles) of the 65 GCM projections, it is estimated that annual demand for WRM activities will decrease by 15.3% to 22.7% for the 2050s. While the estimated decrease in total annual WRM expenditures appears moderate, it is not insignificant. At an average of $5.3 million a year (adjusted to 2012 dollars), a 22.7% decrease would be results in an average annual savings of $1.2 million and 15.3% decrease would result in an average of $800,000 in annual savings for the City of Prince George.

5.5 Technical analysis: opportunities for future research

One of the limitations of the above analysis relates to the use of the CFM, which does not account for the possibility of more variability and extremes. Extremes have not been assessed as part of this research, and instead annual and overall averages have been used. The development of scenarios that examine climate variability and extremes is a key challenge facing the climate modeling community (Barrow *et al.,* 2004). Extremes occur infrequently, are localized, and are often excluded from climate scenarios. However, one method that can be employed to further assess the impacts of more or less variable climatic conditions, is to compute synthetic data by permuting the variance of the observational time series, as well as the mean.

These synthetic data can then illustrate possible futures that are not captured in the current suit of available climate models. Synthetic data can be created from any permutation of ΔT and ΔP that are outside the current intermodal range and then applied to the observed data in the same way as is done for the delta method. While the existing models can guide researchers as to the permutations that are most likely, they are unable to convey whole story, as there are not an infinite number of models. While simply computing a wider range of ΔT and ΔP permutations allows for a broader range of possible outcomes, these data still have the same variance in temperature and precipitation as is seen in the delta method and the model output data.

Given that the current research is intended to provide a range of possible futures in order to explore the climate change adaptation decision-making process, the CFM is judged to be an effective and efficient means of obtaining the needed results. However, understanding the value of these estimates and the extent to which they can be used by decision makers remains to be seen. Furthermore, the degree to which planning decision may change as a result of increases or decreases in the projected need for WRM should be investigated.

6 Semi-structured interviews with decision-makers

This thesis uses a semi-structured interview methodology to explore how and in what way(s) site-specific scenario-driven assessments influence decision-making processes with regard to climate change in the transportation sector. The semi-structured interviews provide the contextual understanding of the climate change impact assessment. Semi-structured interviews have been used in investigations of climate change adaptation at the community level in a variety of settings (Wolf *et al.,* 2010; Fleming & Vanclay, 2011). By using semi-structured interviews with key decision makers, the ways in which adaptation decisions are made were explored. The practical benefit of this research is that it is intended to increase the level of climate-change readiness in Prince George and potentially inform decision making by focusing specifically on the issues of snow and ice control in the City of Prince George. Furthermore, the scientific benefit of this research is its contribution to an understanding of the processes by which adaptation decisions are made and the degree to which local, site-specific impact assessments contribute to climate change readiness.

6.1 Method of data collection

6.1.1 Interview script

The literature review of this thesis aided in framing the interview questions and the thesis committee helped to inform and review the proposed interview script. When conducting semi-structured interviews, it is important that "questions must explore the interviewer's topic and fit the participant's experience" (Charmaz & Belgrave, 2002 pg. 351). As such, the interviews followed a general script that was separated into four key sections (see Appendix A for interview questions); however, not all sections were discussed with all participants as the researcher acknowledged the breadth of experiences of the participants.

Section one: community context and municipal decision making

The purpose of this first section was to gain an understanding of the broader challenges and issues facing the community. This was completed by asking a question about past challenges and events the City has faced as well as questions about the decisions-making structure within the municipality to gain an understanding of the roles and responsibilities of residents, employees, and elected officials in the decision making process. Discussion related to this theme helped to position the challenges of WRM more broadly in the landscape of the all municipal decisions and challenges that are taking place.

Section two: current WRM practices

The overall purpose of section two was to gain an understanding of the snow and ice control regime for the municipality. Questions were related to specific practices and the researcher sought to clarify the reasons behind the changes in practices over time that had been evident in the technical analysis portion of this thesis. Other questions in this section related to the process by which WRM budgets are assigned and how the municipality attempts to procure additional resources in winters where a snow control budget deficit is imminent or occurring.

Section three: Climate change adaptation planning

The questions in section three were intended to gauge the degree to which the participants were cognizant of climate change impacts. This section prompted discussion around the concerns climate change impacts the general perception about climate change initiatives in the community. The roles and responsibilities of climate change adaptation initiatives were also broached in this section.

Section four: Climate change scenarios for WRM

The final series of questions drew heavily on the findings from the technical analysis portion of this thesis. A one-page information sheet (Appendix B) that outlined the WSI development and the subsequent projected changes in winter severity was used as a catalyst for this portion of the interview. The one-page summary of results was introduced and explained to the interviewees before discussion regarding climate change impacts and adaptations was initiated. Questions were then asked that related to how the findings of this analysis could change the ways in which decisions were made. This was followed by a discussion of how potential surplus resources could be allocated if the projected changes held true.

6.1.2 Sample design and interview recruitment

Participants were invited to take part in this research through a standardized emailed contact letter. Contact information was obtained through three main methods: 1) recruitment of participants commenced by reaching out to existing contacts the researcher had met in Prince George during a workshop that took place in Prince George in 2011; 2) contact information and email addresses available on the City of Prince George website; and 3) potential participants identified through chain-referral whereby some potential participants directed the researcher to other potential participants (this was especially true in instances when individuals had recently changed positions and these individuals suggested I contact the individuals in positions for which the research was targeting). In this letter, all potential participants were informed of the nature and purpose of the study and interviewees were assured that the person's identity would be kept in confidence and that they would remain anonymous (form letter in Appendix C).

After the initial email contact, a reminder email or phone call was made to answer any questions the potential participants may have had. Given a recent reorganization within the City of Prince George, there was some difficulty in recruiting participants for this study as over half of the potential participants had recently changed positions. The interview phase was intended to start in early March 2014, but due to school holidays the dates were altered to allow for the greatest number of participants. Once participants had agreed to take part in the research, the interview questions were emailed to the participants along with the letter of consent (Appendix C and D). Interview times were arranged with the participants and all meetings took place at the City of Prince George City Hall, or at the municipal maintenance yard.

6.1.3 Interview process

Semi-structured interviews (between 30 minutes and 1.5 hours in length) were conducted with seven individuals who are involved with WRM operations, engineering, asset management or municipal planning in the City of Prince George. Following the principles outlined by Corbin and Strauss (2008), the interviews and interview analysis occurred concurrently while the researcher was fully immersed in all stages of this process. Written notes were taken during and after each interview, and with the permission of the participants, the interviews were recorded. The iterative process of the semi-structured interview process allowed the researcher to gain more insight into important issues or events. Furthermore, this process is useful for allowing the researcher to re-assess possibly misleading facts or inaccurate statements made by the participants. For example, based on the information gained from completed interviews, additional questions were added to the interview script. An illustrative example of this was that the response to the December 2013 winter storm became a central discussion point during all seven of the interviews. This storm was not included as part of the original interview script, but it became a critical piece of this research as this event was illustrative of the ways in which decisions are made with regard to WRM.

Another example of the value of the iterative approach was that there was considerable confusion regarding the allocation of resources collected from taxpayers for snow and ice control in the City of Prince George. In the City of Prince George, a 'Snow Control Levy' appears on resident property tax bills as a separate line item, similar to a school tax. Some participants indicated that under no circumstances could the snow control levy collected from the taxpayers be re-allocated to different needs within the city. Others, however, indicated that there was no reason why excess funds from the snow reserve couldn't be reallocated to other resources. Further questioning of higher-level management indicated that the latter was true and the resources could in fact be reallocated if needed. These two examples illustrate the importance of contextualized research and iterative schematics for conducting interviews and for interview analysis as the responses provided in section four of the interview script were highly influenced by participants' understandings of legislative processes by which taxes are collected from city residents.

6.2 Semi-structured interview data analysis

The interviews were transcribed verbatim and entered into *Microsoft Excel.* The coding process evolved to allow for themes and categories of themes to emerge. The coding process was very iterative and the coding guide transformed as the interview analysis evolved. The researcher listened to each of the interviews a minimum of four times while coding and making notes on the verbatim transcriptions. At the end of this iterative coding process the responses from the seven interviews were coded for four main attributes: 1) broad theme (*e.g.*, triggers of change); 2) sub-theme (*e.g.,* 2006 salt management plan, role of champions); 3) perceived tone (*e.g.,* neutral, annoyance, excitement); and 4) timing of statement in relation to the presentation of the climate change projections (before or after).

After the analysis of the interviews, the research questions proposed at the beginning of the interview research phase were revisited. Exploring how adaptation decisions would be made, and how they would be affected by empirical estimates of changes in WRM practices provided unique insights into the adaptation planning process. The aim of conducting these semi-structured interviews was to answer two main research questions. The first aim was to explore how site-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate-change adaptation planning. The second aim was to explore whether decision makers are more likely to support climate change adaptation initiatives that involve the expenditure of resources rather than support those that involve the scaling back of resources. Despite entering into the interview phase of this research with preconceived notions of aims and questions to be answered, the researcher strived to allow for additional themes to transpire throughout the interviews and the interview analysis. The interview questions acted merely as a guide in the conversation with participants.

6.3 Interview findings – thematic analysis

6.3.1 December 2013 storm

A key theme of the interviews was the winter snow event that occurred in December 2013. The script for the semi-structured interviews contained no reference to specific snow events, but the interviewees, in a number of instances, repeatedly discussed this snow event. While the purpose of this thesis was not intended to research individual storm response, this December snow event did provide a useful context from which to assess the ways in which decisions are made with regard to WRM in the City of Prince George. This snow event was considered in terms of the physical characteristics of the storm, the process by which City employees worked to cleanup from the storm, as well as the resident pushback from perceived a quality gap, and the subsequent efforts brought forth to Council to ensure improved response to future winter storms.

6.3.1.1 Storm characteristics

From Tuesday December 10^{th} to Thursday December 12^{th} over 40 cm of snow fell in the City of Prince George. This was then followed by rain that was then followed by a series of days with cold temperatures (Tmin = -17°C, and Tmax = 16°C). As there was insufficient time to remove snow from all streets before the rain and the freezing temperatures, there was a high accumulation of ice on the road surface that had been rutted from the traffic on snow before the freezing temperatures. As such, this uneven and icy road surface severely impeded the mobility of residents and compromised driving conditions, a situation that persisted for months after the storm. The interviewees all commented on the length of time it took to clean up from this storm and noted that even three months later there were still efforts to remove some of the accumulated ice.

> *"Right now in 2014 we are cleaning up still from that December storm. It was very cold and we couldn't remove the ice and had to wait until it warmed up".*

6.3.1.2 Resident feedback and the role of residents

There was a general resident outcry and the City received 598 calls for service during this one event and recorded 900 calls in the first two weeks of January 2014 whereas there is an average of 2000 calls for service annually (Gaal, 2014a). As previously discussed, the *Snow Control Policy* prescribes that there is a five-day plan to remove snow from all city streets, and this schedule restarts on each day in which there is more than 7.5cm of snow. As such, over the course of the storm, the priority 1 roads were plowed repeatedly and the lower priority roads did not receive any maintenance from the City. As such, the residential roads were not maintained immediately after the storm leading to a perceived service quality gap that became the focus of Council meetings in the early part of 2014.

Interviewees were asked to provide their personal feedback on the level of post storm service in December 2013. While some interviewees thought the level of service was adequate, others thought there were areas in need of improvement. Interestingly, those working closely with snow and ice control recognized that there were areas of the operations that needed to be tweaked:

> *"The continuation of service in my mind could have been better. Sure we react according to protocol and off we go. But do we continue on and check that what is being done is going to get the job done. It's a very complicated answer. But there is definitely room for improvement. Whether that be more money or communication, I really see opportunities for approaching it differently".*

Others, however, who were more removed from the day-to-day operations expressed the opinion that the service was appropriate:

> *"It's going to be completed dependent on each and every person's perception. From my own personal standpoint it's just something I deal with because I live in a winter city. And to me versus what I hear of the people and we have frequent fliers who complain on certain stuff. It kind of does make you wonder to what extent is it truly the population as a whole because you have a lot of people that are just not going to complain. People who don't think it is going well aren't going to bring it up too often as compared to those who are unsatisfied. For me, the level of service was great"*

Ultimately, however, governments endeavor to be reelected and regardless of whether there was a service quality gap or not, elected officials respond to the needs of the electorate. There is a sense of frustration from the City employees that the directives of the operations are so closely entwined with resident perception, as the residents can influence Mayor and Council:

> *"They* [Mayor and Council] *don't see that. I mean, I don't want to speak negatively of Mayor and Council, but they don't get it. Every year we get the same complaints. I can guarantee next year at the start of the snow season one of the first complaints we'll get is 'this is the worst it's ever been' – or it's the worst they've ever seen it' and we get that every year. And is it worse than every other winter? No, people just forgot. Or it's how it affects them; at the time that changes their perception. And… I mean, they* [Mayor and Council] *just respond to the public".*

It is interesting to note that, as of yet, there is no current program in place to monitor or evaluate the quality of service for snow and ice control. As one interview stated, they are just in a state of "*chasing fires*" and there is little inclination to pursue reflective evaluation of their practices. As such, there has been little effort to communicate the way WRM decisions are made to the public; this could be contributing the perceived service quality gap as the residents are unclear as to the policies and procedures for WRM activities.

6.3.1.3 Response

In response to the resident outcry a number of reports went to Council outlining the successes and challenges of dealing with the December 2013 storm (Gaal, 2014a, Gaal 2014b). The Operations Department put forth a proposal (Gaal, 2014b) for $6.08 million expenditure to add more equipment to the snow operations fleet. This was in addition to the $583,000 amount requested to increase the 2014 Snow Levy to accommodate for the snow control budget deficit. While the increase in the Snow Levy was approved, the $6.08 million for capital expenditures was rejected. Instead a 'Snow Committee' was put in place to assess Snow Operations policies and procedures and to develop a proposal for going forward. There is now a strong push from the Operations Department and Council to increase snow clearing capacity and equipment to levels not seen in a decade. Much of this action occurred because of the resident outcry and subsequent pressure from local Councilors. There are many articles found in local newspapers that discussed the December 2013 storm and highlighted the political pressure for changes.

> *"For myself and many other people, enough is enough and, as a city councilor, I can set some policies but have no control over what happens with the day to day operations. Not that I should - but we need to make some serious changes with the way we remove snow… Really what I'm looking at is making sure what happened with the snow removal this year, make sure it doesn't ever happen again - if possible." – City Councilor (Evelyn, 2014).*

The role of residents was evident in the aftermath of the December 2013 storm. While resident influence can be an important enabler of change in municipal contexts, it can also be a barrier to changing policies and procedures. In the context of adaptation planning in the City of Prince George, there was mention by numerous interviewees that residents have played a pivotal role in impeding climate change adaptation initiatives such as the construction of a new dike system that would mitigate flooding in the downtown area. So while resident influence was an important enabler in changing WRM practices in the City of Prince George, there is also evidence that it has been a barrier to adaptation initiatives in the City. Overall, the December 2013 snow event was a recurring theme throughout the interviews and a considerable portion of time was spent discussing the topic. In the following analysis, reference will be made a number of times to the December 2013 storm.

6.3.2 Triggers of regime change

The second broad theme is the triggers of past regime changes for snow and ice control operations in the City of Prince George. The process by which past decisions have been made can provide insight as to the enablers and barriers to altering policies, programs and procedures at the municipal level. The December 2013 snow event previously discussed is an example of an event that has be used as a catalyst for change. A number of other examples were brought forth by the participants that highlighted a number of 'triggers' that served as the impetus to change snow and ice control practices in the City of Prince George. As evidenced by the external triggers of change identified in this research, path dependency is an important barrier to changing practices. External forces, such as these triggers of change, are important for overcoming path dependency and initiating change.

These triggers of change can be classified as episodic or continual and as internal or external (Weick & Quinn, 1999). Continual changes are almost exclusively internal and driven by individuals or groups of individuals within the municipal institution of the City of Prince George and are very closely tied to the snow and ice control program. These continual triggers would be initiatives that fine tune the day-to-day snow-and-ice control regime. These can be changes in the numbers of employees, types of equipment used, or the introduction of newer technologies. These continual changes are more difficult to see when looking at the maintenance data whereas the episodic changes are more evident. **Figure 27** below highlights the episodic triggers of regime change for WRM operations in the City. There were four key episodic changes that emerged from the interview process, and these triggers have proved useful in explaining the temporal variations in materials use in the City of Prince George.

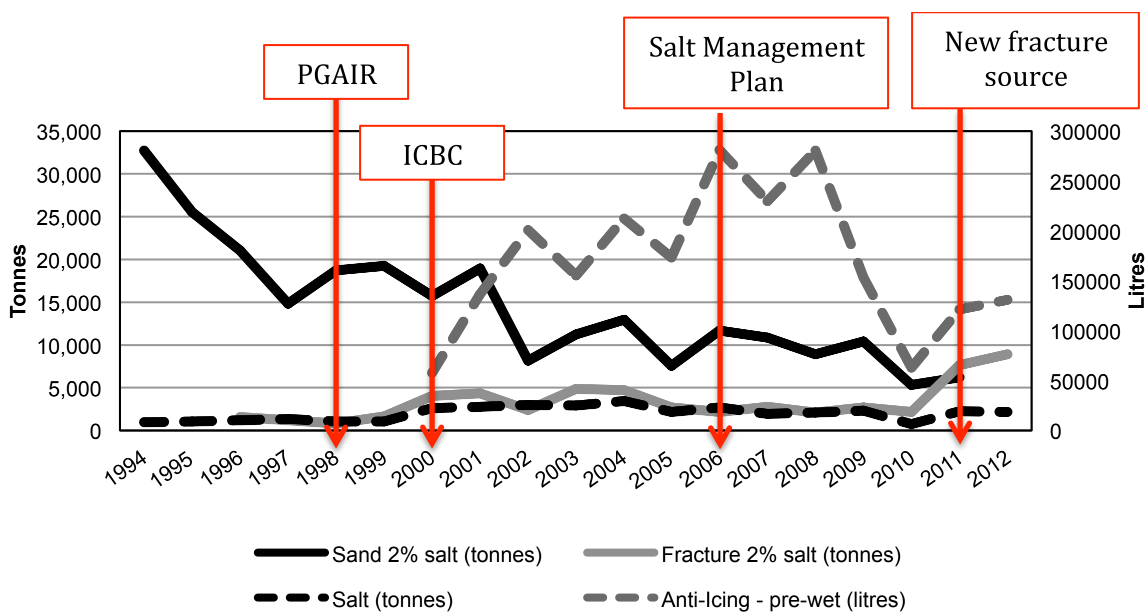

Figure 27: Materials use and regime changes in the City of Prince George over time

6.3.2.1 Prince George Air Improvement Roundtable

The Prince George Air Improvement Roundtable (PGAIR) was mentioned by a number of participants as an active institution that has played a key role in reducing the amount of sand applied to roads in the winter, and improving the cleanup of sand in the spring. PGAIR is a community-based non-profit formed in 1998 that comprises representatives from the industry, business, the general public, community groups, and government. Due to the efforts of PGAIR, the City of Prince George implemented a Clean Air Bylaw that included strict requirements to reduce emissions from sanding and sweeping. Due in part to the efforts by PGAIR there is a notable decline in the use of sand over the past 15 years (**Figure 27**).

6.3.2.2 Insurance Corporation of British Columbia

The Insurance Corporation of British Columbia (ICBC) was instrumental in developing the anti-icing program in the City of Prince George. The anti-icing initiative was a province-wide initiative by ICBC that was implemented in an effort to reduce claims from winter car accidents. This program helped to support the capital costs of an anti-icing program in Prince George, and elsewhere, with the use of liquid de-icing solutions as a pre-wet application to road surfaces. This program also provided training to municipal staff to help transition to this new technology. As can be seen in **Figure 27**, there had not been any use of liquid de-icing pre-wet until the implementation of this initiative in the 2000-2001 season.

> *"That was an initiative started with ICBC (insurance) – and it was a province wide initiative where they said they would help giving municipalities money to look at different ways of doing snow removal and the ultimate goal was to help reduce car accidents in the winter time"*

6.3.2.3 2006 Salt management plan

While the ICBC imitative was instrumental in helping to decrease the amount of sand used in the City of Prince George, by using the liquid de-icing pre-wet solution, the steady increase in the use of liquid deicers became an environmental concern (Blues, 2006). In an effort to adhere to the Transportation Association of Canada's *Synthesis of Best Practices* for salt use, the City of Prince George contracted the services of AMEC to develop a salt management plan (AMEC, 2006). After the implementation of the salt management plan a decline the amount of both rock salt and anti-icing salt brine was observed (**Figure 27**).

> *"The impetus* [for the salt management plan] *was that federally and provincially there was a push to have people, have municipalities and businesses and that manage their salt consumption, storage and what not. So that was the impetus for the plan… It was the manager at the time was the one that took that information to that report* [AMEC 2006 report], *and applied it to what the City of what Prince George would have to do to manage the salt".*

6.3.2.4 Fracture suppliers

Road authorities use fracture, also referred to as abrasive or aggregate, to improve winter traction in inclement road conditions. Fracture particles must be smaller than 12.5mm, and more than half of the material should have a minimum of two fractured faces. Fracture has a number of benefits over sand in that it stays in place longer and creates substantially less dust than sand. The disadvantage of fracture is that it usually costs more than sand. As such, road authorities must balance costs of the fracture with its environmental and operational benefits. It emerged in the interviews, however, that part of the reason for the recent increase in fracture use in 2011 and 2012 was not because of environmental initiatives, but instead because of reduced cost.

> *"… because we deal with air quality in the downtown we use winter fracture which is predominately small rock particles and not sand. Basically to minimize the fine particulate in the air shed. But one of the concrete suppliers has a byproduct of their concrete operation so we've been able to get the winter fracture cheaper than we have sand – so we've started using winter fracture throughout the whole city. We're only doing this because its cost savings right now. If we weren't able to get the fracture material for the price we're getting it, we would then use sand in the outlying areas and fracture downtown… it's a byproduct of their concrete operations… They've had to modify their screening and crushing techniques to meet our standards for that material. But it's still significantly cheaper. It's about 35% of what the other people were charging before"*

There have been a variety of triggers that have changed, sometimes substantially, the way in which snow and ice control operations are implemented in the City of Prince George. The researcher was well aware of the implementation of the 2006 Salt Management Plan (AMEC, 2006) as it has been well documented in the past. The other initiatives, however, were only discussed during the interview process and provided useful insight as to the enablers of regime shifts with regard to WRM in the City of Prince George. All of these examples are top-down initiatives that were adopted by the City of Prince George. The most substantial change in practices came from a higher-level institution (ICBC) with the implementation of liquid de-icing pre-wet. Without the financial support provided by ICBC it is unlikely this change in technology and practices would have been implemented at that time. Finances were one crucial motivation for the broader shift from sand to fracture in the last two seasons.

The role of champions within the organization was another important factor, especially in the adoption of the 2006 Salt Management Plan (AMEC, 2006) where there was a very keen individual in a management position who had the will and authority to seek funding for the research, and approval for the implementation of the Salt Management Plan. The role of champions is well cited in sustainability literature more broadly (Schaefer, 2004; Garavan & McGuire, 2010), but it also especially important in climate change adaptation and mitigation (Picketts *et al.,* 2014; Carmin *et al.,* 2012; Yamin *et al.,* 2005), and this was exemplified throughout the interview process. The role of champions is important in overcoming institutional inertia.

6.3.3 Institutional memory

6.3.3.1 Institutional memory: champions

Consistently, in every interview, the researcher was referred to a few key individuals whenever the topic of climate change impacts and adaptation was broached, or when there was discussion regarding the historical WRM practices and how those decisions were made. There was clearly a level of awareness amongst the participants that illustrated that municipal employees are well aware of the climate change impacts and adaptation efforts that have taken plus thus far. However, there is still a substantial disconnect and lack of integration between the various departments within the City of Prince George and the attitude presented by respondents was that any work related to climate change impacts and adaptations was outside the scope of their job role.

> *"* [talking about climate change] *And I know that* [name], *our* [job title], *has worked with some university students up at the university here and has done research into climate change and how it affects the city. So we are looking at it- and I know reports have gone to city council, but where that's at. I'm not sure. But I know we are looking at those types of things but you should speak to* [name].*"*

The value of champions for both climate change mitigation and adaptation, and any sustainability initiative more broadly, is well cited in the literature (Picketts *et al.,* 2014; Schaefer, 2004; Garavan & McGuire, 2010). However, one of the disadvantages of having strong champions is that the knowledge is 'locked up' in these individuals. This is true both when assessing current vulnerability and decision-making processes, but also when exploring the impacts of climate change. This is especially true for institutions that have high turnover and frequent restructuring. When the capacity, knowledge and motivation lies with an individual, that momentum can be lost when that individual leaves. This is particularly important considering the changes the City of Prince George is currently facing.

6.3.3.2 Institutional memory: political timelines and succession planning

When asked about specific circumstance in which decisions were made, interviewees consistently made references to individuals who had previously been in the job role that the respondent currently held. Furthermore, there were numerous references to divisions, initiatives or strategies that used to be a priority but had since fallen off the radar. Throughout the interview process it was found that the political directive provided by Mayor and Council are critical for guiding day-to-day operations. The difficulty therein lies in that with each election cycle the priorities would change, and the employees of the municipality would be required to follow suit. Since the researcher started working with the City of Prince George in 2011, there was an election in November 2011, after which there was a restructuring and 28 jobs were removed. This restructuring also included the entire removal the Environmental Department. There was again a restructuring in early 2014, and with an election due in November 2014 it is possible priorities will shift again.

> ***LM:*** *"you mentioned that you didn't have the capacity to work on those projects* [related to climate change] *anymore… was that a change in funding?"*
>
> ***Interviewee:*** *"change in direction. Because we can see right now – based on what came out of the myPG and for the Council of the day* [that] *was definitely their priority and also we had a different City manager in at that time as well. So – we can see it was – they were wanting to look at each of the three legged stool and how our City government functions within that three legged stool of sustainability. Right now we can see the existing Council – their priorities in terms of trends is very much focused on the economic end of things…so as an organization – we base our priorities very much around Mayor and Council priorities."*

This three-year election cycle has recently been increased to four years. Independent of political timelines and structural reorganizations, the City of Prince George is also in the process of succession planning, as there is a very rapid turnover as a number of individuals are set to retire in the near future. Previous climate change adaptation work in the City of Prince George has also cited succession management and high employee turnover as a barrier to capacity retention with regard to adaptation planning (Picketts, 2013). The challenges posed by political timelines to adaptation planning have been identified in previous climate change adaptation studies (Burch, 2009; Picketts, 2013). The findings from the interviews conducted as part of this thesis illustrate that political timelines continue to be a barrier to climate change adaptation planning in the City of Prince George.

6.3.4 Perception of weather and climate

6.3.4.1 Perception of weather and climate: use of weather information

Winter weather predicates the need for snow and ice control (Blackburn, 2004) and the use of weather forecasts and road weather information systems (RWIS) are fundamental for preventative road maintenance (Sato *et al.,* 2004). Section two of the interview script was focused on understanding the decision-making process for snow and ice control in the City of Prince George. The *Snow Control Policy* is entirely reactive. Despite efforts to initiate pre-wetting and some preventative maintenance (see section on ICBC initiatives), this practice has not been fully integrated into the WRM regime. Integral to the process for completing preventative maintenance is the need for forecast weather data to know when preventative anti-icing methods should be applied. Throughout the interview process it became evident that there is no formal mechanism for obtaining or using weather information for their snow and ice control operations.

> *"In a typical snow event, lets say there is 6 inches and 6-8 inches forecasted, we would probably just bring out trucks to deal with arterials and collectors and then would let night shift get started… I mean … one of the biggest challenge in terms of resident expectation is they look at from when the snow starts, and we look at it from when the snow stops. Because I mean, if we get 6 inches today and 6 inches tomorrow, it doesn't really matter what we got today because our priority means we go back to downtown again. So we might plow downtown two nights in a row just because the snow hasn't stopped".*

It is at the complete discretion of the foremen and supervisors to initiate snow and ice control. The *Snow Control Policy* dictates the amounts of snow that need to fall before the maintenance regime begins and there is no policy for preventative maintenance.

> *"… I mean in terms of forecasting and everything else, we're more reactive. We can plan all we want but the snow has to fall for us to react so I mean, we obviously follow the forecast but I don't really care what it says seven days in advance because I don't necessarily believe that its accurate – so you know what I mean, we try to watch the radar. That's something that's legitimate…".*

> *"We use Environment Canada. We used to have a program with a weather office in the airport, they would phone us and give us warnings but we didn't find it was a real benefit, we were better at jumping on it. Because as soon as we've seen something we just call Environment Canada anyway. As foremen we're always ahead of it. They are looking at weather differently than the way we look at weather. We look at weather for removal, sanding, salting all that – it's a different way of looking at it so we are ready to jump on it every time we see a storm coming in from the west – we'll track it right from the coast from the satellite thing – we'll track it to see when its coming, try and figure out when it's going to hit us"*

6.3.4.2 Perception of weather and climate: weather as an 'unknown'

One of the themes that emerged from the interview process was an underlying attitude that WRM practices in the City of Prince George are very reactive with little attention to preventative maintenance. There was a general sense that the weather dictates what needs to be done and the operations staff has little control or flexibility in the process by which they clean up after a snow event. Interviewees working closely with the snow and ice control use weather as a way to justify their expenditures and service quality. While weather was mentioned during the interview process, this sentiment of the weather as 'an unknown' was presented in many of the news articles about WRM in the City of Prince George. This quote from an online news article in the Prince George citizen (Evelyn, 2014) exemplifies the attitude towards weather as a source of demand for snow and ice control:

> *"It's so dependent on weather. At the end of the day, I wish people would understand we are doing the best we can, but it's not an exact science". – Operations Supervisor* (Evelyn, 2014)

> *"I wouldn't say we're not aware of costs, because obviously we are aware, but cost has never changed our focus…It's one of those things where there's the budget and then there's also – we go over every year – so I mean, I mean we have the budget but it's more of a guideline than anything because it's not like we stop plowing when we get to our budget. We still have the snow policy that says when we plow"*

The interviewees who were not in positions closely related to snow and ice control seemed at times, based on their tone, exasperated and mentioned that Council is also looking for further justification as to why the expenditures on snow and ice control are high.

> *"I don't know how it works in terms of how they fund… I've always heard it's well funded as much as possible because we never know what we're going to get…Very recently, which I'm sure you pulled up in council agendas, there's been a lot of pressure in terms of these costs – asking for the Transportation Division to be reporting back on getting useful data as to why it is we're budgeting this much and what's the plan moving forward"*

It is interesting that the City of Prince George does not have a formal mechanism for identifying what exactly constitutes 'weather'. On the municipal website, and in the various Reports to Council, the total snowfall accumulation is used to explain the demand for WRM. However, this thesis, and other studies (Andrey *et al.,* 2001; Thornes, 1993; Venäläinen & Kangas, 2003), have shown that the demand for snow and ice control is much more complex than just this single weather variable. It will be interesting to observe whether the City of Prince George will continue to use the WSI calculator as a management tool. An interviewee in a higher-level management position expressed optimism that tools such as the WSI calculator would be used in the future and went on to indicate that there is a need to be more cognizant of the processes by which the demand for WRM is understood.

> *"I don't think weather has ever been constant I don't think it ever will be. We have to adapt and change our approaches as we learn more about the weather. We know more now than we did 20 years ago. We are learning more as we going along, but now we need to take the information we know and it apply it to our standards – what do we need to change in our design standards, what do we need to change in our maintenance standards. What will help? What will be the optimization of this information?".*

The interviewees indicated that expenditures have been steadily rising and as such there is a need to increase budgets. There was a common perception amongst the interviewees that the winters are becoming more severe and as such there is a greater need for WRM activities and subsequent expenditures. However, if weather if the theoretical demand for WRM, then the data don't support this. The analysis completed for this thesis, as well as the analysis completed in the 2011-2012 reports for the City of Prince George, show that in the past two decades there has not been a worsening of the severity of the winters as measured by the WSI. However, there was consistently a perception that the weather was getting 'worse', and as such there was a need to increase the budgets for WRM. Based on recent experiences, the City took action to reduce their risk of

> *"We would have been cleaning up the effect of December* [In January] *and also just the scrutiny elevated everything that was done. So basically for the back half of the winter since that* [December 2013] *snow event – we've been operating at a level that we've never done before. We've gone out and done things. We went out and leased two additional graders at considerable additional cost mainly because they didn't want what happened in December to happen again".*

6.3.5 Planning for the unexpected

One of the themes that emerged from this is how the City plans for unexpected events such as infrequent, but very heavy snowfalls. The City of Prince George has an existing plan to cope with heavy snowfalls by contracting the services of external equipment and operators. Traditionally, external equipment has been hired to help clean up the downtown area after major snow events. The benefit of using contract services is that it is more cost-effective to pay a premium in the event that more equipment and labour is needed. There has been a continual tension between choosing to hire seasonal employees for the duration of the winter season, or whether to hire fewer employees and buy less equipment, and rely on contracted services.

> *"I honestly don't believe that to have sustainable budgets, sustainable operations, and maintenance that you can plan for these types of things* [December 2013 storm]. *So these are going to be, as stated, anomalies that will occur. We have the ability to hire external equipment, but then we also have to take into consideration markets that are happening at the time. So that is a major concern. You can look at retainers, but then you're looking at you get no snow, then you're paying. So those are the balances that need to be determined. But to be perfectly honest from a budget and sustainability – we can't plan for that* [December 2013]. *We can have emergency preparedness for it, but then it is emergency. It's not something that can be included in the budget, because your budgets would be even greater than what they already are, and people have a perception of what they should be".*

The use of contracted services has been used as a contingency plan for the past two decades, however, there is the risk that if the available labour is not hired, they would move to other industries. As seen during the December 2013 storm, the changing economic landscape in the region has had an impact on this practice of contracting services. The role of external economic forces is challenging the way that decisions have been typically made in the City of Prince George. While traditionally there has been little difficulty in finding contracted services and equipment, the economic development that is currently taking place in northern BC is attracting available labour and equipment away from the City of Prince George.

> *"We had a very difficult time finding contractors that were able to supply us with equipment this year by that I mean we could find the equipment but they couldn't find the operators. Personally myself I think this is one thing that is going to be a continuing problem for us and that's because of the work that's happening up north in British Columbia with the mining industry taking off. People are not willing to stay around and maybe work for the odd time a couple weeks here and there. When you can go up there – yeah you got to work at camp but you get good money and all the work you want – so they had a difficult time with finding equipment operators"*

This has implication for climate change adaptation planning in the City of Prince George, as there the current mechanism in place that can be used to scale back resources in the event that there is a reduction in the need for WRM will no longer be available. A few of the interviewees mentioned that scaling back of contracted services would be first initiative to be undertaken if there was a need to reduce WRM expenditures because of a reduced demand for WRM.

> **Interviewee:** *"We use an awful lot of external equipment and external employees – so it's there that will be the first scale down – then you can always scale it back up but it may come at a premium though in the future. Or you borrow from other communities".*
> **LM:** *"Yeah, I heard it was difficult to get equipment this year".*
> **Interviewee:** *"Yeah – equipment and operators – it was very difficult and it came at a very inopportune time. The week before Christmas. Everyone was up in arms".*

Given the changing economic landscaped in the region, it may be more difficult to use the reduction contracted services as a mechanism for reducing WRM expenditures in the future. It is a possibility that, given the changing economic landscape, the City of Prince George will need to hire more full-time and seasonal employees to ensure that a minimum level of service is achieved.

6.4 Semi-structured interviews: synthesis

The fourth objective of this thesis was to explore how site-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate change adaptation planning. Overall, through exploring the five key themes that emerged from the semi-structured interview process, it was evident that the interviewees were receptive to the new knowledge that was presented, but the degree to which this knowledge creates readiness remains unclear. There are a number of other barriers and enablers to planned adaptation that emerged from the interview process illustrating the complexity of decision-making processes, especially in a municipal context.

Despite a number of instances where respondents indicated that CCIAV assessments were valuable and worthwhile initiatives for the municipality to undertake, there was overwhelming response from participants that the City would respond to changes in the need for WRM in a purely reactive manner. It should be noted that this thesis, and associated research projects completed for the City of Prince George were initiated under the principle that the City of Prince George sought to better understand the projected impacts of climate change for WRM activities. This was done partially so as to plan and budget accordingly. However, after seeing the results, nearly all participants indicated that adaptations would be undertaken only as a reaction to budget surpluses.

[Discussing climate change adaptation **before** the one-page fact sheet was discussed]

> *"I think the City of Prince George should be looking at climate change because it does affect a lot of things that we do here. And when it comes down to what we do here, it affects budgets. If we plan to project what we need in future for budgets, we need to know what those impacts will be in the future."*

[Discussing climate change adaptation **after** the one-page fact sheet was discussed]

> *"I think we'd have to see significant climate change* [before the budget would be changed]*." – I mean if you were to come in under budget for a number of years – then they may decide we'll reduce that* [the budget]*."*
>
> *"Yeah I don't think you'll ever be looking 30-40 years ahead of time with your budgets. The most you'll be looking at is 5 years ahead. I think as you build your reserve, and let's say you continue to build a reserve and you have money sitting there, I think at that time you'll start revisiting your budgets and I think that's when we'd probably put our recommendation through and just use reserves and save that money for another time."*
>
> *"If all of a sudden you're running into years back to back with money left over, then obviously, Mayor or Council will see that and say maybe we don't need all that money for snow. Maybe there is something else we can do with it. How that's done – I would imagine that's through Mayor and Council."*

WRM is an inherently reactive process whereby action is taken in response to weather event. However, there are a number of components of winter road maintenance regimes that are anticipatory, especially the investment in technologies and equipment and these decision-making processes can benefit from projections of future changes. Furthermore, while there is some internal capacity to modify WRM practices that are within the purview of the operation department, Council governs ice control policies, and the operations personal have limited authority to make decisions outside of what the *Snow Control Policy* dictates. If policies were to be changed because of the projected implications of climate change, then this would require a coordinated effort by both employees and elected officials.

Overall, the one-page summary of projected impacts for WRM in Prince George did not facilitate as much discussion concerning long-term adaptation planning as had been anticipated, but it was an useful tool for facilitating discussion around how current decisions with regard to snow and ice control are made. The one-page summary of the empirical analysis of the impacts of climate change on WRM provided a consistent reference point for all of the interviews. There was much more interest in the development of the WSI than there was in the climate-change projections. The WSI development and associated findings were a tangible result that all participants were able to grasp. Those working closely with snow and ice control were pleased that the WSI 'justified' the perceived quality gap with regard to the December 2013 storm and Operations department management was excited at the prospect of having a management tool for WRM in the City of Prince George.

The one-page summary of projected impacts for WRM in Prince George was also useful for exploring the fifth objective of this thesis. The fifth objective was to explore whether decision makers are more likely to support climate change adaptation initiatives that involve the expenditure of resources rather than support those that involve the scaling back of resources. Each and every interviewee indicated that climate change would have an impact on various areas of the City's operations. In discussing the climate change projections for WRM in the City of Prince George, interviewees were asked about any outstanding needs that could benefit from increased resources in the event that resources were available. However, while all interviewee indicated that there were areas that could use those resources they suggested these resources could be reallocated to initiatives in the department they either currently work for, or a department they had worked for in the recent past. Overall there was the sentiment that City would follow the demand for service or expenditures in a reactive manner. The interviewees were just as open to removing resources from a budget, but only insofar as these resources could be spent elsewhere that was important to them.

However, all reallocation of resources was discussed in the context of reactive decision-making. The dominant theme of reactive decision-making was true both in the short term (snow event level) and in the long term (climate change planning). There was a consistent message from the respondents working closely with the snow and ice control operations that a great deal of decision making was out of their control, partially because of what the *Snow Control Policy* dictates, but also because they just 'react' to the weather. There was the general sentiment that WRM expenditures are not something that can be controlled in either the short- or long-term.

6.5 Semi-structured interviews: opportunities for future research

The semi-structured interviews were valuable for exploring the last two objectives of this thesis. Furthermore, a number of important findings, outside of the stated objectives, emerged from this process that shed further insight into the barriers and enablers of climate change adaptation planning, and the process by which planned adaptations would be initiated. However, there are two main limitations of this approach that could be overcome in future research.

The first limitation of this research is the relatively small sample size. While there was often agreement between the interviewees, with only seven individuals all working in related departments, it is difficult to ascertain if their views are indicative of the broader institution. Furthermore, the interviews took place only with individuals directly involved in decision-making roles within the City of Prince George. Due to time and resource limitations, combined with the recent organizational restructure, a limited the pool of available interviewees was available. Future research could look to broaden the range of target interviewees to include those outside of the City of Prince George, including, consultants, contractors, elected officials and individuals from the provincial government.

The second limitation is the lack of interviewer experience. Interviewer experience is an important aspect of the research that uses semi-structured interviews (Olson & Bilgen, 2011; Starks & Trinidad, 2007). As a first-time interviewer this research project did not benefit from a wealth of experience in conducting expert interviews. While notes were taken and the researcher endeavored to bring new information from preceding interview forward, it is possible that there were missed opportunities to further explore an emerging theme. After completing the coding process and the thematic analysis, there were some instances that could have benefited from further follow-up questioning that was missed in the moment. However, in all of these instances it was possible to find supporting clarification through council minutes and online news articles. As such, despite the limited interview experiences of the researcher, the results can still be seen as reliable.

7 Conclusions and discussion

A primary purpose of this thesis was to explore how adaptation decisions are made, and how they are affected by empirical estimates of projected changes in the demand for WRM. This thesis employs a case study methodology and uses a blend of quantitative and qualitative techniques. The City of Prince George was selected as the study area for this research. In achieving the aims and objectives of this thesis, a WSI model was developed that quantified the relationship between current WRM expenditures and winter weather based on 18 years of WRM expenditure data from 1994-2012. This WSI was then applied to modeled climate data to obtain an estimate of projected changes in the demand for WRM by the mid-2000s. The empirical results of this thesis were summarized and presented to individuals in decision-making roles in the City of Prince George. This information was explored though a semi-structured interview process to establish the extent to which site-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate change adaptation planning. The stated objectives and subsequent findings are outlines below.

1) The first objective sought to develop a WSI model that explains the temporal variation in WRM expenditures using weather data as the explanatory variables.
    a. A WSI was created that explains year-to-year variations in WRM expenditures in the City of Prince George. This WSI has two main components: the number of days of snowfall and the number of days with the potential for icing during or after rainfall.
    b. This index illustrates a clear relationship between the weather of a given year and the millions of dollars spent on WRM activities. The coefficient of determination (R^2) between annual WSI and annual expenditures is 0.93, which represents a very good fit.
    c. With a MSE of 0.088, this WSI is considered to have reliable predictive accuracy. As such, this WSI can be seen as an appropriate tool, when combined with modeled climate data, for estimating future WRM expenditures in the City of Prince George.

2) The second objective looked to compare two methods, the model output method and the CFM, of obtaining and using modeled climate data for climate change impact studies.
    a. The initial phase of obtaining the empirical estimates of change for WRM was limited to five models; three RCMs and two GCMs. This was completed so that the model output method and the CFM methodology could be compared. The results from the model output method indicated that there is a projected decrease in the demand for WRM into the 2050s of between 21.8% and 29.9%. The results from the CFM methodology indicated that there is a projected decrease in the demand for WRM into the 2050s of between 15.8% and 21.8%.
    b. Both approaches indicated that there is a projected net-benefit for the City of Prince George with regard to WRM expenditures in light of climate change. Both methods indicate that there will be a reduced demand for WRM activities, but the degree of change is different between the two methods. The CFM approach is more conservative because it assumes that weather variability will remain constant. However, given the ease of implementation, the CFM approach was chosen as the superior method for obtaining a range of estimated changes for WRM expenditure in the City of Prince George for the mid-century.

3) The third objective of this thesis was to apply the WSI model to modeled climate data to obtain a wide range of empirical estimates of the projected demand for WRM expenditures in the City of Prince George into the 2050s.
    a. Acknowledging the need for a broad range of estimates for projected changes in WRM expenditures, the CFM approach was employed. As such, climate anomalies were downloaded from the CCCSN website for the Prince George region for 65 GCMs, spanning three scenario groups.
    b. Annual precipitation in the City of Prince George is projected to increase by 3.7% to 10.6% for the 2050s based on the mid-range of 65 GCM

projections. Annual temperatures are projected to increase by 1.5°C to 2.4°C for the 2050s based on the mid-range. Although the 65 climate simulations are not identical in terms of magnitude, they all project that by the 2050s, the City of Prince George is expected to be warmer and wetter.

c. All 65 GMCs indicated that there would be a net benefit for the City of Prince George in terms of WRM. Despite increasing precipitation, the warmer temperatures will result in more precipitation falling as rain rather than snow. Seeing as a substantial portion of WRM expenditures is allocated to snow removal, it is estimated that there will be a net benefit for the City. Based on the mid-range of the 65 GCM projections, it is estimated that annual WSI score will decrease by 15.3% to 22.7% for the 2050s.

4) The fourth objective of this thesis was to conduct semi-structured interviews to explore how site-specific and sector-specific climate change impact assessments help to overcome the barrier of lack of local knowledge in climate change adaptation planning.

   a. It became evident that the empirical analysis of projected changes in the demand for WRM activities did lead to the development of new knowledge. However, the degree to which this knowledge creates climate-change readiness remains unclear. There are a number of other barriers and enablers to planned adaptation that emerged from the interview process illustrating the complexity of decision-making processes in a municipal context.

   b. Overall, the semi-structured interview process highlighted a number of barriers and enabler of adaptation planning action at the municipal level. Institutional inertial, path dependency, the role of governance structure, political timelines, resident influence, and uncertainty surrounding weather and climate information were all barriers that emerged from this process. The role of champions within an organization and the investment in climate change impacts research were enablers of climate change adaptation action in the City of Prince George.

5) The semi-structured interviews were also intended to explore whether decision makers are more likely to support climate change adaptation initiatives that involve the expenditure of resources rather than support those that involve the scaling back of resources.
    a. Overall, the semi-structured interview process found that the interviewees were open to reallocating resources away from WRM budgets but only insofar as these resources could be spent elsewhere within the City.
    b. All reallocations of resources were discussed in the context of reactive decision making. There was a dominant theme of reactive decision making that was true both in the short term and in the long term, indicating that regardless of the development of new knowledge and estimates of change, there would not likely be initiatives for anticipatory adaptations in the context of WRM at the municipal level in the City of Prince George.

The empirical estimates of change indicate that the City of Prince George will see a net reduction in the demand for WRM activities into the 2050s. While the estimated decrease in total annual WRM expenditures appears moderate (25th to 75th percentiles is estimated that annual demand for WRM will decrease by between 15.3% to 22.7% for the 2050s), it is not insignificant. At an average of $5.3 million a year (adjusted to 2012 dollars), a 22.7% decrease would be results in an average annual savings of $1.2 million and 15.3% decrease would result in an average of $800,000 in annual savings for the City of Prince George. Again, it should be noted that the CFM approach likely underestimates the reduced demand for WRM because the CFM approach used only one temperature (Tmean) anomaly instead of three (Tmin, Tmean, Tmax). As such, the decrease in total demand for WRM activities is likely to be even lower than the projected estimates provided in this thesis.

In summary, this thesis has led to the development a new tool, the WSI, which can be used as a program management tool by WRM managers in the City of Prince George. It is hoped that this tool will be used as part of the WRM regime and will lead to knowledge-based decision-making for WRM activities and resource allocation. Furthermore this thesis has provided the practical benefit of developing new knowledge, the projections of future change for WRM activities, with intent to increase the level of climate-change readiness in Prince George. It is unclear, however, the degree to which this knowledge informs decision making and thus this thesis' scientific contribution is an improved understanding of the process by which adaptation decisions are made and the degree to which local, site-specific impact assessments are beneficial for adaptation planning.

Much of the climate change and adaptation literature highlights the need for increased resources in a variety of contexts (Moser & Ekstrom, 2010; Füssel, 2007). There have long been studies that indicated an array of sectors and communities would face substantial costs due to the impacts of climate change (Hellegatte *et al.,* 2011; Held & Hervey, 2011). Many of these studies provide the cost estimates of a variety of adaptation initiatives that would mitigate the risk to that community or sector (Hellegatte *et al.,* 2011; McDonald *et al.,* 2011). In response to this increasing awareness some communities have begun to assess the projected impacts for their communities as to forecast and budget for adaptation initiatives that may be needed. In many of these case studies there are sectors, communities, or processes that are identified as areas that would benefit from investment as to reduce their vulnerability to the projected impacts of climate change.

In this case study, the narrative shifts when the projections indicate there is a net benefit for a community with regard to a specific sector. There is the perception that while communities may be keen to request more resources for anticipatory adaptations, they are more inclined to reallocate resources in a reactive manner. As of the writing of this thesis, very little work have been completed on investigating the decision-making process for adaptation planning when there is a projected net benefit for a sector in a community. This is unsurprising seeing as the goal of adaptation planning is firstly to reduce vulnerability and secondly to take advantage of possible benefits. Much of the scientific literature focuses on vulnerability reduction. However, by focusing on sectors that will benefit there is the opportunity to make available resources for other adaptation initiatives that aim to reduce vulnerability – such as flood mitigation. Going forward it will provide a unique perspective to replicate this study across multiple municipalities that have a blend of projected decreases and increases in the future demand for WRM activities.

It is possible that there is less inclination for anticipatory adaptation initiatives that result in the reallocation of resources because of concerns over the certainty of projections. Current climate models contain inherent uncertainty, but the decision-making protocols of many institutions require a certain level of confidence before decisions can be made based on available data. Moving forward, it can be foreseen that there will be a push towards finding avenues for enabling the empirical aspect of CCIAV assessments to become compatible with the decision-making protocols. This is especially true for sectors that are heavily influenced by the engineering community, such as transportation. In the future there will be a move towards providing clearer estimates of certainty to enable decision makers to better understand the probabilities of future estimates.

Another possible cause for the hesitation to reallocate WRM resources in an anticipatory manner is due to the heightened risk perception in reaction to the 2013 snow event. Often decisions are made based on personal experiences and perceptions of risk (Gifford, 2011; Moser & Ekstrom, 2010). In the context of WRM, risk perception is an important consideration in the decision-making process. Given the events that unfolded after the 2013 winter storm, the individuals in charge of WRM are looking to improve their already high levels of service in case another anomalous snow event were to occur. Recent research has begun to look at the influence of risk perception in the context of climate change adaptation planning (Gifford, 2011; Moser & Ekstrom, 2010). This literature indicates that there is a strong link between the perceived level of risk and the amount of climate change action that is undertaken. As such, in the case of the City of Prince George the perception of risk with regard to another potential large snow event is heightening their hesitation to undertake anticipatory action that would reduce their response capacity in the event of a severe snow event.

The projections of extreme events were not something that was completed in the course of this thesis. The tools and projections developed for this thesis relied on annual averages instead of the frequency and magnitude of extreme events. Understanding the impact of climate change on extreme or anomalous events is more difficult than working with averages (Min *et al.,* 2011; Katz, 2010); however, these types of estimates may lead to more action as they result in more tangible projections.

While it is possible to build projections and construct tools that enable these projections, they may not necessarily be valuable for climate change adaptation planning or for facilitating planned adaptations. As highlighted in the interview process, there was a keen interest in the development of the WSI, but only insofar as it could be used for decision making in the short-term. The tools unto themselves are beneficial from a program management perspective, but they may not be useful for climate change planning in the context of snow and ice control. Moving forward it is important that such tools continue to be developed as to improve reduce vulnerability to climatic stimuli in the current climate.

Although there is a broad consensus that global climate change is taking place and will result in a wide range of impacts, there has been a continued discussion in the literature pertaining to how various institutions can implement mitigation and adaptation programs and policies (Grasso, 2006; Biesbroek *et al.,* 2009; Stehr & Rhomberg, 2011; Leal-Arcas, 2011). Much of the climate change adaptation literature has focused on formal, hierarchal government institutions with little regard for the role of businesses, community members, advocacy groups and educational establishments. Transitioning to a more sustainable and climate-change-ready system will entail a great deal of cooperation and coordination from multiple institutions. The complexity and path-dependency inherent in socio-technical systems such as transportation greatly inhibits the ability for sustainability transitions to take place (Geels, 2010). The existing infrastructure, behavioural norms, investment in equipment, and short election cycles all impede a transition (Geels, 2010).

Many of these impediments to planned adaptation were confirmed in this research. Particularly evident was the role of short election cycles, especially seeing as the City of Prince George has historically had a three-year election cycle. This three-year election cycle has recently been increased to four years, but the political directive provided by

Mayor and Council are critical for guiding day-to-day operations. As such, when there is a change in Mayor and Council, then there is often a change in the policies and procedure. Previous climate change adaptation planning work in the City of Prince George has also cited succession management and high employee turnover as a barrier to capacity retention with regard to adaptation planning (Picketts, 2013). This issue of political turnover and capacity retention is well cited in the adaptation planning literature and will continue to be an issue for many communities (Adger *et al.,* 2005; Dessai & Hulme, 2004; Dessler & Parson, 2009)

Adaptation planning, especially at the community level has historically focused on the decision making protocols of the traditional municipal institution. Moving forward there will be an increased trend towards taking a multi-governance perspective that combine bottom-up and top-down approaches to climate change adaptation planning. Bottom-up approaches allow for strategies to be tailored at the community level, recognizing that spatial heterogeneity of socio-demographic and political attributes enable or impede different initiatives. Top-down approaches have the benefit of authority and agency to change policies, plans and procedures. While some authors have acknowledged there is a need for both bottom-up and top-down strategies given the benefits and limitations of each (Rayner, 2010; Lutsey & Sperling, 2008; Kern *et al.,* 2008), much of this literature has still focused on formal, hierarchal government institutions with little regard for the role of businesses, community members, advocacy groups and educational establishments.

Multi-level governance has emerged in recent literature as a useful lens through which to explore how and in what ways various institutions influence climate change policies at a multitude of scales. Institutional inertial, path dependency, the role of governance structure, political timelines, and resident influence, were all barriers that emerged from this thesis, all of which are related to governance structures. Traditional approaches for climate change adaptation planning assume that higher levels of government (national and provincial) are the dominant institutions in forming policy. However, in recent years, there has been a re-allocation of authority and a de-centralization of decision-making power (Hooghe & Marks, 2001). The thesis focused exclusively on the decision-making process within the institution of the City of Prince George. It became evident throughout the interviews, however, that businesses, community members, and educational establishments, among many other types of institutions, have played a significant role in facilitating change with regard to WRM in the community of Prince George. PGAIR, ICBC, the Government of BC, and a local concrete plant were integral in catalyzing change in WRM practices at the City of Prince George.

As a socio-technical system, there are many institutions involved that all play a role in influencing change. Into the future it is likely that work on climate change adaptation in the transportation sector will employ a holistic approach that assesses both the technical aspects of the issue at hand, but will also endeavor to further assess the socio-technical responses and explore how decisions are made. As this thesis has highlighted, the development of knowledge does not fully overcome the barrier of climate change adaptation action. The development of knowledge in this case study is important for understanding the current WRM regime in the City of Prince George, but the value of this knowledge for improving climate change readiness remains to be seen.

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Appendix A: Semi-structured interview questions

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Semi-structured interview questions for the City of Prince George

Note: This is the complete list of questions. Interviews with participants will draw on an individualized subset of these questions depending on the specific roles and responsibilities of each individual.

1. **Community context and municipal decision making**
   1.1. What are some of the challenges facing the community of Prince George?
   1.2. Can you give me an example of an event that the City of Prince George has faced, and tell me how the City responded?
   1.3. I realize that transportation is a major responsibility for municipalities, and that related decisions may be made by different officials/authorities. Which types of decisions are made by Council and which others are made by employees?

2. **Current winter road maintenance practices**
   2.1. I was wondering if you could describe the main aspects of your winter road maintenance operation?
   2.2. When I was last here for a workshop on climate change adaptations for transportation in 2011, there were a few aspects of your winter maintenance practices that stood out to me. These included the clearing of snow from the ends of driveways, and removal of snow at night. Can you clarify if theses are still normal practice in Prince George?
   2.3. Are some of the practices used by the City of Prince George different than those of cities of similar climate and comparable size?
   2.4. Winter road maintenance has evolved over time. Can tell me when last, or how often, winter road maintenance practices are reassessed in Prince George?
   2.5. Can you tell me the process for assigning winter road maintenance budgets?
   2.6. Was there a time when the transportation department required more resources for winter road maintenance than had been allocated? If so, from where were the resources found?

3. **Climate change adaptation planning in the City of Prince George**
   3.1. Would you be able to provide insights into how you, as a city employee perceive climate change.
   3.2. If there are concerns about climate change in Prince George, what will they be?
   3.3. Who do you think is responsible for climate change adaptation planning in the City of Prince George?
   3.4. Can you think of examples of climate change adaptations that have already occurred in the City of Prince George?

4. **Climate change scenarios for winter road maintenance and safety (Show range of scenarios)**
   4.1. How would your decisions pertaining to resource allocation change based on each of these scenarios? (show graphs from analysis of secondary data)
   4.2. If the budgets were to be altered based on these projections, what would be some of the concerns you would have?
   4.3. If resources were freed up from the maintenance budgets, how would the City begin to think about reallocating these resources?
   4.4. What are the outstanding needs in the community, outside of transportation, that would benefit from increased resources?
   4.5. Is anything else you would like to add about climate change in the context of the many challenges facing community of Prince George?

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Appendix B: Information sheet presented to interviewees

Lindsay Matthews, MES Candidate
Department of Geography and Environmental Management
University of Waterloo

March 2014

Snow and Ice Control in the City of Prince George

A winter severity index has been created to explain season-to-season variations in winter road maintenance expenditures in the City of Prince George. This index illustrates a clear relationship between the weather of a given winter and the millions of dollars spent on winter road maintenance activities (R^2=0.932).

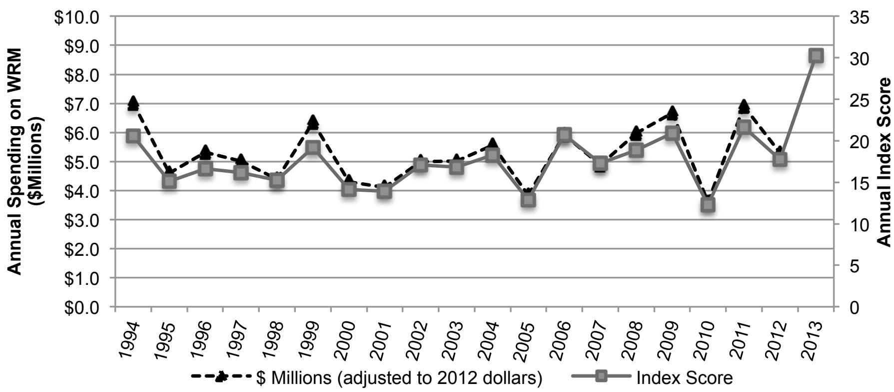

Figure 1 – Winter Severity and Winter Maintenance in Prince George over the past 20 years

This index has two main components: the number of days of heavy snowfall and the number of days with the potential for icing during or after rainfall (rain occurring on days where temperatures are within the freezing range).

- Budget data were adjusted to 2012 dollars to account for inflation
- The average index score for the past two decades was 17.2.
- Average annual expenditures on snow and ice control were $5.4 million annually from 1994-2012 (adjusted to 2012 dollars).

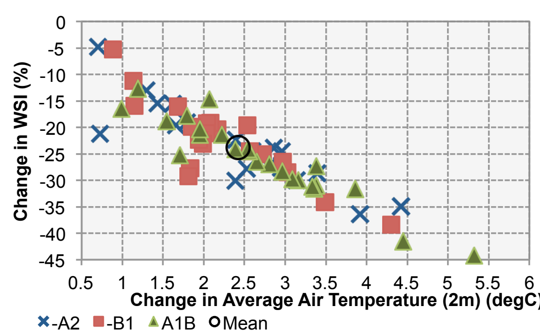

Figure 2 – Projected Annual Changes to Temperature and Winter Severity in Prince George for the 2050s

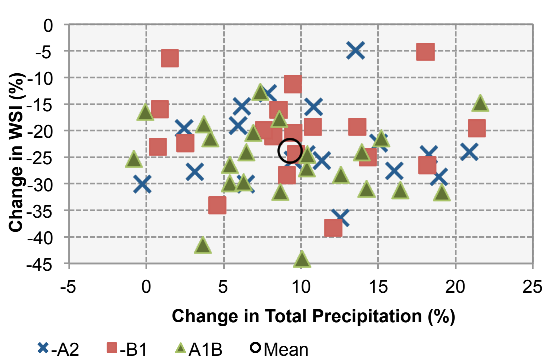

Figure 3 – Projected Annual Changes to Precipitation and Winter Severity in Prince George for the 2050s

This index was then applied to modeled climate data for 65 scenarios to project changes in expected budget for snow and ice control into the 2050s.

- The average annual winter severity index score for the 2050s is 13.1.
- The lowest annual index score for the 2050s is 3.6 and the highest is 25.1.
- Of the 65 models that were run, there was an average of 5 years out of 30 that would have winter severity index scores higher than 17.2.

Appendix C: Contact letter

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February 20th, 2014

Dear NAME,

This letter is an invitation to consider participating in research I am conducting as part of my Master's degree in the Department of Geography and Environmental Management at the University of Waterloo under the supervision of Professor Dr. Jean Andrey. In the text below I provide more information about this project and what your involvement would entail if you decide to take part.

Study Overview
The purpose of this study is to explore the way(s) in which public agencies consider and respond to weather, climate and projections of climate change, especially in terms of winter road maintenance. The project is situated more broadly in the context of community adaptation planning. The interviews will share, and build on, empirical analysis that has already been completed on weather-related road maintenance and safety in the City of Prince George. I believe that, given your role as the TITLE with the City of Prince George, you are well suited to speak to this issue. The specific themes of the interview are included at the end of this document.

Your Involvement
I hope to interview approximately 10 people who are involved in transportation planning and decision making in the City of Prince George. As a participant in this study, it is your right to request further clarification of any question, to decline to answer any specific question, or to end the interview at any time. There are no known risks or benefits of taking part in this research. To ensure anonymity, your name will not appear in any thesis or publication resulting from this study and any information you give me will not be used to identify you. The interview would last between 30 minutes and 45 minutes. To ensure the accuracy of your input, I would ask your permission to audio record the interview. Also, with your permission, anonymous quotations may be used in the thesis or future publications. Recordings and data will be kept confidential and stored with no personal identifiers in a secured location for two years and then confidentially destroyed. This research poses no known or anticipated risks to participants.

Contact Information
You may also contact me at any time to learn about the progress of the research project. If you have any questions regarding this study, or would like additional information to assist you in reaching a decision about participation, please contact me at 519.954.1329 or by email at l2matthe@uwaterloo.ca. You can also contact my supervisor, Dr. Jean Andrey at 519-888-4567 ext. 33629 or email jandrey@uwaterloo.ca.

I would like to assure you that this study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, please contact Dr. Maureen Nummelin in the Office of Research Ethics at 1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

I very much look forward to speaking with you and thank you in advance for your assistance in this project.

Yours Sincerely,

Lindsay Matthews
Master's of Environmental Studies Candidate

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Appendix D: Consent form

CONSENT FORM

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

I have read the information presented in the information letter about a study being conducted by Lindsay Matthews of the Department of Geography and Environmental Management at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.

- I am aware that I have the option of allowing my interview to be audio recorded to ensure an accurate recording of my responses.
- I am also aware that excerpts from the interview may be included in the thesis and/or publications to come from this research, with the understanding that the quotations will be anonymous.
- I was informed that I may withdraw my consent at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through a University of Waterloo Research Ethics Committee. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Director, Office of Research Ethics at 519-888-4567 ext. 36005.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

☐YES ☐NO

I agree to have my interview audio recorded.

☐YES ☐NO

I agree to the use of anonymous quotations in any thesis or publication that comes of this research.

☐YES ☐NO

Participant Name: ____________________________ (Please print)

Participant Signature: ____________________________

Date: ____________________________