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A winter index for benchmarking winter road maintenance operations on Ontario highways

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A WINTER INDEX FOR BENCHMARKING WINTER ROAD MAINTENANCE OPERATIONS ON ONTARIO HIGHWAYS

By

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Abstract

Canada is one of the snowiest countries in the world, and winter road maintenance activities cost in the order of a billion dollars a year. These activities vary considerably over both space and time, partly due to differences in winter weather, but also because of differences in road and traffic mix, terrain and other factors. The thesis explores the association between winter road maintenance activities and winter weather. The first objective is to characterize the spatial and temporal variation in severe winter weather in Ontario. The second objective is to identify a winter weather index that is sensitive to road maintenance activities in Ontario. The third objective is to modify the identified winter index based on Ontario's climate and road maintenance situations. To account for the variation in winter weather from year to year and across the Province, three winter weather indices were applied to Ontario data. Monthly index values were correlated with monthly salt usage, on a maintenance district level, for the recent five winters. One of these indices was then modified to better reflect the Ontario situation. Road information was also considered. The main results include: the spatial and temporal variation of winter weather severity in Ontario is quite large. Among the winter indices concerned, the SHRP winter index is most suitable for Ontario winter road maintenance. After assigning particular weights on certain climate variables and adding a freezing precipitation variable, the modified SHRP index correlated better with salt usage than the original SHRP index did in most MTO districts. Salt usage regression models with temperature and precipitation as the explanatory variables performed similarly to the SHRP index at the district level, but the model coefficients varied considerably from one district to another indicating that there are substantial place differences in how road maintenance authorities respond to winter weather. The significance of the results is realized when applied to winter road maintenance management procedures. The SHRP index can be used at the district level to interpret temporal differences in regional salt usage and winter severity. This index can also be used to indicate the spatial distribution of winter severity and road salt usage across the province, aiding in the allocation of maintenance resources to different regions based on winter weather.

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1 Problem Statement

1.1 Introduction to the problem

Canada is one of the snowiest countries in the world. From British Columbia to Atlantic Canada, most parts of Canada occasionally receive large amounts of snow. Northern Ontario's annual snowfall varies from 171cm near Dryden along the Ontario-Manitoba border to 352cm at Timmins in Northeastern Ontario. In southern Ontario, the heaviest snowfalls happen in a belt lying inland from Lake Huron and Georgian Bay. This area annually receives about 300 - 400cm of snowfall (AES, 1961-1990 normal). It should be emphasized, however, that the variation in snowfall from one year to another is great and the spatial variation is also very high.

Heavy snowfalls can be disruptive to the human system, by impeding air and surface traffic, and damaging structures such as power lines and roofs of buildings. Generally, direct damage, consisting mainly of the loss of physical property, can be evaluated in terms of dollars. For example, the January 1998 ice storm that hit eastern Ontario and western Quebec destroyed 40% of the power distribution network for this region, leaving more than 1 million people without electricity for 3 weeks. The federal government gave 75 million dollars in the wake of the ice storm to local governments in Quebec and eastern Ontario (Weather Network, 1998). There are also hidden or underlying costs of adjusting to severe winter weather, which may be much higher than direct costs.

The main challenges of snowfall are felt in the transport sector, namely on mobility and safety. Heavy snowfalls associated with high wind and low temperature pose a major problem for road transportation. Impacts vary from slippery roads to driving advisories to closed road and stalled vehicles (Rooney, 1967). Hanbali and Kuemmel (1993) analyzed traffic volume reductions due to winter storm conditions in the US. Their main conclusion is that traffic volume is reduced due to winter storms. The more severe the storm, the larger the reduction. An associated rise in traffic accidents has also be linked to severe winter weather. Snowfall and associated weather conditions produce dangerous situations for drivers, namely the loss of friction with the pavement and poor visibility. A Canadian study suggested that the number of accidents during snowfall conditions, relative to other winter conditions is roughly twice as high (Andrey, 1993). The number of accidents on icy roads would obviously be much higher if there were no winter maintenance. Hanneman (1992, p.432) cites a study by Hanke and Levin which states that traffic accidents are cut by 75 percent when icy and snowy roads are salted.

Canadians adapt to snowfall hazards. Both individuals and society prepare for, and respond to, snowfall events. For example, people residing in snowbelt regions purchase snow tires, shovels, snow brooms and scrapers for winter; during storms, they slow down and drive more cautiously to compensate for the slippery road conditions, or even cancel some trips (Andrey and Knapper, 1993). Municipalities and provincial highway authorities salt, sand or plow roads to keep mobility and safety at an acceptable level.

Social response in the form of winter road maintenance can be very expensive. Many cities in North America annually budget millions of dollars to remove snow from city streets. Most cities have programs of sanding and salting roads to keep the snow from being compacted by traffic and turning into ice. The total cost of snow and ice control in North America is almost $2 billion per year (Thorne, 1990). For Ontario alone, more than $100 million is spent by Ontario Ministry of Transportation (MTO) on winter road maintenance, and similar amounts are spent by municipalities annually (Perchanok, 1998).

Winter road maintenance costs vary over time and space, partly as a function of the weather, but possibly also due to other factors, such as topography, road mix and institutional guidelines. The winter experience varies from place to place in severity as well as in time. A general characteristic of snowfall patterns in the Great Lakes' region is that they are highly variable, especially in southern Ontario, "where a single storm may bring as much or more snow to a locality in one or two days than it would receive in an entire winter some other year" (Phillips, 1990, p.103). Even in regions that experience similar weather conditions, road maintenance costs may vary, due to different degrees of urbanization, road conditions or efficiency of the snow removing operations.

Despite the general understanding, there has been limited research on the spatial and temporal variations in winter road maintenance activities in Canada and on the role of weather versus other factors in defining these patterns. This information is important, not only in working toward more effective/efficient road maintenance programs but also as a basis for anticipating and adapting to potential impacts of climate variability and change.

1.2 Objectives of the study

The purpose of this thesis is to improve the understanding of how public agencies adapt to winter weather, specifically through publicly funded road maintenance programs. The goal of the empirical analysis is to document the spatial and temporal variation of winter road maintenance activities on provincial roads in Ontario over the past five years, and to explore the role of weather and other factors in explaining these patterns.

Objective 1

The first objective is to characterize the spatial and temporal variation in severe winter weather in Ontario. Various climate variables, such as snowfall, snow days, and temperature, will be considered. The weather data will be extracted from the Climatological Archives of the Atmospheric Environment Service, Environment Canada. This analysis is based on 20 winters' (1978/79 to 1997/98) monthly weather data for 25 selected weather stations. This objective provides background for the analysis.

Objective 2

The second objective is to identify a winter weather index that is sensitive to road maintenance activities in Ontario. Various indices, which have been developed and applied in either Europe or the United States, will be applied to Ontario data.

These indices include the following:

- the number of salt days (Cohen, 1981)
- the modified Hulme index (as developed by Hulme, 1982 and modified by Thornes, 1991)
- the SHRP winter index (named after the Strategic Highway Research Program, Thornes, 1993)

Each index will be applied to 12 locations corresponding to a principal weather station in each of Ontario Ministry of Transportation (MTO)'s 12 maintenance Districts. The relationship of winter weather severity and winter road maintenance activities will be examined for the recent 5 winters (1993/94 to 1997/98).

The index values then will be correlated with road salt usage in order to assess the performance of each of the models and identify the best index for application in Ontario. Two kinds of analysis will be done for this objective, temporal variability of salt usage vs. winter indices within each district and spatial variation among the 12 districts.

Objective 3

The third objective is to modify the identified winter index based on Ontario's climate and road maintenance situations. Different time scales will be examined; the coefficients, the weights and the climate variables included in the index will be modified based on Ontario's climate conditions. Also, a regression model of salt usage vs. different climate variables will be identified for every district.

1.3 Contributions of the thesis

To the best of our knowledge, a winter weather index that is oriented to road maintenance has not been applied to Canadian data. This study will provide insight into the appropriateness of established indices to the climate and transportation system of Ontario.

Knowledge of the spatial and temporal variation of winter road maintenance operations is limited at present. This study will provide summary data and maps for provincial roads in Ontario. The results of the regression model of winter index and salt usage can be used to estimate the salt usage of a given district; the winter index can also be used to evaluate the cost-effectiveness of new technology in snow and ice removal (such as road weather information systems) by monitoring the salt usage and winter severity.

1.4 Thesis format

The format of this thesis is as follows: chapter one provides the general problem statement. The literature review is covered in chapter two, where issues associated with applied meteorology, weather-related transportation impacts, snowfall hazards and highway meteorology, and the winter index and road maintenance are examined. Chapter three outlines the methodology, including the spatial and temporal context of this study, the data sources and general characteristics, and the methods of analysis. Chapter four provides the results. The temporal and spatial variability of winter weather and winter indices will be examined. The winter index that is most suitable to Ontario's climate and road maintenance situation will be identified and modification to this index will be discussed. Chapter five contains the conclusions and discussions of the research.

2 Literature Review

2.1 Introduction to Applied Climatology

2.1.1 Definitions, applications and developments

Applied climatology, which is a widely used term, may be defined as "the use of archived and real-time climatic information to solve a variety of social, economic and environmental problems for clients and managers, in fields such as agriculture, industry and energy" (Smith, 1987 as cited in Hobbs, 1997, p.3). Applied climatology has been defined, in part, by the atmospheric scientists and geographers who practice and identify with it, and in part, by the many users beyond the atmospheric sciences. A wide range of professionals in a variety of field such as engineering, economics, agriculture, tourism, botany and geography commonly examine the relationship between climate and their special area of study.

There is general agreement that the Second World War gave a major impetus to the development of applied climatology (Hobbs, 1997). Applications of climatology developed greatly at that time, with more extensive data networks, improved methods for sorting and analyzing data and expansion of archives. This growth can be attributed partly to the development of specific skills and techniques using modern methods of data handling linked with improved understanding of statistical theory, particularly as related to extreme events and probability analysis (Hobbs, 1997).

Recent concerns about possible severe climatic impacts on a growing global population have brought applied climatology more and more into the public area. The potential vulnerability of the modern world to climatic variability, and an awareness of environmental consequences of the continued consumption of fossil fuels have led to a 'coming of age' for applied climatology. But as Hobbs suggests, there is commonly a gap between the availability of climatic information and products and their application. Concerns include questions about data quality, and the delivery of useful products to those who need them. Despite this, it has been claimed that "applied climatology is the oldest and by far the major success story of the atmospheric sciences in service to society" (Hobbs, 1997, p.4).

2.1.2 Climate impacts and adaptations

Climate impacts and adaptations are important parts of the broad field of applied climatology. Hobbs (1997) cites Parry's opinion that great realism can be introduced to climate-society studies by considering adaptation and adjustment to climate variability and change. It is possible to consider factors like the vulnerability or resilience of different systems to an impact, which can in turn affect how societies can and do respond to climate change. Furthermore, research can focus on direct human concerns such as the role of decision making, constraints on choice, and the formulation of strategies (Hobbs, 1997).

Weather sensitivity is determined by the balance between what are perceived as atmospheric resources and hazards. As Smith (1989) notes, these terms reflect personalized value judgments which are not always helpful because the atmospheric processes responsible for such events are neither benign nor hostile, but entirely neutral.

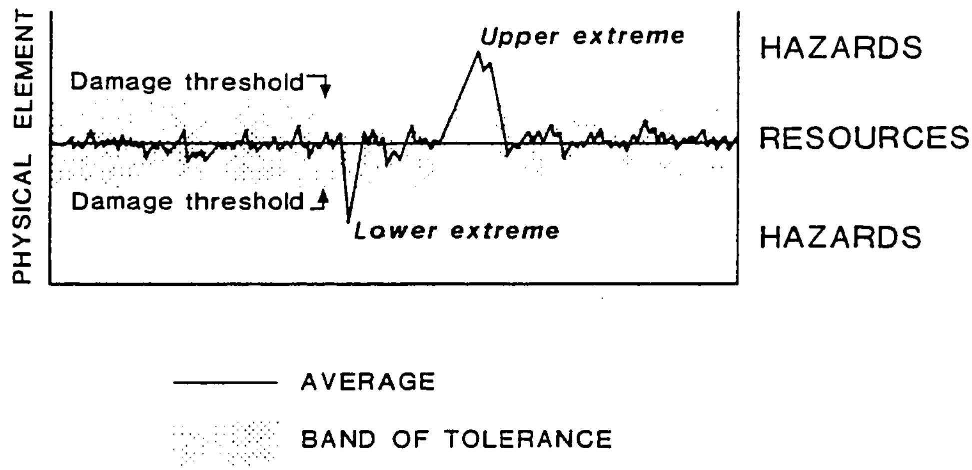


Figure 2.1 Weather sensitivity expressed as a function of atmospheric variability and social-economic tolerance.
(From Smith K., 1989, p.4 in Weather Sensitivity and Services in Scotland, edited by Harrison S.J. and Smith K., Scottish Academic Press, it was modified from Hewitt K., and Burton I., 1971, The Hazardousness of a place, University of Toronto Press).

Figure 2.1 shows the boundaries conventionally imposed on atmospheric conditions to identify resources and hazards. As Smith (1989) suggests, most social and economic activities are geared to some expectation of 'average' conditions or thresholds of tolerance. As long as the variation of any element remains fairly close to the expected, activities are well adjusted to the conditions, and the atmosphere may be regarded as a resource. However, when conditions exceed some threshold, then the same element is regarded as a hazard (Smith, 1989). In practice, the hazards merely represent the unexpected outer limits of a distribution that would otherwise be regarded as a resource. Frequently, there is no clear line distinguishing the two, e.g., between snow as a resource on the ski slopes and as a challenge on the winter highways.

To complicate things further, rarely does a straightforward cause and effect situation apply. As Hewitt (1997) suggests, society and environment are fully intertwined. "Every society is constructed as a complicated 'negotiation' between artifice and nature, a two-way flow of materials, control and mutual adjustments" (Hewitt, 1997, p.175). We have to view natural hazards as aspects of, or breakdowns in, the web of relations linking society and natural conditions. Natural hazards arise at the interface of society and the environment, and depend upon the context in which that occurs.

The relationship between exposure and vulnerability is further complicated by the fact that both entities are dynamic and may change independently through time. Since Canada is a big country, bordering three oceans and encompassing major mountain chains and huge inland lakes, it experiences a range of air masses from very cold to hot and from desert-like to very humid. As such, Canadians experience a broad range of atmospheric hazards. The prairies are most frequently affected by hail storms, drought and forests fires; while heavy snowfall, blizzards, and freezing rain are common problems in South Ontario and Quebec, especially around the Great Lakes (Etkin and Maarouf, 1995).

This thesis attempts to address social response to climate by focusing on snowfall hazards. These are common throughout Canada, and the adjustments to the associated risks are embedded in our every day life. The focus here is on understanding how municipalities and provincial agencies adapt to the impacts of winter snow hazards, and more specifically on the relationship between winter weather severity and winter road maintenance operations by the Ontario Ministry of Transportation (MTO).

2.2 Weather-related Transportation Impacts

2.2.1 Weather-related impacts by mode

An efficient, safe and cost-effective transport system is vitally important. All sectors of a country's economy rely on transport, and all transport services are affected by weather and climate. The atmosphere acts as both a resource and a hazard to different forms of transport. From the resource point of view, aircraft rely on air density to fly; and are able to plan freight to take advantage of wind systems, thus improving fuel efficiency. Similarly, vehicle combustion engines require air to mix with the fuel in order for combustion to take place. The hazards associated with the climate are more obvious and involve effects on the vehicles as well as on the transport infrastructure and nodes such as ports and airports. Snow, ice, fog, wind, heat, lightning, heavy rain and flooding can all render transport systems inoperable. Thornes (1997) discussed the sensitivity of all transport forms to weather and climate, including air, rail, road and water transport.

Modern aircraft use the atmosphere more than they suffer from it, and the resource usage of the air far outweights the hazard. But aircraft still have problems in severe weather, mostly when taking off and landing. Some significant weather phenomena such as fog and snow or ice can cause substantial impacts on air transport. As a visibility hazard, fog can cause delay of the aircraft. Heavy snow and ice on runway even cause close of airports for some period, as happened over new year 1999 in many cities in North America. With advanced technology, most severe weather can be predicted and avoided in flight. Also, most airports have "round the clock" snow and ice control, since airports are designed to be kept open every day of the year in all weather conditions.

The main role of rail transport in Canada today is freight movement. Rail is responsible for moving 250 to 300 billion tonne-kilometres of freight each year (Nix, 1995). In the Canadian Country Study of 1997, Andrey summarized climate impacts and adaptations on the transportation sector. In terms of the rail sector, she notes that heavy rains and associated flooding and mudslides pose a potential problem for rail track, and Canadian's harsh winter, heavy snowfall and low temperature increase both operating costs and the probability of delay or derailment. So rail companies have plans for dealing with winter weather, such as snow removal programs (CN Rail, approximately $5.5 million in the winter of 96/97). Also temporary slow orders (travel speeds reduced by up to one-third) are given when temperature drops below –20° C.

Water transport is extremely weather sensitive. A historical survey of Canadian disasters shows that almost one-third of all disasters occur at sea, and 80% of these are weather related, e.g. Johanna B and Capitaine Torres sank in Gulf of St. Lawrence, 1989, (39 died); and the Salvador Allende sank 900 km south of Nfld, 1994, (29 died) (Etkin and Maarouf, 1995). Due to its northern latitude, much of the water adjacent to Canada experiences permanent or seasonal sea ice which is a hazard to water travel. The weather can affect the day to day running of a harbor, with wind and rain critical to loading and docking strategy. Weather forecasts such as storm track and intensity, as well as marine forecasts including the routine and violent action of waves, tides and currents are important to water transport.

Road transport is the dominant mode in Canada. There are more than 300,000 km of surface roads and 530,000 km of unpaved roads across the country. Roads currently support approximately 90% of all inter-city passenger trips and 75% of Canadian freight shipments by value (government Canada, 1998). For other forms of transport, like air and rail, the impact of ice and snow is most keenly felt at a limited number of points on the transport network -- at track points (switches) and at airports -- but on the roads the problems are more widespread. Weather and climate sensitivity to road transport is of great consequence. The impacts of weather on road transport will be discussed separately in the following sections.

2.2.2 Impacts on road transportation, mobility and safety issues

Far more attention has been paid to road transport than to other modes. Weather-related road hazards can cause substantial delays in the movement of goods, people and services; they also contribute to vehicle accidents which produce property damage, injuries, and deaths. Hazardous weather affects road transportation in two ways: first, weather affects the amount and type of traffic on the road, such that there is a change in the number of road users exposed to the risk; and second, weather affects the risk per unit of travel because of slippery roads and poor visibility. Often mobility and safety are examined together, e.g. in Codling's studies (1974) and in Rooney's (1967) studies on hierarchies of disruption. The main conclusion from previous studies is that when inclement weather occurs, the volume of traffic decreases, while the number of accidents increases significantly. But the quantity of the volume reduction and increase of the accident risk is different in different case studies.

Codling examined the weather-related impacts for road transport in Great Britain on the six snowiest days of 1969-1970. He found that "snow days" traffic was reduced by anywhere from 12 and 26 percent, whereas traffic accidents increased between 4 and 52 percent with an average increase of 24 percent. Codling emphasizes two noteworthy points. First, precipitation decreases traffic flow but causes an increase in the number of accidents. Secondly, for accidents, he found the effect depended upon the extent of snow and ice: moderate amounts led to more accidents, while larger amounts led to fewer accidents than expected under dry conditions (Codling, 1974).

Hanbali and Kuemmel analyzed traffic volume reductions due to winter storm conditions in the US. They suggested that winter storms with snow precipitation of 25mm to 375mm have an average traffic volume reduction of 7 to 53 percent during weekdays and 19 to 56 percent during weekends (Hanbali and Kuemmel, 1993).

An early study on the urban snow hazard which attempt to examine the varying degrees of disruptions in the US was done by Rooney (1967). He developed a hierarchy of disruptions related to the degree of disruption to both internal and external transportation systems of urban complexes in the US. Another related study by Duerden (1977), examined some aspects of the urban snow hazard in Ontario. Duerden defined disruption as the extent to which normal lifestyle in a settlement is affected by snowfall depth and/or wind speed. Traffic accidents, business slowness, school closures, absenteeism, and varying degrees of traffic chaos are all seen as being symptomatic of disruption. What Duerden found was that the incidence of disruption in a center was related to both climatic severity and the degree of preparedness, preparedness being a response to climatic severity (Duerden, 1977).

For road safety issues, it is difficult to separate out the effect of weather (e.g., snow/rain, wind, fog, glare) from other contributing factors. Still, weather is an important risk factor (Andrey, 1997). As a starting point, it is instructive to consider aggregate numbers. In many parts of Canada, precipitation occurs only 10 to 15 percent of the time, but approximately 20 percent of all the personal injury collisions occur while precipitation is occurring, which suggests that accident rates increase significantly during rainfall and snowfall. This has been confirmed in detailed studies by Andrey for several Alberta cities (Andrey, 1989; Andrey and Olley, 1990; Andrey and Yagar, 1993), and a recent study by Suggett (1999) for the city of Regina. The results of these studies indicate that accident rates increase from 40 to more than 300 percent during precipitation, with the increase being greatest for property damage collisions and least for fatal crashes.

2.3 Adjustments and adaptation to weather related transportation impacts

Transport industries, government agencies and the Canadian public expend considerable effort and spend substantial sums of money to reduce the risk of delay or incident due to inclement weather (Andrey, 1997). A useful review of the relationships between the atmosphere and road transport is contained in *Highway Meteorology*, edited by Perry and Symons (1991). Some Canadian studies have also summarized meteorological influences on transportation infrastructure and operations, such as the Canada Country Study, Climate Impacts and Adaptations for Transportation Sector by Andrey, 1997.

Highway Meteorology is the first book to give highway engineers and meteorologists a complete overview of the subject and related technological developments. It examined the weather hazards that reduce road friction and visibility including topics such as snow and ice control, snow drifting modeling and control, winter maintenance of highways, and fog hazards. It also introduces new technological developments in the field of winter road maintenance. Ice detection systems, thermal mapping and weather radar are used by many authorities in Europe and North America. There is intense interest in the performance, reliability and cost-benefits to be gained from employing these relatively new technologies.

In *the Canada Country Study, Climate Impacts and Adaptations on Transportation Sector*, Andrey (1997) summarized the literature concerned with this topic. Weather sensitivities are reflected in the design, construction and maintenance of transportation infrastructure. For example, snow and rain affect roadway decisions about drainage and surface texture and roughness; snow fences are specially designed for preventing blowing snow or drifting snow in bridges or other highway sections; salting and sanding roads and snow removal are common winter road maintenance activities in Canada.

Weather forecasts and road advisories that allow those responsible for maintaining or operating transport systems to make informed decisions. Individuals tend to drive rather than walk during snowstorms in order to stay out of the elements. Few studies estimate the frequency with which drivers cancel trips and adjust operating speed during inclement weather, such as Andrey and Knapper (1993). As Andrey suggested, a range of adjustments is available, but the effectiveness of these adaptive measures is poorly understood. More research on human response to weather hazards is needed (Andrey, 1997).

2.4 Winter Road Maintenance

2.4.1 The importance of snow removal

Roads that are safe in all weather are a prerequisite of modern society, and large amounts of money are spent by highway authorities, especially in winter, to make travel safe. In Canada, winter maintenance commonly falls under the mandate of the public works department of a local governing body, such as a municipality or a township, or the province, depending on who is responsible for a given road. Due to the particularly harsh Canadian winter, the winter road maintenance programs often involve considerable expenditure on personnel, equipment and abrasives/chemicals in order to keep highways in a condition that is safe for road users. Typically winter road maintenance operation involves communication between meteorologists, who are called upon to provide advance warning of dangerous conditions, and highway engineers who must be available to take remedial action.

Many cities in North America spend millions of dollars annually for snow removal. This money is spent on de-icing chemicals and abrasives, snow removal equipment and labor. The annual cost of winter maintenance activities in North America is nearly $2 billion (Thornes, 1990). The snow removal budget of Montreal, Canada, in 1993 totaled

$57 million (Girard, 1993). In Ottawa 15% of the taxes is spent on snow removal; and snow removal is the fifth most costly city program (more than a quarter of the police budget and half that of fire protection (Phillips, 1990)). MTO spends more than $100 million on winter maintenance annually (Perchanok, 1998).

2.4.2 The factors affecting winter road maintenance activities

Winter road maintenance is sensitive to weather conditions. But there are also other factors, including the choice of de-icing chemicals, information systems and new technology. All these factors can affect the efficiency and effectiveness of snow removal activities.

Weather variability

Weather variability is a major factor that affects winter road maintenance activities. As for variability, the climate of southern Ontario can undergo dramatic fluctuations on a daily basis and can be radically different from one location to the other. These variations are created by the topography, proximity to the Great Lakes, the prevailing winds, and the nature and frequency of the weather systems crossing southern Ontario. The large geographical difference in snowfall accumulation will affect the allocation of snow removal expenditures. Bryant (1991) describes the variation in precipitation and response to the snow hazard around the Great Lakes. Buffalo and Hamilton, within 60km of each other, have totally different responses to snow as a hazard. Each city allocates different sums of money for snow removal operations. Buffalo removes its snow from roads and dumps it into Lake Erie. Hamilton uses sanding and salting operations to melt smaller amounts of snow, and only resorts to snow removal for the large storms. In the severe winter of 1976-77, Buffalo's well-planned snow removal budget was decimated by a succession of blizzards. On January 28, 1977, a severe blizzard swept off Lake Erie through the city. The storm raged for 5 days and the final clearance bill totalled more than $200 million, more than five times the budgeted amount for snow removal. In contrast, the city of Hamilton was relatively unaffected by this blizzard, and ended up loaning snow removal equipment to Buffalo as part of an international disaster rescue operation (Bryant, 1991).

In any given place, snowfall accumulation also varies from year to year, which also affects snow removal budgets. For example, annual road salt expenditures for the Regional Municipality of York increased by 80% from 1992 to 1993, primarily due to the cold winter conditions which plagued southern Ontario during 1993-94 winter. As a result, the region's salt budget ended up being 64% over budget in 1993. Conditions in 1994/95 were more favorable as indicated by the $14 million savings in winter road maintenance costs reported by the Ontario Ministry of Transportation over 1993/94 (Andrey, 1998).

This raises the issue of how winter road maintenance plan and budgets are determined. Montreal's annual budget is set using a hypothesis based on the experience of the ten previous years (Girard, 1993); Metro Toronto uses an estimate of projected snowfall based on an average of previous 7 winters (Wilson, 1992); and some municipalities, such as the City of Waterloo, use a 5-year average to budget the coming year (Waterloo Chronicle, Jan. 5, 1993). By contrast, climatologists define normals using a minimum 30 year period. The climate normal should be a better indicator of a particular region's average weather conditions. Seasonal forecasts might also be considered in planning for winter road maintenance operations.

De-icing chemicals

Salt is the most commonly used deicer. Each year, over four million tons of de-icing salt is spread by provincial and municipal road crews across Canada to clear our roads of ice and snow (Samuels, 1989). Because of the varying temperature regimes across Canada, salt is not effective in some colder areas. Salt de-ices effectively when temperature is at or above -6°C; below -12°C it cannot melt and break down the ice-pavement bond. However, in the presence of sun and heavy traffic volume, which creates a higher road surface temperature, salt can be effective down to an ambient temperature of -18°C. In practice, salt is use during or after a storm; after plowing, when the temperature is between -7°C and -12°C; or the temperature is at -12°C ~ -18°C and the temperature is rising (MTO, 1982). Calcium chloride, another de-icer works effectively at temperatures lower than sodium chloride but is more expensive.

Despite its excellent de-icing capability, salt has many negative effects on our environment. Salt increases the rate at which vehicles corrode, reinforced concrete highways, bridges, parking garages and buildings; it is environmentally destructive. There are studies concerning the impacts of road salt on water, soil and vegetables (Jones et al., 1992; Kelsey and Hootman, 1992; and Gales and VanderMeulen, 1992). The soils and vegetation at the roadside show the effects of the road salt. The presence of salt in the soil has an impact on vegetation through an increase in the osmotic pressure of the water in the soil (Jones et al., 1992, p.53). This makes it harder for some species of plants to draw water from the surrounding soil, effectively dehydrating the plant, possibly to the point of death (Gales and VanderMeulen, 1992, p.142). As well, plants, which are close to the road itself, are affected by the spray of salt-rich water created by traffic or the action of plows. As road salt is blown away from the road surface, it may join streams, rivers, ponds or lakes. It has been shown that road salt application has a positive correlation with elevated chloride levels in surface waters (Jones, et al., 1992, p.34). The most significant physical impact of these elevated levels is in ponds and small lakes.

Because of side effects and salt effective temperature limits, government agencies across Canada are looking for alternative de-icers that perform as well as salt but are environmentally safe and eliminate corrosion. Some communities have tried a no-salt policy and have concluded that such a policy deteriorates driving conditions to the extent that the economic costs of not salting far exceed the economic costs of salting, and such a policy is not acceptable. Overend (1975, p.37) cites the example of Burlington, which tried to ban salt in 1971 and experienced an accident rate which was the highest monthly total seen in three years. Samuels (1989, p.16) reported on the experience of Midland, Ontario, which passed a no salt policy "only to find the policy overruled shortly after an ice storm".

Considering both the costs of salt and its unwelcome environmental impacts, the highway engineer is interested in using the minimum amount of salt necessary to maintain the highway in a safe condition, while at the same time ensuring that the statutory requirement to keep the highway safe is met. The new technological development, such as Road Weather Information Systems (RWIS), is considered the most promising.

New technology and Information system

New technology and information systems have altered the face of winter road maintenance operations. Road Weather Information Systems (RWIS) are the most important one in the technological development in that they provide measurements and predictions of road surface conditions. A series of studies by Thornes provides an overview of recent development in road-weather monitoring and communications primarily for winter maintenance activities (Thornes, 1989, 1991 and 1993; Cornford and Thornes, 1996).

An effective winter road maintenance program needs precise timely weather information. RWIS provides one solution and their use by road masters to determine when to use deicing chemicals on roads is increasing. These systems are specialized computer networks which collect, process and disseminate information about weather conditions relating to highway transportation. RWIS have been used in countries, such as UK and Denmark, since the late 1980s. In the1996/97 winter, MTO installed advanced RWIS in its Maintenance 2001 test site located on highway 26 between Stayner and Barrie. (MTO, 1998). Integration of advanced RWIS with other leading-edge maintenance practices and technologies, such as infrared thermometer, zero velocity spreader, is all part of an effort to increase the efficiency of winter road maintenance activities.

2.5 Winter Index Correlated with Winter Road Maintenance Activities

Many weather indices are widely applied because of their being easy to use and their links to warnings of corresponding risks. Phillips (1990) summarized several weather indices, including wind chill, humidex, growing degree days, and heating degree days. Two climate discomfort indices commonly used in Canada are wind chill and humidex. Wind chill is a simple measure of the chilling effect experienced by the human body when strong winds are combined with freezing temperatures. It is a good indicator of what we should wear to be protected from the cold. Humidex is a measure of what hot weather "feels like" to the average person. It is a good measure of climate discomfort. Growing degree days is widely used in agroclimatology, it is defined as “the average annual number of days with daily air temperature above 5°C” (Phillips, 1990, p.25). It is an indicator of net radiate energy income during the growing season. The heating degree days index is calculated on a daily basis according to daily mean temperature and a reference/threshold temperature of 18°C. It is an indicator of the consumption of fuel needed to keep the interior of a building at about 21°C. This index is used routinely by those in business, industry, government, and by individual home owners (Phillips, 1990). The goal for this thesis is to identify a winter index that is suitable for winter road maintenance operations on Ontario highways.

2.5.1 Winter Index—An Indicator of Winter Severity

Highway maintenance authorities spend a lot of money on winter road maintenance in Canada. However, expenditure varies considerably from year to year, especially depending on winter severity. Generally speaking, planners can prepare the budget according to past "average" expenditures. But we can never expect the next winter to be just average. This is especially true in areas where climate conditions vary considerably. For example, in the Great Lakes areas, Buffalo used 5 times its budget for the snow removal activities in the severe winter of 1976/77 (Bryant, 1991); while most cities of the Great Lake-St. Lawrence corridor such as London and Montreal, only used 1/2-1/3 their snow removal budget in the warm winter of 1979/80 (Phillips, 1981).

This poses a challenge for the planning of winter road maintenance activities. A winter index can help the planning. As an indicator of winter severity, the winter index allows the comparison between different years and regions for a given winter severity. It can be used to assess the efficiency of the winter road maintenance activities and help in the budget planning. This index may provide a relative climatological index that could be understood by professionals who are interested in weather impacts but not well-versed in climatology. As Hulme (1981) suggested, the basic assumption underlying the weather index is that a season should not be determined as 'good' or 'bad' from one weather element alone. A numerical index based on the combination of more than one element is a better criterion (Hulme, 1982).

2.5.2 Several Winter Indices for Road Maintenance

Climate variability means that no two winters are likely to be the same. Thornes (1993) suggests that the main weather parameters that affect winter maintenance are road-surface temperature (below 0°C), precipitation (especially snow), and humidity (frost information). In an ideal world these parameters could be used to assess the severity of a winter. De-icing practices at MTO clearly shows the major climate elements which affect the winter road maintenance operations are temperature and precipitation (Perchanok, 1991, p.29). There are several winter indices, which combine these climate elements and have been developed and applied in either Europe or the United States for road maintenance. These indices include the number of salt days (Cohen, 1981), the modified Hulme index (as developed by Hulme, 1982 and applied in modified form by Thornes, 1991, 1993), and the SHRP winter index (named after the Strategic Highway Research Program, Thornes, 1993).

The salt days index is defined as: the number of days with snowfall accumulation greater than 0.5 inch (1.3 cm) and mean daily temperature between 15 and 30 degrees F

(-9 to -1 °C) (Cohen, 1981). It is an index defined by temperature and snowfall simultaneously. Although this simple index was developed nearly two decades ago, it has not been widely applied; indeed in recent articles on winter weather indices by Thornes (1993), it is not even mentioned. In the original application in 6 stations in Illinois, i.e. Chicago, Moline, Peoria, Springfield, St. Louis and Cairo, Cohen did not correlate monthly salt days with salt usage. Instead, he correlated November and December temperatures with salt days in February. Based on this he concluded that salt days index was useful for making short-term forecasts of snow removal budgets. Thus it remains to be seen whether the salt days index provides an accurate reflection of winter road maintenance activities.

The Hulme index was developed by Hulme (1982). It was constructed for the period 1929/30 to 1980/81 for four stations in the UK: Durham, Edgbaston, Leuchars and Swansea. The Hulme index uses three variables: mean maximum air temperature, T, total number of ground frosts, F, and total number of days with snow, S such that

$$WI = 10T - F - 18.5S \qquad (1)$$

This index has been modified by Thornes (1991) and used as a measure of winter weather severity at Manchester airport in England for the period of 1975-1991. The modified Hulme index has the following formula:

$$WI = 10T - F - (18.5S)^{\frac{1}{3}} \pm C \qquad (2)$$

C is a constant such that the climate averaged WI is zero. The modified Hulme winter index was correlated with seasonal Great Britain rock salt usage. Seasonal salt usage was also plotted against the modified Hulme winter index for Cheshire County to assess the cost-effectiveness of the RWIS. The result is that an approximate 20 percent saving in salt use can be seen for a given winter severity (Thorne, 1993).

Cornford and Thornes also used the Modified Hulme Index to analyze the relationship between winter severity and road maintenance expenditure in Scotland. Their main conclusion is that winter severity is a plausible secondary variable when attempting to explain temporal differences in regional expenditure. The major factor is weighted lane length, which is a measure in km of the length of road within a region weighted by their importance (Cornford and Thornes, 1996).

The SHRP Winter Index was developed by the University of Birmingham for the Strategic Highway Research Program (SHRP). It was designed to be a simple objective indication of winter severity with a value ranging from –50 (most severe) through 0 (not too severe and mean level of maintenance) to +50 (warm and no need of maintenance). It is based on daily temperature and precipitation data and averaged for the period concerned. Thornes (1993) found that there was an inverse relationship between this winter index and winter road maintenance costs. The seasonal SHRP index values across US, averaged over 1950/51 to 1985/86, range from lower than –40 in the north to higher than +40 in southern US. Thornes (1993) claims that this winter index has general application for other countries, but to the best of our knowledge, it has not been applied elsewhere.

After reviewing the body of literature related to winter indices and road maintenance activities, it is clear that the thesis varies from the previous work in the following ways:

These indices were developed and used in the US or the UK. Although Canada has harsh winters and winter road maintenance programs are routine activities of associated institutions, there has been little research on the spatial and temporal variations in winter road maintenance activities and on the role of weather versus other factors in defining these patterns. The thesis research is aimed at improving our knowledge in these areas.

As these winter indices attempted to summarize seasonal weather, the weather variation of a shorter time scale cannot be revealed. In the case of a cold and snowy December and January followed by a mild February and March, the winter index for the whole season might be only slightly lower than average. The immense social and economic disruptions caused by the cold and snowy weather in December and January will not be reflected in the winter index value for the season. To amend this limitation, different time scales (seasonal, monthly, biweekly) will be examined in the analysis.

Canada experiences winter weather that is different than the US and the UK. Modifications to the winter index may be necessary so that the winter index is suitable to Canadian climate and road maintenance situations.

3 Methods

The research methods will be discussed in this chapter, including the spatial and temporal scale of the study, data sources, format and accuracy. An overview of winter weather and road maintenance activities in Ontario will also be presented. Finally, calculation of the indices and software used in the analysis will be discussed.

3.1 Spatial and temporal context of the study

This thesis analyzes the relationship between weather severity and winter road maintenance activities in Ontario. The temporal scale of the thesis includes two periods: a 20 years analysis of winter weather severity from the winter of 1978/79 to the winter of 1997/98; and a more detailed analysis of winter indices versus winter road maintenance activities for 5 recent winters from the winter of 1993/94 to the winter of 1997/98. The focus is on provincial highways which are under the jurisdiction of Ontario Ministry of Transportation (MTO). As Canada's second largest province, Ontario covers 1.1 million square kilometers with a population of almost 11 million in 1998. Over one-third of Canadians live here. Ontario is Canada's business and financial center. It is the leader in long term industrial activity and job creation. The value of output in the Ontario economy was $302 billion in 1994 (government of Ontario, 1998).

Ontario also has an excellent network of road, air, and rail facilities. There are about 16,100 km of highways and over 145,000 km of other roads across the province

(MTO, 1998). Roughly 82% percent of the road system is under municipal jurisdiction; 17% percent makes up the provincial system; and about 1% percent is Federal and National Highway System (Transportation Canada, 1998, p.68). The advanced transportation system provides a solid economic base for the movement of commerce and goods. Located adjacent to the Great Lakes, Ontario has rich water resources, but this also results in wet winters and heavy snowfalls, which bring a considerable challenge to road authorities.

Figure 3.1 Location setting of the study

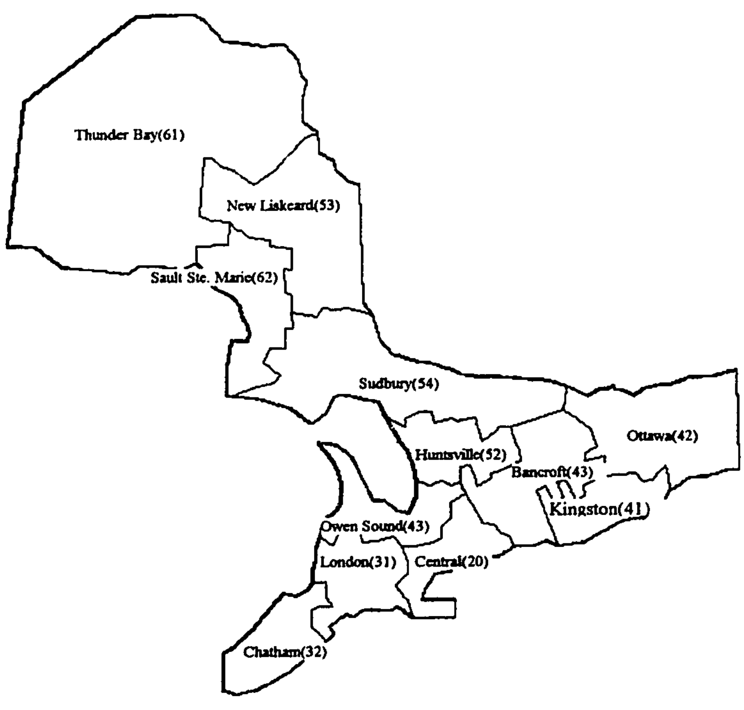


Figure 3.2 MTO district boundaries
Source: Regional and district boundaries, derived from the Official Road Map of Ontario 1994/95

3.1.1 Winter weather of Ontario

General weather patterns

Located near the center of North America, Ontario has a continental climate, although, in the central and south western parts, it is markedly modified by the Great Lakes. Generally speaking, Ontario has a temperate climate in the south with chilly winters, warm summers, and high humidity. In the north, the temperatures are very cold in the winter, and precipitation is relatively low. The following discussion is intended to give an overview of the winter weather of Ontario. It is based primarily on the writings of Phillips (1990), and Hare and Thomas (1979).

The dominant air mass during winter is cold and dry continental Arctic air in the North. But southern Ontario also receives its share of clear, cold and sunny days under Arctic air. Other two kinds of major air masses that affect southern Ontario are cold and moist, modified continental Arctic air, and moist and mild maritime Arctic air mass (Phillips, 1990, p.100). Storms develop along the fronts that separate those contrasting air masses. These storms bring strong winds, freezing rain, ice pellets and snow, or a mixture of these conditions. Under these weather systems, the region experiences a great variety of weather. But because of the rapid movement of those systems, good or bad periods usually do not last for more than a few days.

Generally, temperature decreases as one moves to the east and north in Ontario. Winter temperatures are highest along the Great Lakes; from Niagara to Windsor the mean January temperature is about -4°C. In major cities in southern Ontario winter temperatures are 2 to 3°C warmer than the surrounding rural areas on average because of the urban effect. Similarly in northern Ontario, the warming effect of Lake Superior keeps average temperatures at 3 to 5°C above those at stations inland. North of Superior, winters are extremely cold, with an average of -20°C in January from Lake of Woods to south of James Bay. The lowest temperature ever recorded in Ontario was -58.3°C on January 23, 1935, at Iroquois Falls. By contrast, along the north shore of Lake Erie and in the Niagara Peninsula, winter low temperatures seldom fall below -25°C. Along the St. Lawrence River and in Eastern Ontario, winter extremes can be as low as -35°C but midwinter averages are around -10°C (Phillips, 1990).

Precipitation in southern Ontario is relatively uniformly distributed throughout the year. Northern Ontario, with its more continental climate, receives its maximum precipitation in summer. The greatest precipitation occurs on highlands downwind of the lakes. " The south is about one third wetter than the north, with totals ranging from 500mm in the Patricia area in northwestern Ontario to more than 1000mm on the western flanks of the highlands of Lake Superior, Lake Huron, and the Georgian Bay. Another heavy precipitation area is along the St. Lawrence River. The driest areas are in the extreme southwest, the Niagara Peninsula, and in the rain-shadows of the highlands" (Phillips, 1990, p.101).

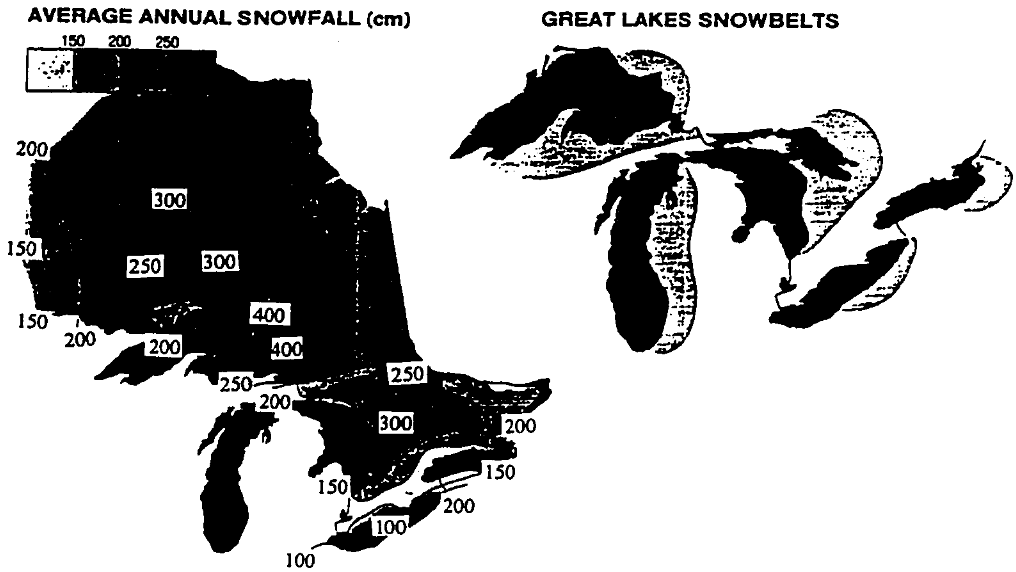


Figure 3.3 Average annual snowfall (cm) and Great Lakes snowbelts
Source: from David Phillips, 1990, The Climates of Canada p.102

As shown in Fig.3.3, Ontario's heavy snowfall areas are on the upland slopes facing Lake Huron, Georgian Bay, and Lake Superior, with annual snowfall in the 300 to 400cm range. "The highlands south of Owen Sound, and northeast of Sault Ste Marie are also snow favored as are the areas along the St. Lawrence River and around London. Areas to the lee of the lakes but on the downslope side of higher ground receive less than half the annual snowfalls of the upslope snowbelt areas" (Phillips, 1990, p.102). Toronto, Hamilton, and the southwest area of Ontario receive less snowfall.

There are more than 75 snow days a year on average in the snowbelts. There are between 75 and 100 snow days each year from Lake Superior to the shore of Hudson Bay. Over 40 days of snow occur annually on the north shore of Lake Ontario, and there are 50 days in the Ottawa Valley. In the extreme southwest, there are fewer than 20 days a year (Phillips, 1990).

Intense winter storms are frequently accompanied by low temperature, ice or glaze, and heavy snow. One or two bad blizzards strike the province each winter. Heavy icing, especially when accompanied by strong winds, causes considerable damage to trees and power lines, and creates extremely hazardous conditions. Late in January, 1978, a very intense storm with wind was responsible for twelve deaths and enormous losses to property in the province (Hare and Thomas, 1979). An ice storm, which hit eastern Ontario and western Quebec on January 5-10, 1998, was labeled as the worst ever to hit Canada. It left more than 100 thousand people without power for over 3 weeks, and resulted in at least 25 deaths. Final damage and expenses for the ice storm relief were estimated to over $1 billion (Weather Network, 1998). Occurrences of freezing precipitation vary from 10 days each winter in the north to 20 days in the south. Another winter hazard is blowing snow, which occurs 10 to 20 days each year, and occurs mostly in snowbelt areas to the lee of the Great Lakes (Phillips, 1990).

The study period

The thesis analysis is based on two time periods – a general analysis of the past 20 years of data (1978/89 to 1997/98) and a more detailed analysis of most recent 5 years (1993/94 to 1997/98). Although snow conditions vary spatially and annually, for the purpose of the thesis, winter is defined from Nov. 1 to March 31, because this period covers most of the winter road maintenance operation season. This is longer than the climatic definition of winter (from Dec. to Feb.) used in various Atmospheric Environment Service (AES) bulletins.

In the 20 winter study period, there is a good mix of winter conditions. The winter of 82/83, 86/87, 90/91/, 94/95 and 97/98 were warmer than normal for both the Great Lakes areas and northern Ontario, as shown in Figure 3.4. The winter of 78/79, 81/82, 85/86, 93/94 were colder than normal. For the precipitation, in southern Ontario, the winter of 83/84, 84/85, 96/97 were wetter than normal; and winter of 79/80, 86/87, 88/89, 95/96 were much drier than normal. In northern Ontario, the winters of 84/85, 87/88 and 96/97 were wet with more snowfall; while the winter of 79/80, 82/83, 94/95, 97/98 were dry with less snowfall.

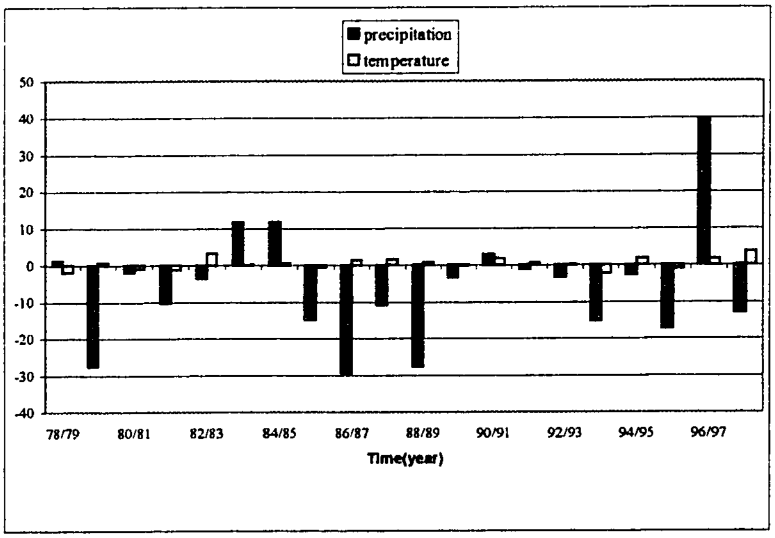


Figure 3.4 Winter precipitation (%) and temperature departures (°C) from 1948-1998 average in Great Lakes region

Source: http://www1.tor.ec.gc.ca/ccrm/bulletin, Data compiled by Atmospheric Environment Service, Environmemt Canada, Downsview.

In terms of the most recent 5 winters, the winters of 1993/94 and 1995/96 were dry and cold. In fact, 1993/94 was the second coldest year since 1948 with a temperature of 3°C lower than normal in southern Ontario. Northern Ontario was also dry and cold. Also, the winter of 1995/96 was colder and drier than normal in the Great Lake/St Lawrence region. Average winter temperature (from December to February) was 1°C below normal, and winter precipitation was 19% below normal (1948-1996), making it the 9th driest year since 1948. For the selected northern stations, the winter mean daily temperatures were 1.5°C to 2.2°C colder than the 1961-1990 normal. But there was more snowfall than normal in the north.

The other three winters were warmer than normal as indicated by the temperature summaries of selected weather stations (Table 3.1, 3.2, 3.3). The 1994/95 winter had normal precipitation and warmer temperatures in the south, with warm temperatures and less snowfall in the north. The winter of 1996/97 was wet and warmer than normal across the Province. Southern Ontario averaged 1.7°C warmer than normal; northern Ontario was 0.6°C warmer than normal. As for the precipitation of this winter, southern Ontario experienced its 2nd wettest winter since 1948, 37% wetter than normal. For selected northern stations, temperatures were colder than the 1961-1990 normal, while southern stations were warmer. All the stations examined had heavier snowfall and more snow days than normal.

Table 3.1 Mean winter daily temperature (°C) of selected stations for the study period

station	1993/94	1994/95	1995/96	1996/97	1997/98	5 winter average	1961–90 normal
Ottawa Int'l A	-7.66	-3.52	-7.14	-5.68	-3.80	-5.56	-5.86
London A	-4.40	-0.90	-4.20	*	*	*	-2.70
Kinston A	-5.28	-1.62	*	*	*	*	-3.54
Toronto Pearson Int'l A	-4.22	-0.64	-3.88	-2.10	0.24	-2.12	-2.78
Windsor A	0.82	0.92	-2.20	-0.44	1.96	0.21	-0.88
Peterborough	-6.74	-2.82	*	-4.34	-2.04	*	-4.58
Owen Sound MOE	-4.54	-0.64	- 4.10	- 2.22	*	*	-2.62
Huntsville WPCP	-7.72	*	-7.08	-5.46	*	*	-5.66
Sudbury A	-10.8	-6.16	-10.64	- 9.04	-5.96	-8.52	-8.44
Wawa A	-11.68	-6.82	*	*	-6.3	*	*
Iroquois Falls	-13.88	*	-4.16	-1.78	*	*	-12.08
Kenora A	-12.26	-8.64	-14.26	-12.94	-6.72	-10.96	-11.4

* is missing data, year and normal average is five winter month average (from November to March the next year).

Source: Canadian climate normals (1961-1990), and National Climate Data Archive of Canada. Data compiled by Atmospheric Environment Service, Environment Canada, Downsview.

The winter of 1997/98 was much warmer and drier than normal. The Great Lake/St Lawrence region experienced its warmest winter for the 51 year period since 1948, with an average winter temperature 3.7°C above normal. Precipitation was 13.0% less than normal in southern Ontario. Northern stations also had warmer temperature and less snowfall and snow days than normal.

Table 3.2 Mean winter snowfall (cm) of selected stations for the study period

station	1993/94	1994/95	1995/96	1996/97	1997/98	5 winter average	1961–90 normal
Ottawa Int'l A	259.0	149.0	261.2	294.2	190.2	230.7	207.1
London A	137.2	138.0	168.5	*	*	*	198.7
Kinston A	191.4	87.8	*	*	*	*	172.8
Toronto Pearson Int'l A	104.2	83.4	127.8	141.8	84.8	108.4	115.6
Windsor A	123.8	89.2	116.8	155.2	91.7	115.3	117.5
Peterborough	131.0	127.4	*	189.8	135.2	*	150.6
Owen Sound MOE	362.1	277.3	419.7	490.5	*	*	329.3
Huntsville WPCP	223.7	*	303.1	279.2	*	*	269.3
Sudbury A	210.4	147.9	266.0	335.0	193.9	230.6	240.1
Wawa A	293.2	188.2	*	*	208.6	*	*
Iroquois Falls	138.5	*	169.1	148.6	*	*	197.1
Kenora A	71.5	116.2	159.2	204.7	92.7	128.9	149.3

* is missing data, year and normal average is five winter month average (from November to March the next year).

Source: Canadian climate normals (1961-1990), and National Climate Data Archive of Canada. Data compiled by Atmospheric Environment Service, Environment Canada, Downsview.

Table 3.3 Mean winter (Nov. to March) days with measurable snowfall of selected stations for the study period

station	1993/94	1994/95	1995/96	1996/97	1997/98	5 winter average	1961–90 normal
Ottawa Int'l A	62	51	69	83	61	65.2	60
London A	55	46	62	*	*	*	64
Kinston A	44	37	*	*	*	*	51
Toronto Pearson Int'l A	47	35	53	61	40	47.2	44
Windsor A	48	25	55	50	34	42.4	42
Peterborough	59	41	*	59	50	*	57
Owen Sound MOE	58	45	81	72	*	*	63
Huntsville WPCP	47	*	59	66	*	*	50
Sudbury A	63	47	67	88	58	64.6	69
Wawa A	70	53	*	*	56	*	*
Iroquois Falls	47	*	59	56	*	*	51
Kenora A	55	70	76	86	57	68.8	61

* is missing data.

Source: Canadian climate normals (1961-1990), and National Climate Data Archive of Canada. Data compiled by Atmospheric Environment Service, Environment Canada, Downsview.

3.1.2 Road maintenance on Ontario's Provincial Highways

Ontario has 16, 100 km provincial highway and 145,000 km municipal, township and local roads. Placed end-to-end, Ontario's highways would span Canada three times. About 94 percent of all Ontarians regularly travel on the province's highways. Annually, $1 trillion worth of goods are transported on provincial highways (MTO, 1998).

The provincial highway is managed by the Ministry of Transportation of Ontario (MTO). MTO has divided the province into 12 road maintenance districts, as shown in Figure 3.2. In order to maintain safe driving conditions on winter highways, MTO spends about $100 million on winter road maintenance programs (Perchanok, 1998). In general, snow and ice are removed by plowing, sanding and salting. While plowing is the preferred method of achieving bare pavement, it will not remove ice that is bonded firmly to the pavement, so salt is used as a de-icing chemical. When the temperature is too cold for salt to be effective, sand is applied to provide traction on icy or snow-packed surfaces.

Salt is the primary de-icing chemical used in Ontario and throughout North America. The annual usage of salt in Ontario totals about 1.3 million tons, and splits approximately 54:46% between municipalities and MTO (Perchanok et al, 1991, p.9). As indicated in Figure 3.5, the annual salt usage on provincial highways has increased slowly over the years. Compared with the winter precipitation, as shown in Figure 3.6, the result is quite interesting. The maximum salt usage occurred in the winter of 1996/97 with about 8.3 million tons. This corresponds with the wet weather of the winter of 1996/97. The wet winters of 1975/76 and 1984/85 also correspond with relatively high salt usage; the driest winter 1986/87 had low salt usage. But the lowest salt usage during the 20-year period occurred in the winter of 1977/78, which was not the driest year; in fact, the winter of 1977/78 was 9.0% wetter than normal. This confirms the fact that winter road maintenance activities are affected by more than just snowfall amount.

The recommended rate of salt application in Ontario is 130 kg per 2-lane km. This rate provides effective de-icing under most weather conditions experienced in the Province and minimizes the total amount of salt used (Perchanok et al, 1991, p.31). Recommended snow and ice control treatments for roads vary according to weather and traffic conditions, as indicated in Table 3.4. In practice, salt is not applied to dry snow that is not sticking to the pavement, nor under very cold temperature where it would not be effective. It is normally applied at temperatures of -12°C or warmer. But in bright sunshine or heavy traffic conditions, it can be effective down to -18°C. Typically, it is not used before a storm, but can be applied soon after snow begins to fall in order to begin dissolving before snow or ice become bonded to the pavement (Perchanok et al, 1991).

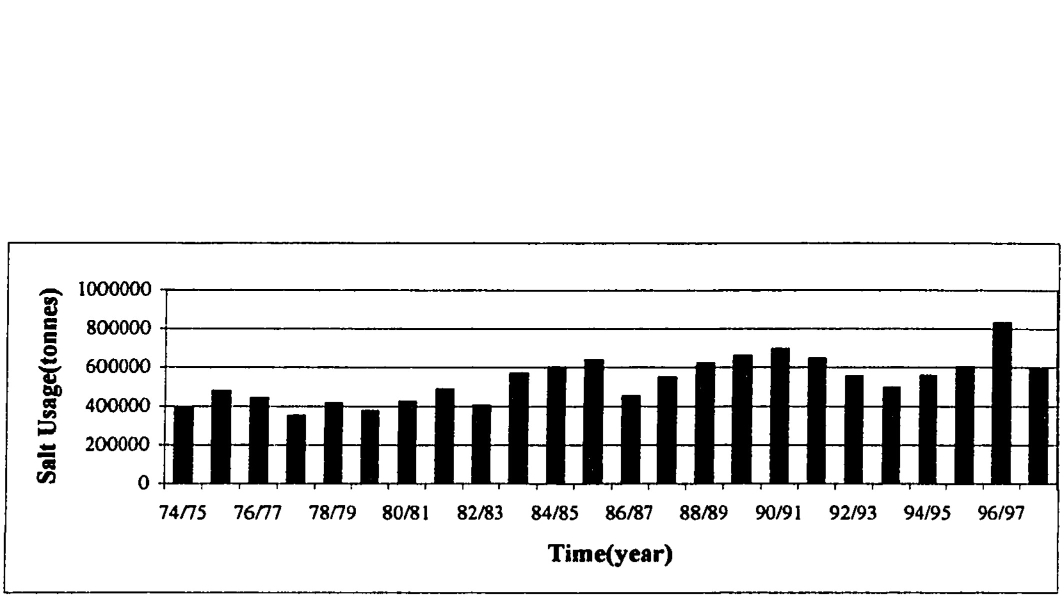


Figure 3.5 Provincial annual salt usage (1974/75-1997/98)
Source: data derived from Ministry of Transportation Ontario, annual salt usage report.

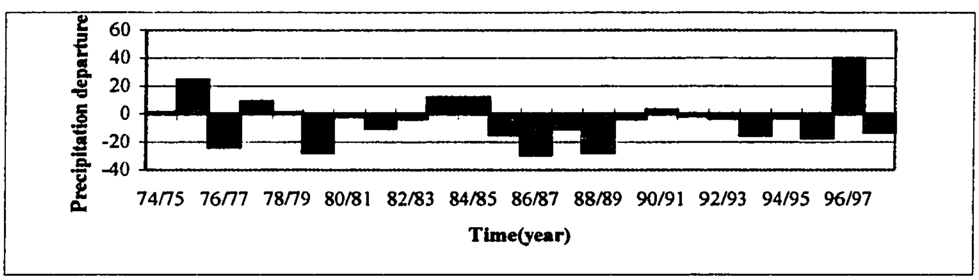


Figure 3.6 Winter precipitation departure in percentage from 1948-1998 average for Great Lakes region, (1974/75-1997/98)
Source: http://www1.tor.ec.gc.ca/ccrm/bulletin/, 1998, Data compiled by Atmospheric Environment Service, Environment Canada, Downsview.

Table 3.4 MTO recommended treatments for removing snow and ice from highways

Source: Ministry of Transportation, Research and development branch, 1991, Highway De-icers: Standards, Practice, and Research in the Province of Ontario, p.29.

	Temperature Range °C	Type of Precipitation	Road Condition	Activity	Recommended Treatment 4/		
					Beginning of Storm	During Storm/1	After Storm/2
1	Below -18°	Dry Snow	No Packing Dry Pavement	Plowing	After 2 cm of snow accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If slippery	Follow after plowing; if slippery	Slippery sections only
				Salting	No	No	If temp. rising, to bare or assist in baring pvt.
2	-18° to -12°	Dry Snow	No Packing Dry Pavement	Plowing	After 2 cm of snow accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If slippery	No	Slippery Sections only
				Salting	No	No	If temperature rising, to bare or assist in baring pavement
3	-18° to -12°	Dry Snow	Packing	Plowing	If temp rising, after salting If temp falling, after 2 cm accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If temp falling, if slippery	If temp falling, follow after plowing, if slippery	If temp falling, slippery sections
				Salting	If temp rising before 0.5 cm accumulation	If temp rising, as necessary after plowing	If temp. rising, to bare or assist in baring pvt.
4	-12° to -7°	Dry Snow	No Packing	Plowing	After 2 cm of snow accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If temp. falling, if slippery	Follow after plowing, if slippery	Slippery sections only
				Salting	No	No	If temp. rising, to bare or assist in baring pavt.
5	-12° to -7°	Dry Snow	Packing	Plowing	0.5h after salting	Continuously	Bare pvt/wing shlds/clean up
				Sanding	No	Follow after plowing, if slippery	slippery sections only
				Salting	If temp rising, before 0.5 cm of snow accumulates	As necessary after plowing, to assist plowing	If temp rising, to bare or assist in baring pavt.
6	Above -7°	Wet Snow	Packing Wet Pavement	Plowing	0.5h after salting	Continuously	Bare pvt/wing shlds/clean up
				Sanding	No	Follow after plowing, if slippery	Slippery sections only
				Salting	Before 0.5 cm of snow accumulates	As necessary after plowing	To bare or assist in baring pavt.
7	Above -7°	Sleet or FreezingRain	Possible Icing Wet Pavement	Plowing	No	No	Remove any slush
				Sanding	No	Yes	Slippery sections only
				Salting	When icing starts	Yes	Slippery sections only

1. During storm conditions plowing should be undertaken to ensure that the accumulation of snow on the road surface does not exceed 2.5 cm for Class I, 4 cm for Class II, and 5 cm for Class III Service Levels.
2. After the storm, plowing should continue to achieve bare pavement within 24 h for Class I and II Service Levels. Plowing after the storm should be done to achieve baring of the centre 2.5 m of pavement within 24 h, whenever possible, for Class III Service Levels, and then bared full width when favourable weather prevails.
3. Wingling back shoulders should usually be done only once after the storm.
4. Recommended treatment for various conditions shown on this chart should be used in most cases. However, unusual circumstances may necessitate departure from the recommended treatment.
5. Temperature rising means temperature to remain in or rise above temperature range.
6. Temperature falling means temperature to remain in or fall below temperature range.

Table 3.4 MTO recommended treatments for removing snow and ice from highways
Source: Ministry of Transportation, Research and development branch, 1991, Highway De-icers: Standards, Practice, and Research in the Province of Ontario, p. 30. (continued)

Class IV Snow Packed Level of Service

	Temperature Range	Type of Precipitation	Road Condition	Activity	Recommended Treatment 1/		
					Beginning of Storm	During Storm 2/	After Storm 3/
1.	Any Temperature	Dry or Wet Snow	Road, Snow Packed	Plowing	Continuously (maintain snow pack)		Wing back shoulders/ scarify slippery sections/clean-up
				Sanding	No	On hills, curves and other hazardous locations	
				Salting	No	No	No (gravel surface) Yes (paved surface) if -12°C and rising
2	Any Temperature	Sleet or Freezing Rain	Possible Icing	Plowing	No	No	Scarify slippery sections
				Sanding	No	Slippery sections	
				Salting	No	No	No (gravel surface) Yes (paved surface) if -12°C and rising
3.	Any Temperature After Storm	No Precipitation	Drifting	Plowing			Continuously (maintain snow pack)
				Sanding			Slippery Sections
				Salting			No

1) Recommended treatment for various conditions shown on this chart should be used in most cases. However, unusual circumstances may necessitate departure from the recommended treatment.
2) During storm conditions, plowing should be continuous to ensure that the accumulation of new snow does not exceed 7 cm.
3) Winging back shoulder should usually be done only once after the storm.

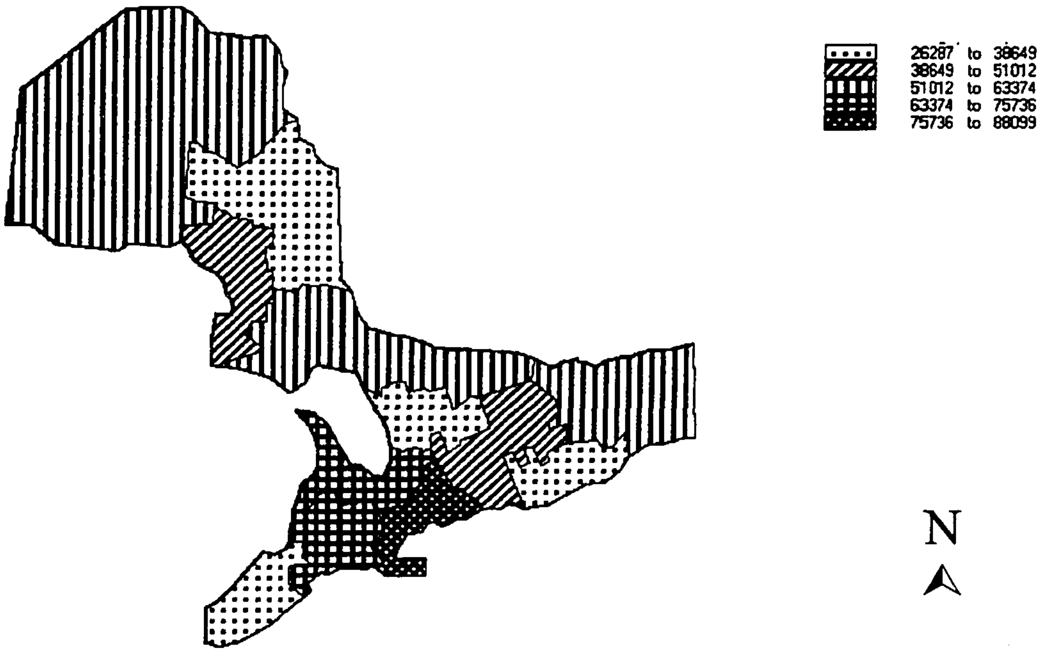


Figure 3.7 Averaged annual salt usage for the study period (1993/94-1997/98).
Source: data derived from MTO salt usage year end summary.

Averaged annual salt usage on Provincial roads from 1993/94 to 1997/98 is shown in Figure 3.7 at a district level. Amounts are clearly sensitive to winter weather, as the salt usage pattern is quite similar to the annual snowfall pattern, with heavy salt usage and snowfall in the Owen Sound, Sudbury and Ottawa districts. Salt usage is also very high in the Toronto district, although the snowfall is relatively low in Toronto. Salt usage in Chatham is very low, corresponding to relatively light snowfall in this region.

3.2 Data

3.2.1 Data sources and format

The goal of this thesis is to investigate the relationship between weather and road maintenance. Two data sources are used; both are governmental in origin. Road salt usage data and road classification data were obtained from MTO; climate data were obtained from the National Climate Data Archive of Canada, which is maintained by Environment Canada.

The analysis is based on two time scales—a general analysis of winter weather severity and road salt usage for 20 years from the winter of 1978/79 to the winter of 1997/98 is associated with Objective 1; and a detailed analysis of the recent 5 winters from 1993/94 to 1997/98 addresses Objective 2 and 3. All 3 objectives require detailed weather data, and Objective 2 and 3 require detailed information on winter road maintenance. The main indicators of winter road maintenance activities are salt and sand usage (tonnage), equipment, and personnel time (hours) and cost (dollars). Road salt tonnage was used in the present study for 3 main reasons. First, personnel time and equipment are directly related to road salt. Secondly, there is increasing environmental concern about the use of road salt. Thirdly, salt data are the only detailed and consistent data available from the MTO. Ideally I would have expected to use 20 years climate and salt data, but the detailed salt usage data was limited to the last 5 years. This latter period provides a reliable record for which both the format and the quality of road salt data are consistent through time and information is available on a biweekly basis.

The locational setting of the investigation includes the 12 MTO road maintenance districts: Chatham, London, Owen Sound, Toronto, Kingston, Ottawa, Bancroft, Huntsville, New Liskeard, Sudbury, Sault Ste. Marie, and Thunder Bay (as shown in Figure 3.2). Also 12 weather stations were chosen, one for each MTO district as listed in Table 3.5. Two criteria were used to choose the weather stations: first, the station should be located at the center of the associated district; second, the station should have all the climate variables required in the analysis for the study period. Climate data from Environment Canada were obtained for these 12 primary weather stations. Equivalent information was obtained for each of the 12 stations. Monthly records of daily data and annual records of monthly precipitation and temperature data were used in the analysis. Variables included in the analysis are summarized in Table 3.6.

Road salt usage data was derived from hard copies of Provincial salt usage report year end summaries from the MTO's data base. The original format was biweekly salt usage data. This was inputted to a spreadsheet file and transformed into biweekly salt usage per saltable 2-lane km in order to be comparable for different districts. There are incompatibilities between the monthly climate data and the biweekly salt usage data. The biweekly salt usage data has a 14-day interval, starting with dates like Nov.3, Nov.17. To remedy this problem, the biweekly salt totals were added and adjusted so that they were as close to the calendar month as possible (e.g. if a salt period is from Jan. 22 to Feb. 5, assign 9/14 of the total salt to Jan. and 5/14 of the total to Feb.).

Road network data were also derived from hard copies from MTO. The network data provide road classification information for each of the MTO districts for the 1997/98 winter. The MTO Operation Instruction specifies levels of snow and ice removal according to roadway traffic volume using a 4-tiered system (Perchanok et al, 1991). The Road Network data can indicate the winter maintenance priority. Within each district, roads are classified in to 4 classes. Class 1 and 2 roads have more maintenance priorities, and class 3 and 4 have less. These data were transformed into a road classification ratio for each district in the analysis. The ratio was calculated by the following formula: (class 3 + class 4) km/(total) km.

3.2.2 Data accuracy

The climate data were extracted directly from Environment Canada's digital form. Each element number has been checked, so there was no error in the transforming of this data set; the salt data were extracted directly from the hard copy of MTO's salt report form and were double checked to eliminate any errors associated with data input. Road network data were derived from recent reports of MTO districts. Since the data sources of this thesis are governmental databases, these should provide detailed, reasonably accurate information. The accuracy of the salt usage data, in particular, has been verified (personal communication with Jim Young, MTO maintenance officer).

Table 3.5 AES weather stations used in the study

Station ID	Name	MTO districts	Location	Elevation (m)	Annual snowfall (cm)	Temperature (°C)
6106000	Ottawa Int'l A	Ottawa	45°19' 75°40'	116	221.5	5.8
6144475	London A	London	43°20' 81°9'	278	212.3	7.2
6104146	Kingston A	Kingston	44°13' 76°36'	93	182.6	6.7
6158733	Toronto Pears. Int'l A	central	43°40' 79°38'	173	124.2	7.2
6139525	Windsor A	Chatham	42°16' 82°58'	190	123.3	9.1
6166418	Peterborough	Bancroft	44°14' 78°21'	191	160.3	5.9
6116132	Owen Sound MOE	Owen Sound	44°35' 80°56'	179	339.6	6.9
6113663	Huntsville WPCP	Huntsville	45°21' 79°10'	321	280.6	5.3
6068150	Sudbury A	Sudbury	46°37' 80°48'	347	266.6	3.5
6059D09	Wawa A	Salt Ste. Marie	47°58' 84°47'	287	N/A	N/A
6073810	Iroquois Falls	New Liskeard	48°45' 80°40'	259	219.3	0.9
6034075	Kenora A	Thunder Bay	49°47' 94°22'	408	178.3	2.4

Annual snowfall and daily mean temperature are 1961-1990 normal. N/A means not available.

Source: Canadian climate normals (1961-1990), Atmospheric Environment Service, Environment Canada, Downsview, Regional and district boundaries, 1994, Ministry of Transportation Ontario.

Table 3.6 Climate variables characterized by numerical codes

Climate variables	Numerical Code	Field description
Temperature	001	Daily maximum temperature
	002	Daily minimum temperature
	003	Daily mean temperature
	042	Mean monthly temperature
Precipitation	011	Daily total snowfall
	049	Monthly total snowfall
	054	Greatest snowfall of each month
Number of days with...	029	Number of days with freezing rain or drizzle
	031	Number of days with snow
	036	Number of days with blowing snow

Source: National Climate Data Archive of Canada. Data compiled by Atmospheric Environment Service, Environment Canada, Downsview.

3.3 Data analysis

3.3.1 Preparing the data for analysis

The AES digital archive of Canadian climatological surface data was used for this study. Climatological data are archived at fifteen minute, hourly, daily and monthly intervals, but only daily and monthly data were used for the current study. Each record consists of station identification, date and element number followed by the data repeated for each time interval. The datum for each time interval is recorded as a five-digit integer plus a leading sign field and a following flag field. The units and decimal position are implied by the assigned element number.

The following steps were used to extract data for the present study using Fortran programming. The major codes and their descriptions are summarized in Appendix 1.

1) Daily maximum temperature, minimum temperatures and daily total snowfall were extracted from the original AES daily archive; these will be used to calculate winter indices. Other variables such as monthly maximum temperature, monthly minimum temperature, number of snow days, number of frost days, and total snowfall were extracted from the AES monthly archived data.
2) For data quality control, after all the above variables are extracted, they had to be matched with each other in terms of the time of the records. This is the most time

consuming part in the data preparation stage. First, the variable with the least records is found; then the rest of the variables are match to it. The best match may be reached in several turns of this kind of trivial matching. During the procedure of matching, months with too many bad records (Trace, Missing, or 9999.9) were dropped. This is why the result is not continuous in time occasionally. The best effort has been made for most fully using the current data sets.

3.3.2 Calculation of the winter indices

1) Determination of salt days

The saltdays index was developed by Stewart Cohen in 1981. It was developed to act as a weather indicator and used to develop short-term forecasts of snow removal budget allocation for Illinois State. According to Cohen (1981), a salt day was defined as a 24-hour period where snowfall was greater than or equal to 0.5 inch (1.3cm) with a mean daily temperatures of $-9 \sim -1$°C. For the thesis, seasonal, monthly and biweekly salt days were calculated for the 12 selected stations.

2) Calculation of the modified Hulme winter index

The Hulme winter index was first developed in 1982 by a UK scientist, Hulme, for four UK climate stations. It was modified and applied by Thornes (1991) and applied in

1993. It is relatively easy to calculate because it is based on monthly data. The modified Hulme index is given as

$$WI = 10T - F - (18.5S)^{\frac{1}{3}} \pm C \qquad (1)$$

where

T is the monthly mean maximum air temperature, in degree Celsius,

F is the monthly total number of days with ground frost,

S is the monthly total number of days with snow,

C is a constant such that the climate averaged WI is zero for a given place; this element was set to zero in my thesis since the analysis involves comparison of winter weather for different districts.

The remaining three variables were used to derive monthly or seasonal values for the monthly and seasonal modified Hulme index. This winter index was also applied to all the 12 selected stations.

3) Calculation of SHRP index

The SHRP winter index was developed by the University of Birmingham for the SHRP H-207 program at 1992. This winter index was developed by UK scientists but for US climate. It is the most detailed one of the winter indices, and its calculation is based on daily data as follows:

$$WI = a(TI)^{0.5} + b\ln\left[\frac{S}{10} + 1\right] + c\left[\frac{N}{R + 10}\right]^{0.5} + d. \qquad (2)$$

where *TI, S, N, R* are four climate variables, and *a, b, c, d* are constants which can be assigned particular weights suitable for the general climate conditions. Some estimation is involved in this index. For the US climate, percentages of 35, 35 and 30 were assigned to *TI, S* and *N*, respectively. And *WI* was designed to be a simple objective indication of winter severity (*WI*) with a value ranging from -50 (most severe) through 0 (mean level of maintenance) to +50 (warm and no need of maintenance). Equation (2) is then derived to be

$$WI = -25.58(TI)^{0.5} - 35.68\ln\left[\frac{S}{10} + 1\right] - 99.5\left[\frac{N}{R+10}\right]^{0.5} + 50 \qquad (3)$$

where:

TI: *Temperature index,* The daily temperature index *TI* is determined using the daily minimum temperature *Tmin* and daily maximun temperature *Tmax*, as follows

$TI = 0$ when $Tmin > 0°C$,

$TI = 1$ when $Tmin < 0°C$ and $Tmax > 0°C$

$TI = 2$ when $Tmax \leq 0°C$.

Then, the seasonal, monthly and biweekly average temperature index values were obtained by simply dividing the summation of the daily *TI* by the number of days in that season, month or two-week period.

S: *Snowfall*, is the mean daily value in millimeters, determined by dividing the sum of daily total snowfall by the total number of days in the time interval.

N: *Number of air frosts*, is the mean daily values of number of days. It is extracted from the daily data, and then its mean value was calculated by dividing the sum of *N* by the total number of days in the time interval.

R: *Temperature range*, is the value of mean maximum air temperature minus mean minimum air temperature in degrees Celsius.

For biweekly, monthly, and seasonal SHRP indices, those variables (*TI*, *S*, *N*, *R*) are averaged over the appropriate time period for each of the 12 selected weather stations.

3.3.3 Analytic framework and techniques

The thesis analysis involves three objectives to identify a winter index suitable to Ontario's climate and road maintenance conditions. The analysis framework of these objectives based on the temporal and spatial scales for the study is indicated in Table 3.7. The first objective provides a background for the spatial and temporal variability of winter weather in Ontario; the second and third objectives are the major focus of the thesis. The three objectives are discussed below.

For Objective 1--characterize the spatial and temporal variation in severe winter weather in Ontario--three seasonal winter indices (salt days, modified Hulme, and SHRP) were calculated for 20 winter seasons from 1978/79 to 1997/98; the temporal variability of winter weather severity and seasonal winter indices were examined for each MTO district for the past 20 years; the spatial difference of winter weather severity and winter index among the 12 MTO districts was also examined.

Table 3.7 Analytic framework

	Time scale	
	Monthly/biweekly winter index for recent 5 winters	Seasonal winter index for the past 20 years
Temporal variability within each district	**Objective 2 and 3 -** Correlation analysis of salt vs. winter index	**Objective1 -** comparison between winter weather severity and winter indices
Spatial difference among the 12 districts	**Objective 2 and 3 –** Correlation analysis of salt usage averaged for recent 5 years vs. winter index averaged for the same period	**Objective 1** Spatial variability of winter weather and winter indices

For objective 2--choose a suitable index that is sensitive to Ontario climate and road maintenance activities--three indices were calculated using monthly data for five recent winters from 1993/94 to 1997/98. A correlation analysis of winter index vs. salt usage for the recent 5 winters was completed for every MTO district. The correlation analysis of salt usage averaged for recent 5 winters vs. seasonal winter index averaged for the same period was applied across the 12 districts.

For Objective 3--modification of the identified winter index--the identified winter index that is suitable for Ontario situation was calculated in biweekly time scale for detailed analysis. A correlation analysis of salt usage vs. modified winter index for recent 5 winters was applied to each MTO district. A regression model of salt usage vs. different climate variables was identified for every district.

Analysis for objective 1 is based on descriptive statistics. The analyses for both objective 2 and objective 3 are based on linear regression and correlation models. The Statistic Package for Social Sciences (SPSS) version 8.0 was used for this purpose. SPSS is a statistical package developed by SPSS Inc., and is widely used in social science research. The recent release of SPSS 8.0 provides many features to handle all steps in analysis ranging from data listings, tabulations, and descriptive statistics to complex statistical analysis.

Linear regression estimates the linear relation between variables when the values of one dependent variable are affected by changes in the values of other independent variables. In the analysis, salt usage was the dependent variable, and various climate and road network variables were used as independent variables. In the linear regression part, SPSS provides several variable selection methods; enter, stepwise, and forward and backward methods. In the enter method, all variables are entered in a single step. Stepwise entry and removal examines the variables in the block at each step using special criteria for entry or removal (SPSS Inc, 1998). These two methods are used in the analysis. The model is fitted to the estimated variogram using a simple least-squares approach, which minimizes the square of the residuals for each model. This is considered to be the best, easily implemented method for fitting variogram models. Missing data are pairwised.

Some basic assumptions have to be tested in the application of the General Linear Model. These are normality, linearity and homoscedasticity. The normality requires that values of the dependent variable are normally distributed and statistically independent. The linearity assumption requires that the means of the dependent variable lie on a straight line known as the true regression line. If the values do not lie on a straight line, the estimate of the correlation coefficients values will be inefficient. The homoscedasticity assumption states that the variance of the dependent variable is the same for all individual values of independent variables (Clark and Hosking, 1991, 367). The validity of the regression model and the tests of the coefficients depend on those assumptions. Without an understanding of the assumptions, the results obtained from those models may prove of little use. Detailed results as well as tests of the assumptions and the validity of the models will be presented in the next chapter.

4 Results

This chapter deals with: 1), the analysis and results from the spatial and temporal variability of winter weather and winter indices in Ontario; 2), the application of existing winter indices to Ontario road salt usage data; and 3), modifications of the most appropriate index. Many of the results are summarized in tabular and map formats, with details in the Appendices.

4.1 Characterize the spatial and temporal variability of winter weather in Ontario

The results from the analysis of the spatial and temporal variation of winter weather and winter indices are examined first. The time series of climatic variables such as winter snowfall and temperature, and seasonal winter indices were examined for each MTO district for the past 20 years. These indices include the number of salt days (Cohen, 1981), the modified Hulme index (Thornes, 1991), and the SHRP winter index (Thornes, 1993). The spatial patterns of winter weather severity and winter index were also examined.

4.1.1 Spatial variability in winter weather and winter indices

Spatial distribution of winter snowfall and temperature

The spatial distribution of winter mean temperature and precipitation averaged for the past 20 winters (1978/79 – 1997/98) was examined and mapped based on data from the 12 weather stations identified earlier plus an additional 13 stations that were used in this part of the analysis only. As shown in Figure 4.1, 4.2, and 4.3, the spatial difference in winter weather among different districts in Ontario is quite large. Northern areas are cold and dry, while southern areas are mild and wet. Mean winter snowfall (from Nov. to March) in southern Ontario ranges from 100cm to 400cm, with the maximum of 404.6cm snowfall and 76 snow days in the lee of the Great Lakes Owen Sound. The mean winter snowfall is less than 150cm in Toronto and Kingston. At Windsor there are 40 snow days and less than 150cm snowfall. The average frequency increases eastwards across the region to 60 snow days at Ottawa. The mean winter snowfall is less than 200cm to the north in the Georgian Bay counties.

The mean winter temperature is low in northern and eastern Ontario. The big bodies of water make winters less severe in the south. Mean winter temperature (from Nov. to March) in the far north is below –7°C. In the south, from Niagara to Windsor, it is around –1°C as shown in Figure 4.3. For the 20 years study period, the lowest Jan. temperature, –26.1°C, occurred in 1994 at Iroquois Falls. The highest mean Jan. temperature occurred in 1990 at Windsor (0.8°C).

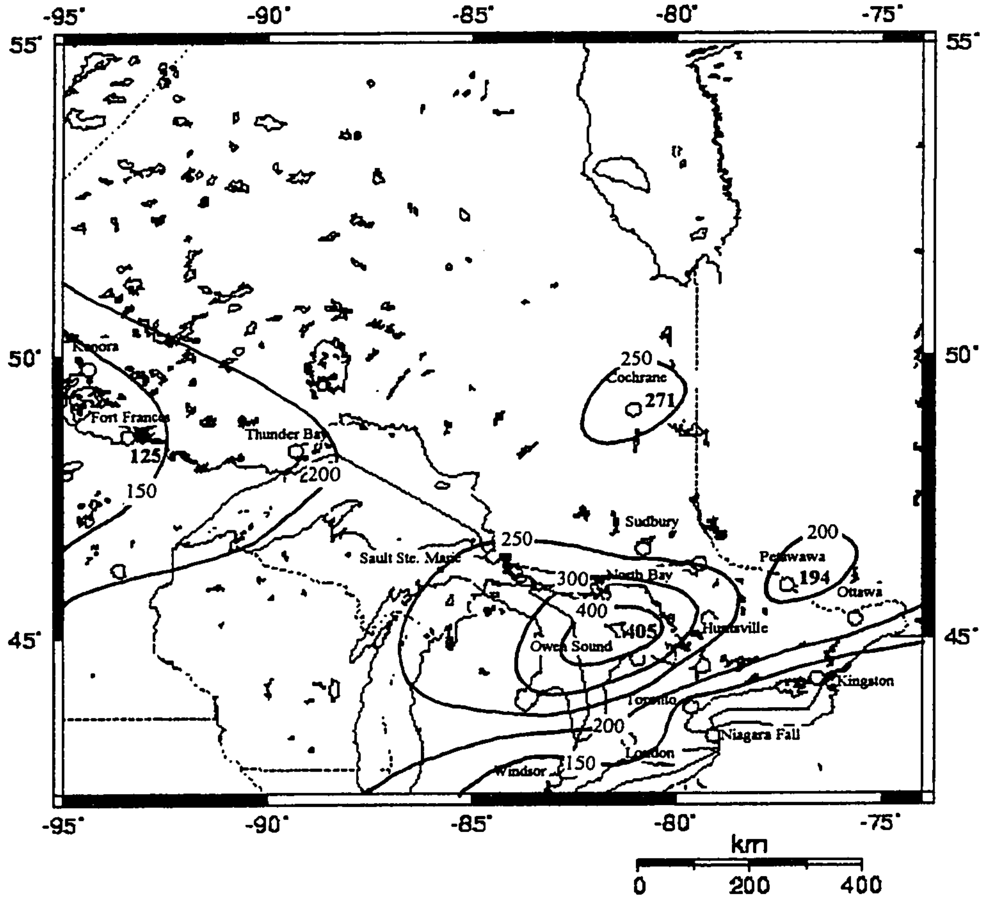


Figure 4.1 Average winter snowfall (cm) from 1978/79 to 1997/98

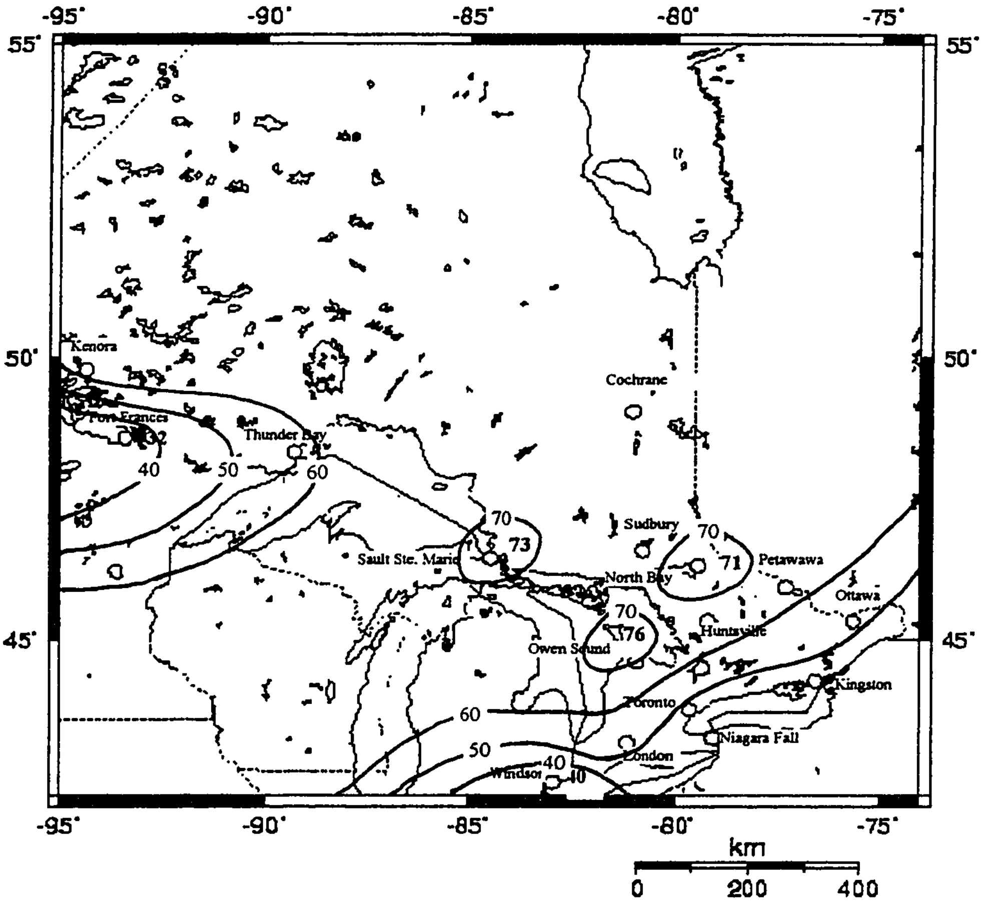


Figure 4.2 Average winter snow days from 1978/79 to 1997/98

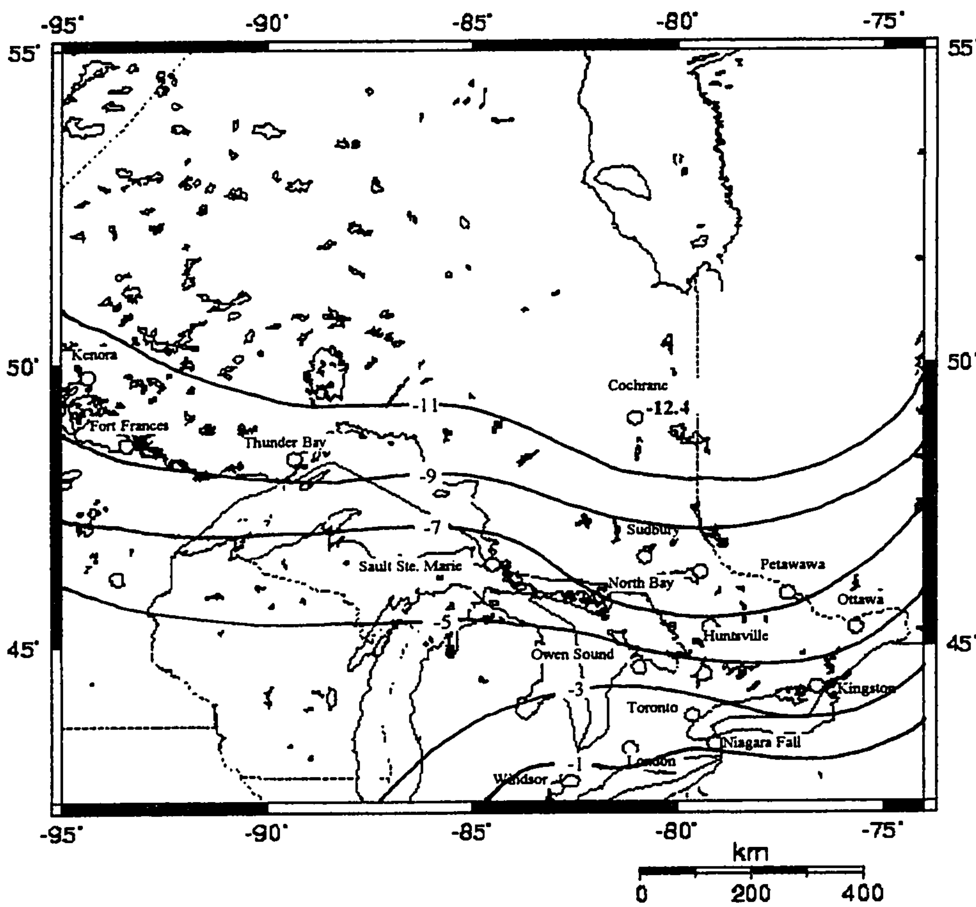


Figure 4.3 Mean winter temperature (°C) from 1978/79 to 1997/98

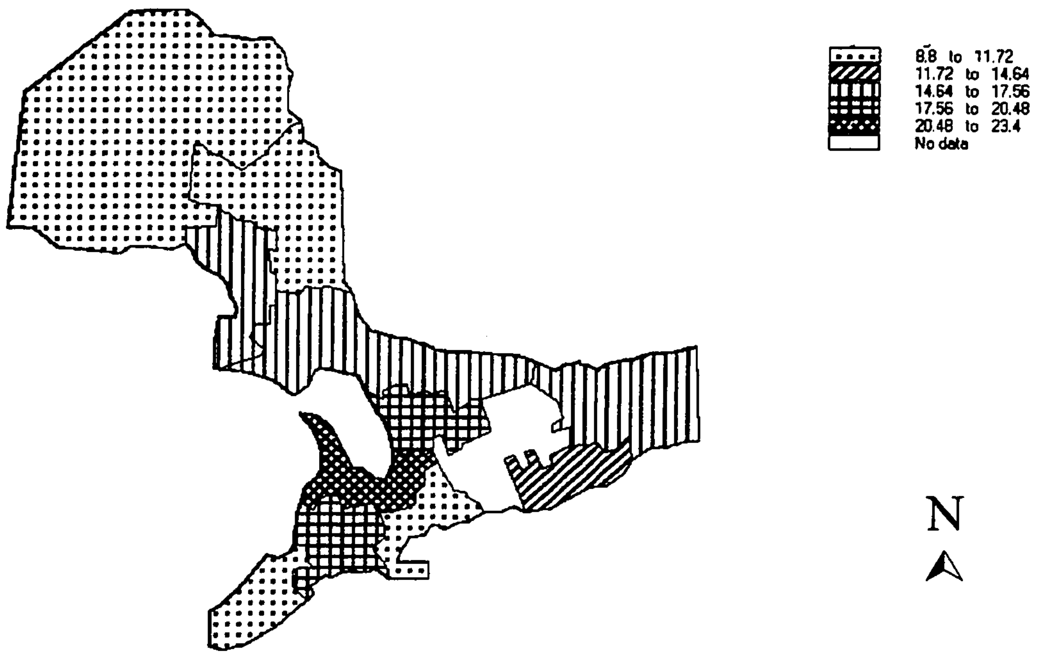


Figure 4.4 Seasonal salt days index for MTO districts averaged from 1978/79 to 1997/98

Figure 4.5 Seasonal modified Hulme winter index for MTO districts averaged from 1978/79 to 1997/98

Figure 4.6 Seasonal SHRP winter index for MTO districts averaged from 1978/79 to 1997/98

Spatial distribution of winter indices

In order to characterize the variability of winter indices across the Province, the seasonal salt days index, modified Hulme index, and the SHRP index were calculated for the 12 MTO districts for 20 years (from 1978/79 to 1997/98). And the averaged winter index values for the study period were mapped.

The spatial distribution of the salt days index is shown in Figure 4.4. The largest salt days index value occurs at Owen Sound with a value of 23.4. The Great Lake's snow belt region has relatively large index values. In Southern Ontario, the index value decreases towards to the south and to the west. From Sault Ste. Marie northward, the index value also decreases. The salt index value ranges from 23.4 at Owen Sound to 8.8 at New Liskeard.

Figure 4.5 presents the modified Hulme index across the Province. The most severe area is in the north, Thunder Bay with a value of –99.8. The winter severity decreases from north to south. In the southern region, the severity decreases from east to west. Ottawa has a modified Hulme index value of –45.3 and Chatham has a positive index value of 4.8. For the whole province, the modified Hulme index ranges from –99.8 at Thunder Bay to 4.8 at Chatham.

The SHRP winter index was averaged for 20 winters (1978/79 to 1997/98) in each of the 12 districts. The most severe winter weathers occur at Sault Ste. Marie with an index value of –36.6, and at Owen Sound with –36.3. Around the snow belt region, such as Huntsville and Sudbury, the SHRP winter index is around –35. The winter severity decreases toward both the south and the north. The SHRP index ranges from –36.6 at Sault Ste. Marie to –12.9 at Chatham, as shown in Figure 4.6.

The spatial patterns of the three winter indices are different from each other. Comparing these patterns with the weather patterns, it is apparent that the SHRP index and the salt days index have similar patterns to the snowfall distribution as shown in Figure 4.1; the spatial pattern of the modified Hulme index is quite similar to the winter mean temperature pattern as shown in Figure 4.3.

4.1.2 Temporal variability of winter weather and winter indices

<u>Temporal variability of winter snowfall and temperature</u>

The temporal variability of winter snowfall is quite large for the study period, especially for the heavy snowfall regions, such as Owen Sound, Huntsville and Ottawa. For the light snowfall region, this variation is much less. The temperature variation in northern Ontario is larger than in southern areas, as summarized in Table 4.1. Detailed temporal variations of snowfall and temperature for the heaviest snowfall area, Owen Sound; the light snowfall area, Toronto; and the largest temperature deviation area, Kenora, are shown in Figure 4.7, 4.8, and 4.9. The winter snowfall variation from year to year is quite large in Owen Sound. Toronto experiences a relatively consistent winter weather, with both the temperature and snowfall variation being relatively low. Kenora has cold winter weather and the temperature variation from year to year is quite a bit larger.

Table 4.1 Mean winter temperature (°C) and snowfall (cm) summary for the study periods (1978/79 to 1997/98)

Station name	20 year average (temperature)	Standard deviation (temperature)	20 year average (snowfall)	Standard deviation (snowfall)
Ottawa Int'l A	-5.6	1.18	209.7	49.20
London A	-2.4	1.28	176.9	42.03
Kingston A	-3.3	1.23	147.5	50.18
Toronto Pears. Int'l A	-2.3	1.26	101.3	25.05
Windsor A	-0.4	1.26	110.9	33.81
Peterborough	-4.3	1.29	142.7	34.79
Owen Sound MOE	-2.4	1.22	320.3	96.49
Huntsville WPCP	-5.7	1.28	279.1	59.39
Sudbury A	-8.3	1.41	245.8	48.78
Wawa A	-9	1.59	279.9	57.86
Iroquois Falls	-12.3	1.07	188.9	38.38
Kenora A	-10.9	2.05	128.8	34.16

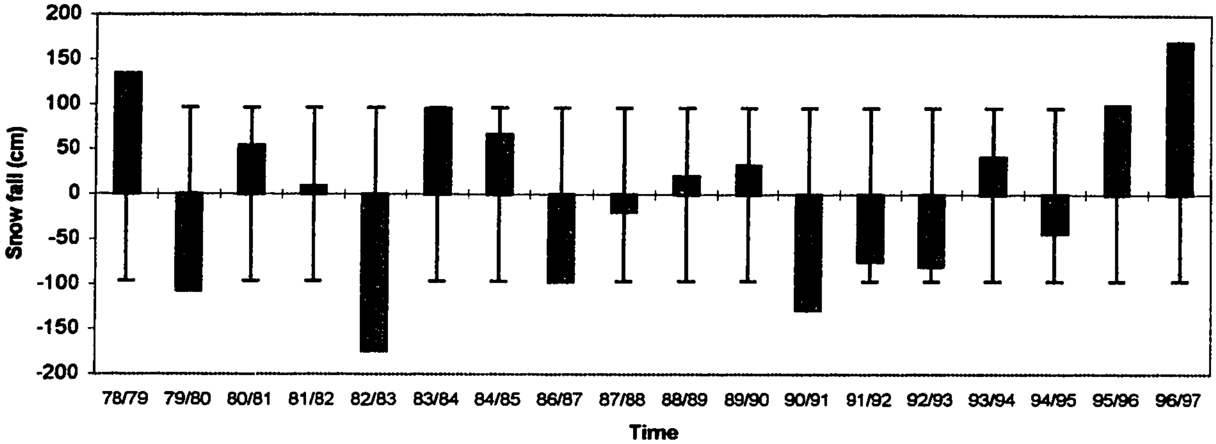


Figure 4.7a Winter snow fall departures from 1978/79-1996/97 average at Owen Sound, as compared to standard deviation

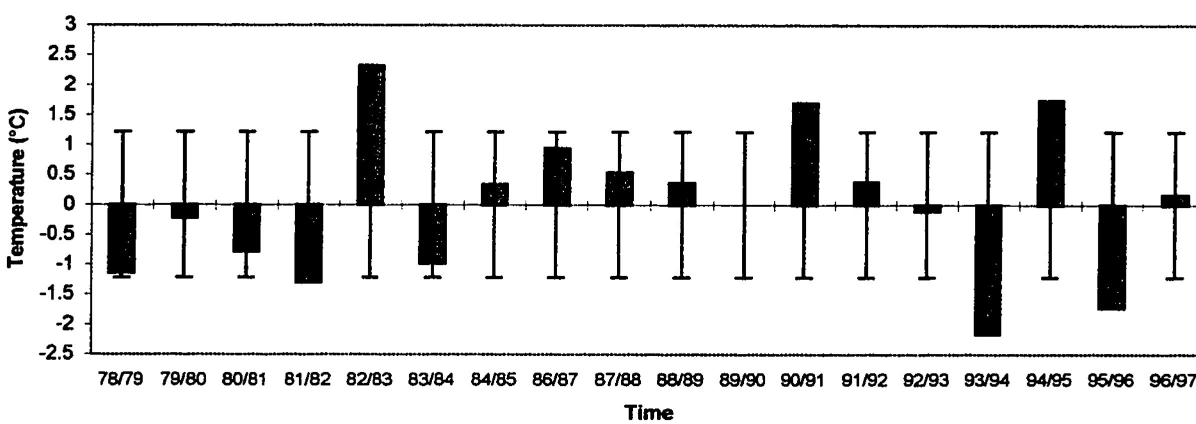


Figure 4.7b Winter mean temperature departures from 1978/79 -1996/97 average at Owen Sound, as compared to standard deviation

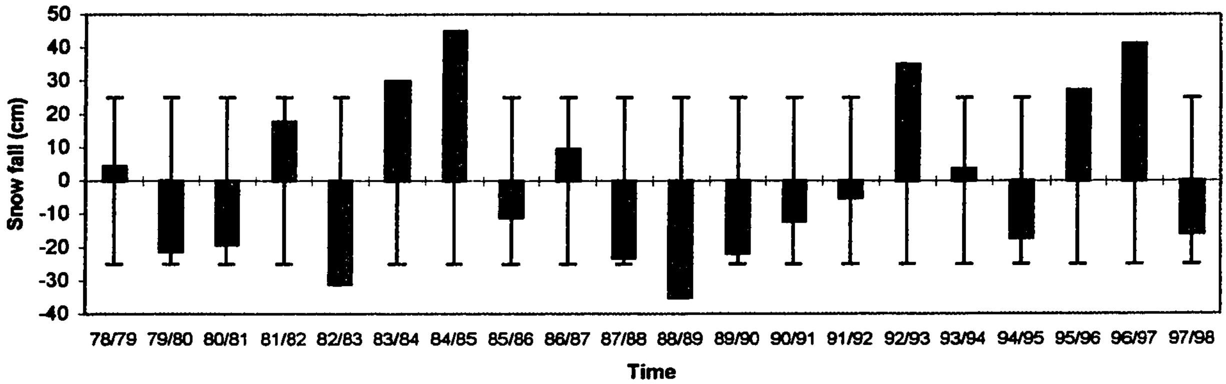


Figure 4.8a Winter snow fall departures from 1978/79-1997/98 average at Toronto Pearson Airport, as compared to standard deviation

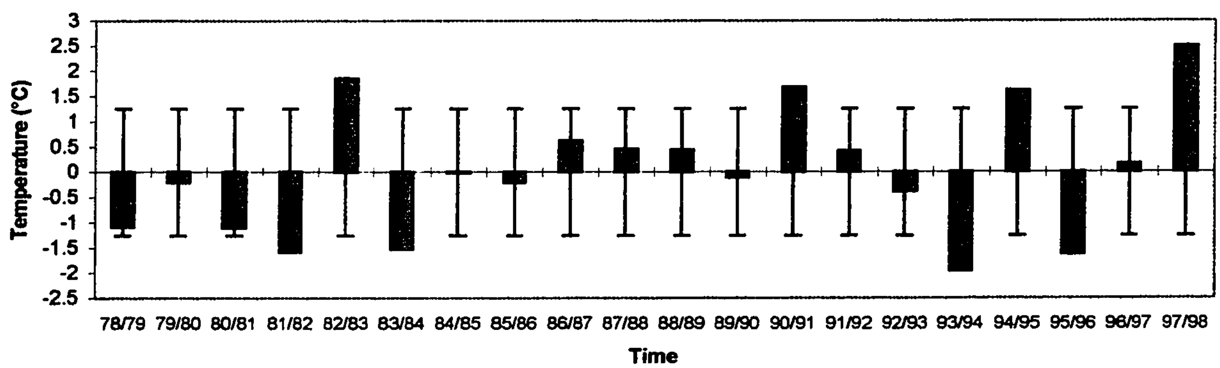


Figure 4.8b Winter mean temperature departures from 1978/79-1997/98 average at Toronto Pearson Airport, as compared to standard deviation

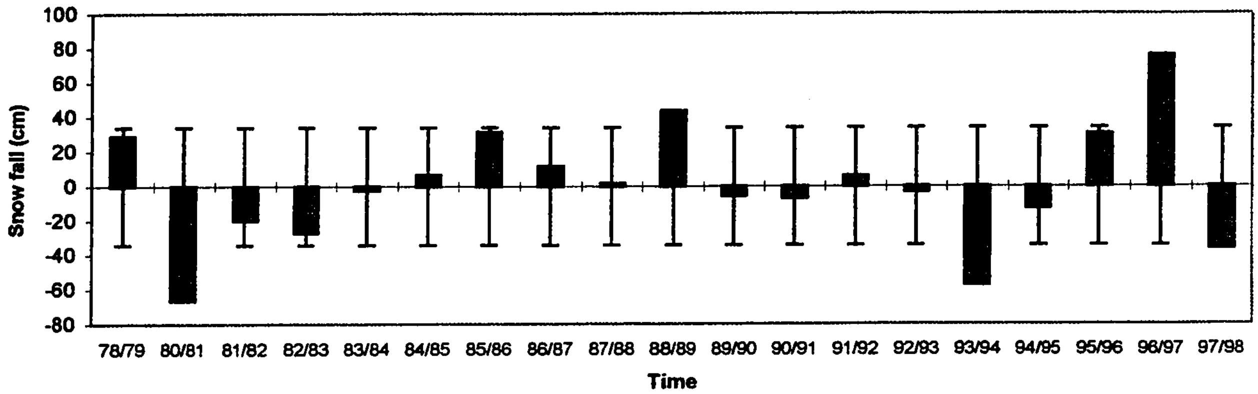


Figure 4.9a Winter snow fall departures from 1978/79-1997/98 average at Kenora Airport, as compared to standard deviation

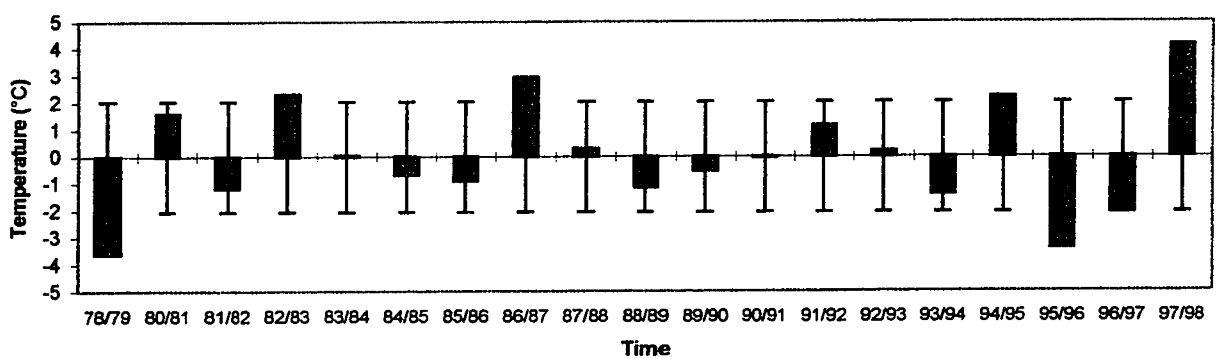


Figure 4.9b Winter mean temperature departures from 1978/79 -1997/98 average at Kenora Airport, as compared to standard deviation

Temporal variability of winter indices

The purpose of this analysis is to describe the temporal variability of these winter indices. The seasonal salt days index, modified Hulme index, and the SHRP index were calculated for 12 stations for 20 years from 1979 to 1998. Detailed results are shown in Appendix 2. The overall degree of temporal variability at each district is summarized in Table 4.2. Within each district, the salt days index has the least temporal variability; the modified Hulme index has the largest temporal variability; and the SHRP index is in the middle. For the salt days index and the SHRP index, the large temporal variation occurs in heavy snowfall areas, such as Owen Sound, Ottawa and Huntsville. For the modified Hulme index, northern districts have a large temporal variation.

Table 4.2 Means and standardized deviations for the winter indices

Station name	Salt days		Modified Hulme		SHRP	
	Mean	Std. deviation	Mean	Std. deviation	Mean	Std. deviation
Ottawa Int'l A	16.85	4.11	-45.30	12.23	-29.13	5.87
London A	17.56	3.75	-16.05	13.23	-23.86	5.19
Kingston A	13.76	4.45	-20.55	13.13	-19.66	6.99
Toronto Pears. Int'l A	10.85	2.64	-11.79	13.42	-13.71	4.52
Windsor A	10.75	3.52	4.77	13.35	-12.87	5.83
Peterborough	*	*	-25.35	12.49	-20.33	5.02
Owen Sound MOE	23.39	5.44	-18.66	12.75	-36.29	8.68
Huntsville WPCP	17.67	4.94	-39.69	12.32	-35.30	5.41
Sudbury A	16.8	3.41	-70.34	13.90	-34.68	4.84
Wawa A	16.5	3.48	-68.12	13.59	-36.55	4.95
Iroquois Falls	8.81	2.95	-92.32	11.51	-28.31	4.21
Kenora A	10.53	2.87	-99.77	19.10	-23.81	4.89

Note: * is missing data.

In terms of the harshest winters, these indices identify different winter seasons. Figure 4.10, 4.11, and 4.12 display these winter indices for several stations. The modified Hulme index isolates five winters with high severity: 1978/79, 1981/82, 1983/84, 1993/94 and 1995/96. From the Climate Trends and Variations Bulletin of Canada (Fig.3.4, http://www1.tor.ec.ge.ca/ccrm/bulletin/), we can see the winters 1978/79, 1981/82, 1993/94 and 1995/96 were cold winters. The precipitation trends show that only the winter of 1983/84 had an obviously above normal precipitation. It looks like that the modified Hulme index is much more sensitive to temperature than snowfall. It captures the coldest winters.

Generally speaking, the salt days index isolates the winters of 1980/81, 1988/89 and 1996/97 as the most severe winters; while the SHRP index identifies the winters of 81/82, 83/84, and 96/97 as being severe for most stations. The Great Lakes area precipitation and temperature chart (refer back to Figure 3.4) shows that The winter of 1980/81 had average temperature and precipitation, the winter of 1988/89 was warm with less snowfall. The winter 81/82 was cold winter; the winter of 83/84 and 1996/97 had heavy snowfall. So the SHRP index captures most heavy snowfall winters as severe winters, but the 2 severe winters identified by the salt days index are actually not severe at all.

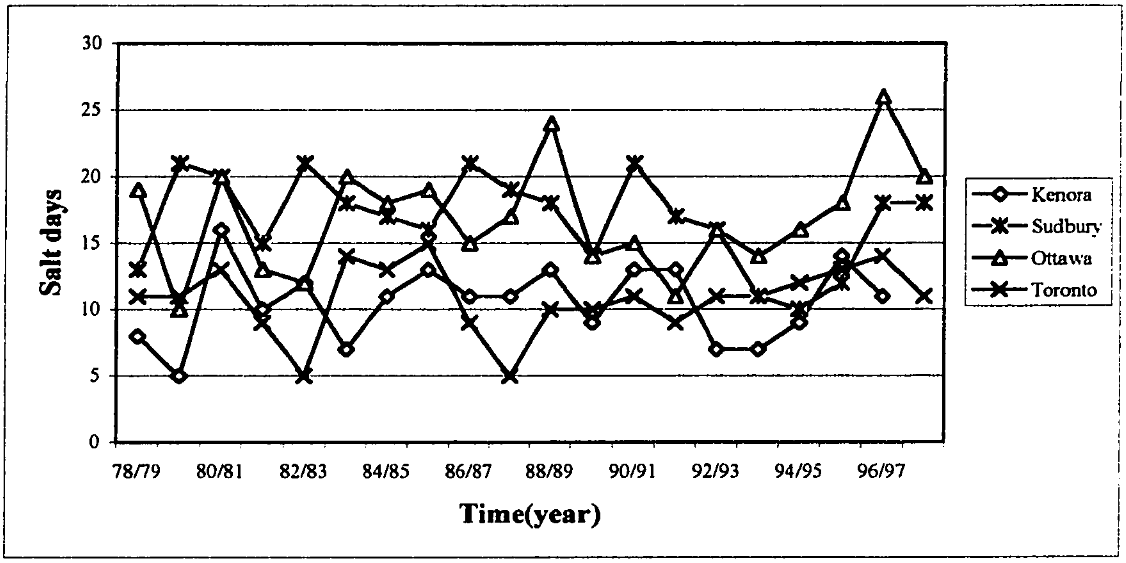


Figure 4.10 Seasonal salt days index for several stations

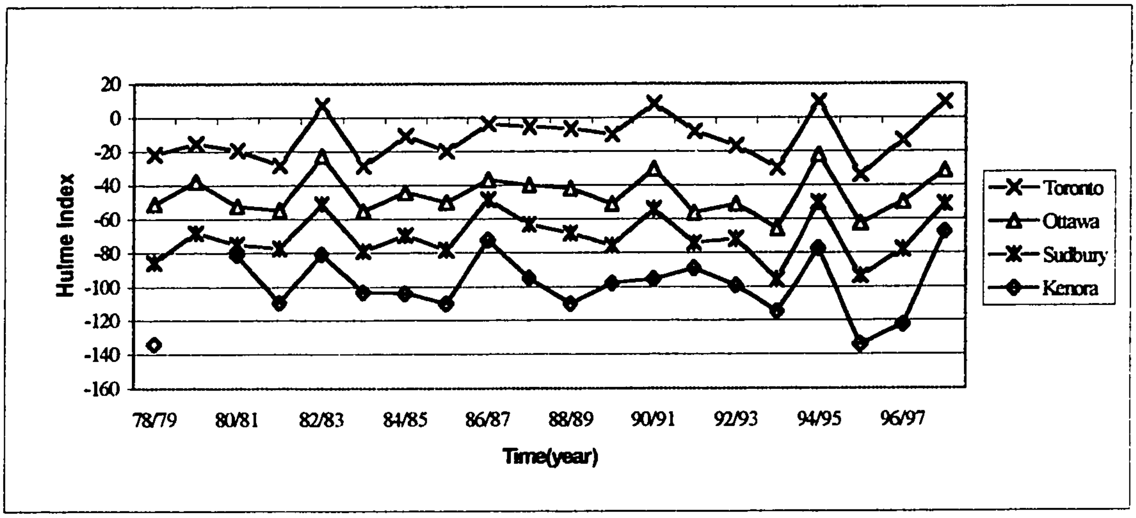


Figure 4.11 Seasonal modified Hulme winter index for several stations

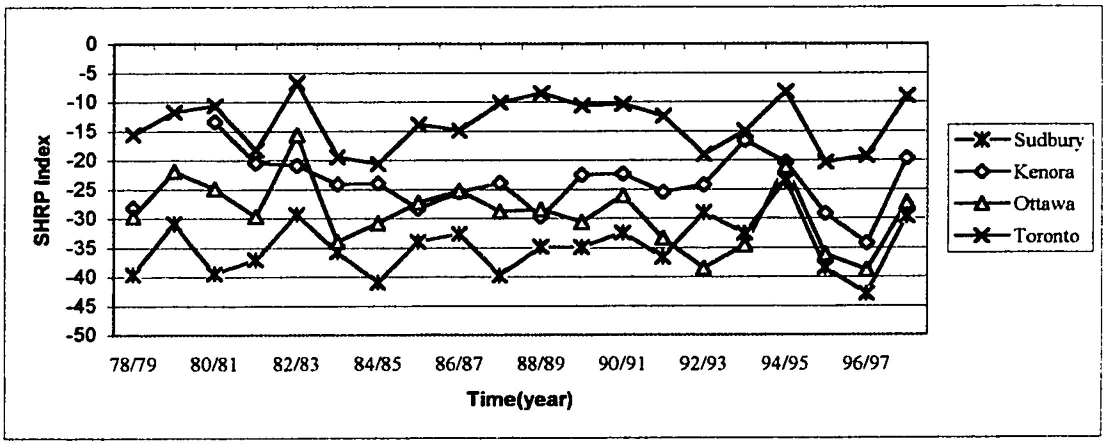


Figure 4.12 Seasonal SHRP index for selected stations

Having checked the overall behavior of these winter indices, Figures 4.13 , 4.14 and 4.15 show some detailed characteristics of these three indices at 3 different stations - Owen Sound, Toronto and Kenora.

As shown in Figure 4.13, in the heaviest snowfall area, Owen Sound, the SHRP index indicates a more severe winter climate overall than the modified Hulme index. The SHRP indices are negative with large absolute values for most winters, with the most severe value of –48.63 in the winter of 1996/97. The SHRP and the modified Hulme indices show similar fluctuations. These are consistent with the salt days index, except that a low number of salt days means a mild winter, whereas a high number means a harsh winter.

Figure 4.14 shows the three winter indices for Toronto, an area with less snowfall and milder temperatures. These three indices all indicate a mild winter weather for this station, but they identify different years for severe winter weather. The SHRP index isolates the severe winters of 1984/85, 95/96, 83/84 and 96/97; the modified Hulme winter index selects the severe winters of 1995/96, 93/94, 83/84 and 81/82; and the salt days index isolates the winters of 85/86, 96/97 and 83/84 as severe winters. Checking the individual weather elements in Figure 4.8, all of the severe winters identified by the SHRP index have heavy snowfalls. The severe winters identified by the Hulme index have either heavy snow falls or very low temperature. The salt days index shows two heavy snowfall winters, but the winter of 85/86 had normal precipitation and temperature.

Figure 4.15 shows the winter indices for a northern station, Kenora. The modified Hulme index indicates quite severe winter weather at this station; it has large negative values for most of the winters and with the severest value of –133.95 in the winter of 95/96. But the SHRP winter index and the salt days index indicate relatively average winter weather at this station. Considering the very low temperature and average snowfall for this station (Figure 4.9), this again suggests the large component of temperature in the modified Hulme index.

Summary

The previous analysis indicates that there is a high degree of temporal and spatial variability in winter weather severity. This is a challenge for planning winter road maintenance activities. The three winter indices do not always tell the same story when trying to explain the temporal winter weather variation. Which climate variables and/or winter index can best explain those variations and can help in winter road maintenance planning? The next section will attempt to answer this question.

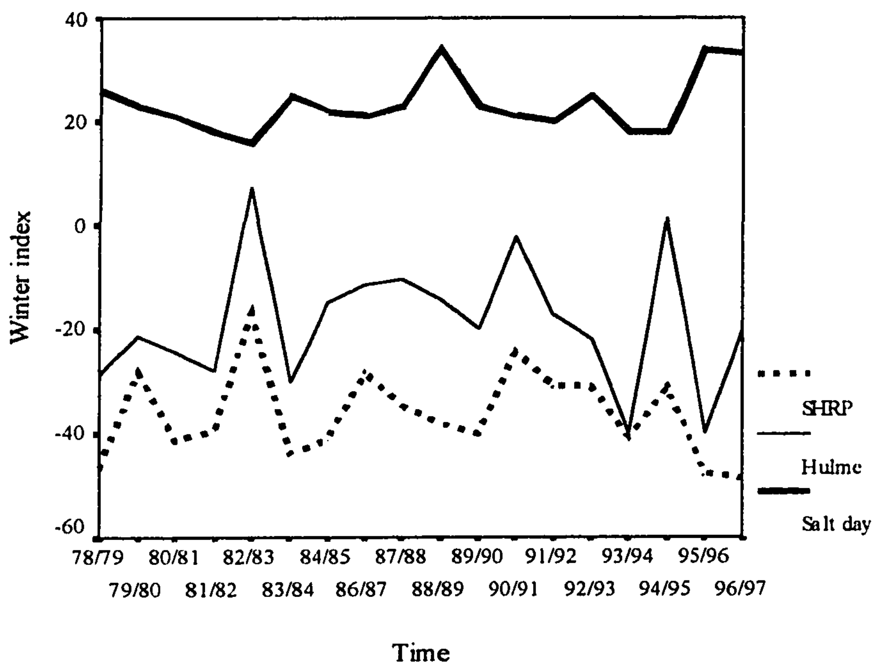


Figure 4.13 Seasonal winter indices at Owen Sound

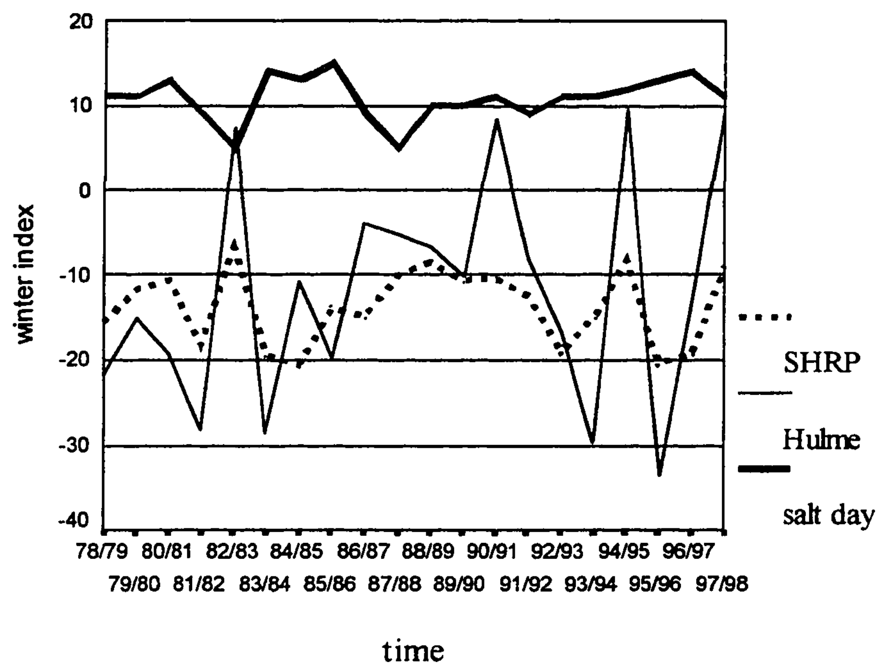


Figure 4.14 Seasonal winter indices at Toronto

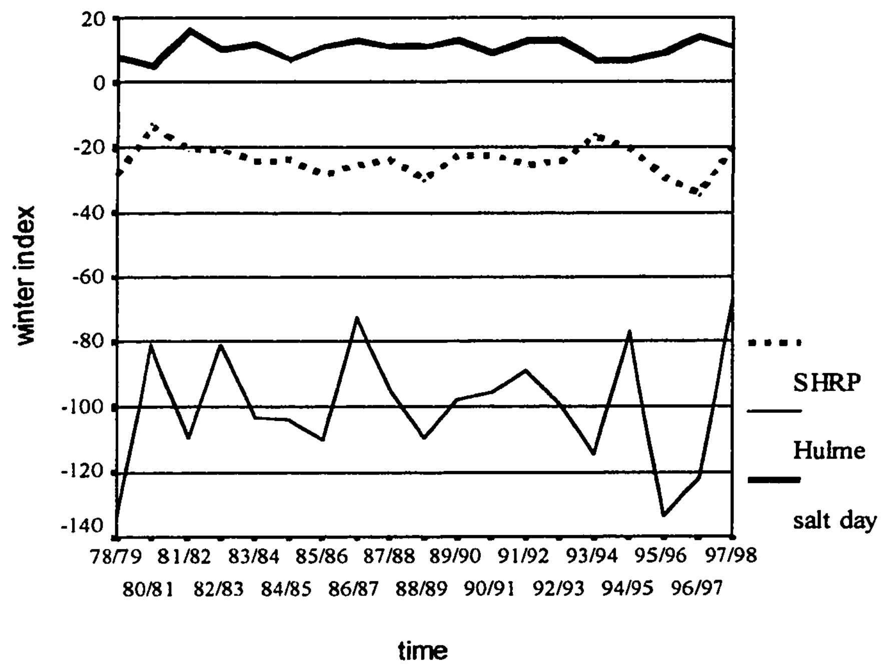


Figure 4.15 Seasonal winter indices at Kenora

4.2 Identification of the winter index that is most sensitive to winter road maintenance activities in Ontario

The next part of the discussion deals with the relationship between winter weather indices and winter road maintenance activities. The objective is to identify the winter weather index that is most sensitive to road maintenance activities in Ontario. Salt usage data were available on a biweekly basis and were transformed to salt usage per saltable 2-lane km.

Three winter indices--salt days, modified Hulme index and the SHRP index--were involved in the analysis. Correlations between salt usage and the winter indices are examined on a station by station basis first, and then the correlations between regional salt use and the winter indices across Ontario are provided. The study period is the recent 5 winters from 1993/94 to 1997/98.

4.2.1 Regional analysis of the temporal distribution

The first step in the analysis was to looking at the regional results for all years for each district and then all regions together. There are 12 MTO districts in Ontario, and 25 winter months were examined giving a total of 268 data values (because of missing data, some districts have less than 25 cases). Monthly winter indices for each district were calculated; detailed results are shown in Appendix 3. Correlation between salt use and winter indices were examined for each district and the whole area; results are summarized in Table 4.3.

Table 4.3 Results of regression model of salt usage vs. winter indices

Station name	**MTO districts**	**r-value salt vs. saltdays**	**r-value salt vs. SHRP**	**r-value salt vs. Hulme**	**Number of cases**
Ottawa Int'l A	Ottawa	0.554	**-0.863**	-0.682	25
London A	London	0.629	**-0.782**	-0.723	22
Kingston A	Kingston	0.452	-0.782	**-0.894**	10
Toronto Pears. Int'l A	central	0.256	**-0.719**	-0.717	25
Windsor A	Chatham	0.846	**-0.877**	-0.752	25
Peterborough	Bancroft	Missing	-0.556	**-0.561**	24
Owen Sound MOE	Owen Sound	**0.827**	-0.729	-0.535	23
Huntsville WPCP	Huntsville	**0.679**	-0.620	-0.399	22
Sudbury A	Sudbury	0.095	**-0.793**	-0.622	25
Wawa A	Salt Ste. Marie	0.251	**-0.581**	-0.522	23
Iroquois Falls	New Liskeard	0.354	**-0.580**	-0.070	19
Kenora A	Thunder Bay	0.181	**-0.484**	-0.312	25
All 12 districts		0.592	**-0.693**	-0.319	268

Note: the maximum of every row is in **bold** type.

The correlations between the monthly salt days index and salt use varies considerably among regions, with the highest *r* value of 0.846 at Windsor, and the lowest, 0.095 at Sudbury. For 5 of the 11 MTO districts, the correlation between salt usage and salt days was significant at 95 percent confidence level. The highest *r* values occur for the heavy snowfall area of Owen Sound and the light snowfall area of Windsor; most of the poor correlation occurs in northern districts. Figure 4.16, 4.17 shows the scatter plots of salt usage per saltable 2-lane km vs. the salt days index for several districts. Also on the plots are the *r* squared values for each region. Figure 4.16 shows the districts with highest *r* squared values and Figure 4.17 shows the 3 districts with lowest r squared values.

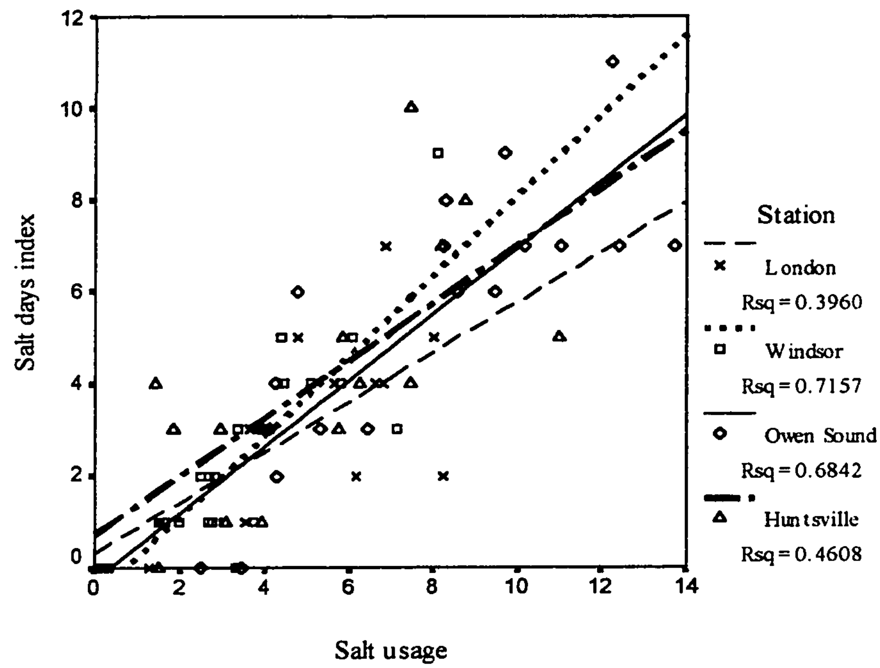


Figure 4.16 Relationship between salt usage (ton per saltable 2-lane km) and monthly salt days index for several stations

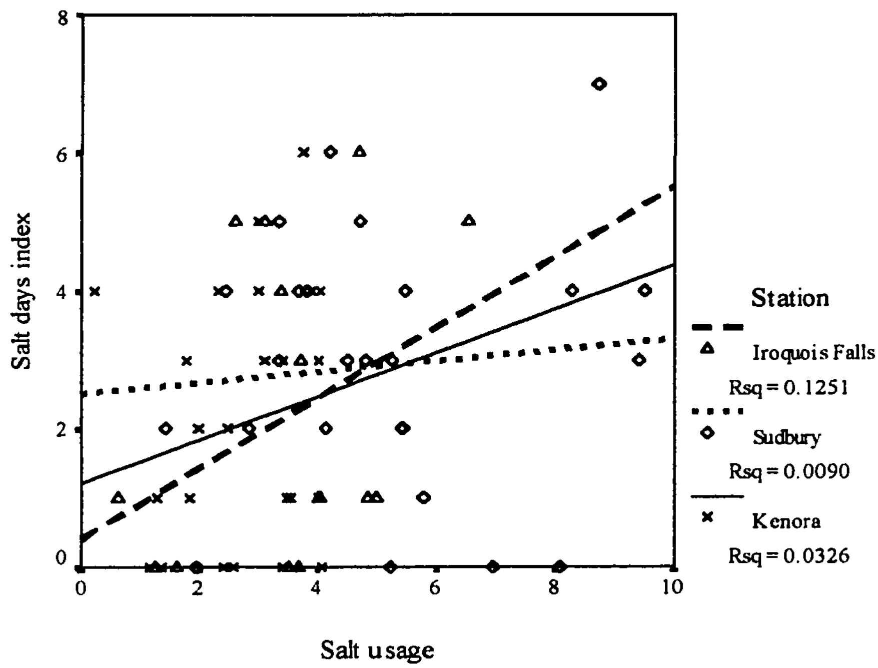


Figure 4.17 Relationship between salt usage (ton per saltable 2-lane km) and monthly salt days index for several northern stations

Table 4.3 also shows the result of correlation analysis of salt usage vs. the modified Hulme index for every individual MTO district. There are major differences between regions, with the highest *r* value of –0.894 at Kingston, and the lowest, 0.070 at Iroquois Falls. Most of the correlations are significant at the 95 percent confidence level. But for the whole area, correlation between the modified Hulme index and the salt usage is very poor.

The Pearson correlation coefficients based on the monthly SHRP index vs. salt usage are higher than other two indices at most districts, as shown in Table 4.3. For the 12 MTO districts, most of the correlation coefficients are significant at 95 percent level. Generally speaking, those MTO districts where salt usage is quite sensitive to the SHRP index tend to be located in Southern Ontario from London to Ottawa. This region is highly urbanized and densely populated. Almost all highways are class 1 roads with high volumes of traffic; the ratio of saltable road/total roads is nearly 1. The winter is mild and the road is treated during snowstorms or immediately after snowstorms. This particular climate is most amenable to effective salt use. Figure 4.18 shows the regression of salt usage (ton per 2-lane km) to the SHRP index, grouped by region. Also on the plots are the *r* squared values for each region, which are all fairly high.

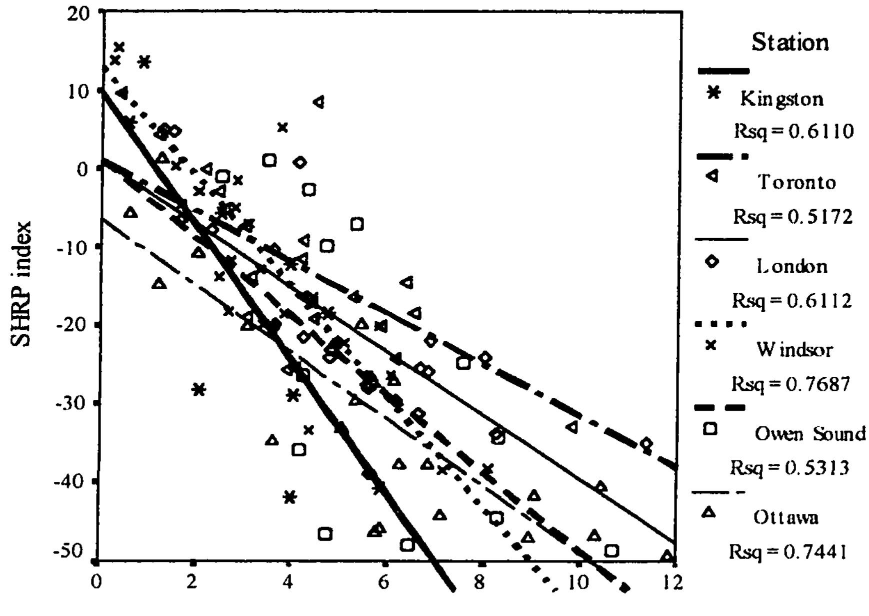


Figure 4.18 Relationship between salt usage (ton per saltable 2-lane km) and monthly SHRP index for selected southern districts

The correlation coefficient between the SHRP index and salt usage is high in one northern district, Sudbury. But the results are poor for other northern districts, Thunder Bay and New Liskeard (associated with the two weather stations at Kenora, and Iroquois Falls, respectively). This area has harsh winters; the winter mean temperature is roughly -11°C (from Nov. to March). Roads are sparse and the road network is different from other areas; the ratio of saltable roads to total roads is just 0.5, only 1/3 to ½ of the roads in the highway network are class 1 roads, unlike in most southern districts where nearly all the roads are class 1. This region also has larger portion of class 4 roads that have relatively less maintenance priority. Figure 4.19 shows the way each district's salt use reacts to changes in SHRP index. This plot shows much more scattering, with much reduced *r* squared values.

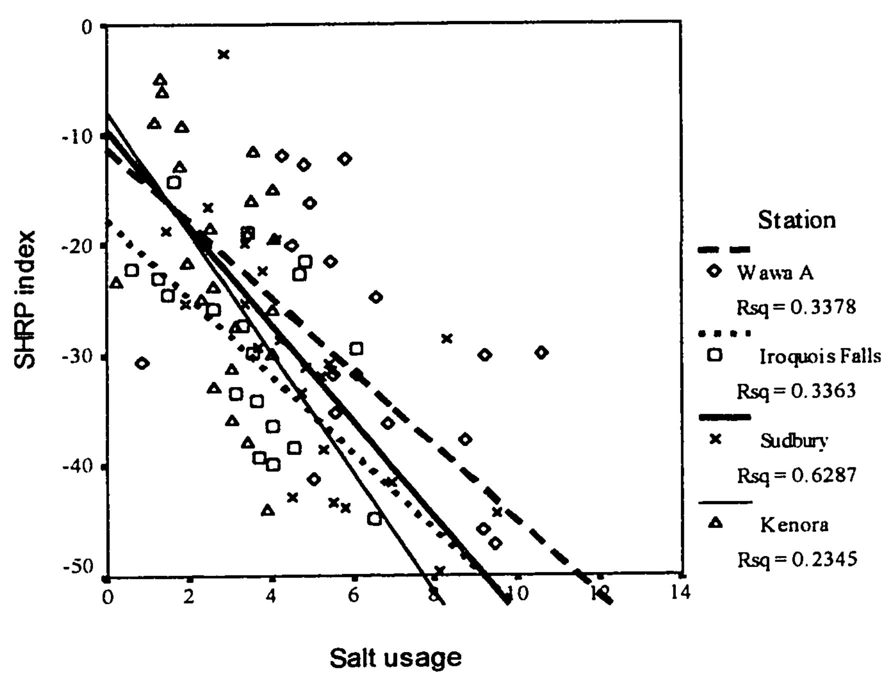


Figure 4.19 Relationship between salt usage (ton per saltable 2-lane km) and monthly SHRP index for several northern districts.

Which index can better explain the temporal distribution of winter severity and salt usage? The previous correlation analysis of salt usage on monthly winter indices attempted to answer this question. Compared with the modified Hulme index and salt days index, the SHRP index is best correlated to salt usage in most MTO districts and in all the 12 districts.

4.2.2 Spatial variation

The main issue for this work is whether these indices could be used to benchmark salt usage. There are two aspects to this question. Firstly, within regions, could the index account for the temporal variability in salt usage? Secondly, for Ontario as a whole, could this index explain the spatial differences in regional salt usage? The first aspect was checked in the analysis reported in 4.2.1. The second aspect is to look for the Pearson moment correlation coefficient between the regional salt usage and the winter indices across the Province. The annual salt usage per saltable 2-lane km averaged for the recent 5 years and the seasonal winter indices averaged for the same time period were used for this analysis. The data set includes 12 cases for 12 MTO districts. Appendix 4 shows the detailed results. The correlation of five-year average salt usage vs. average seasonal SHRP index has a r of –0.827, and r^2 of 0.683, and the correlation is significant at the 99 percent level. This result clearly shows a linear relationship between the SHRP index and salt usage across the province. Compared with the results of the modified Hulme winter index (r = -0.062) and the salt days index (r = 0.791), the SHRP index is obviously the best one to explain the spatial distribution of salt usage. Fig 4.20 shows how annual salt usage, in ton per saltable 2-lane km, correlated with the seasonal SHRP index across MTO districts. It can be seen that there is an inverse relationship and that the district with the highest salt usage and lowest index is Owen Sound. Sault Ste. Marie, Sudbury, and Huntsville have similar winter index values but very different salt usage. Sudbury, New Liskeard and Bancraft have similar salt usage but very different winter index values. This difference is likely due to many factors such as topography, traffic density and maintenance policy. Road mix factor, *cls3_4* (ratio of class 4 and 3 roads to the total road net) can be used to explain some of the variance: class 1 and 2 roads have more maintenance priority, and class 3 and 4 roads have less. A linear regression model was established as

$$\text{Salt Usage} = 7.556 - 0.846\,SHRP - 9.895\,cls3\_4$$

with a r of 0.87, and a r^2 of 0.757. The seasonal SHRP index and road mixture can explain 75.7% of the spatial distribution of the salt usage difference for the whole province. The spatial distribution of the seasonal SHRP index across Ontario is provided in Figure 4.21.

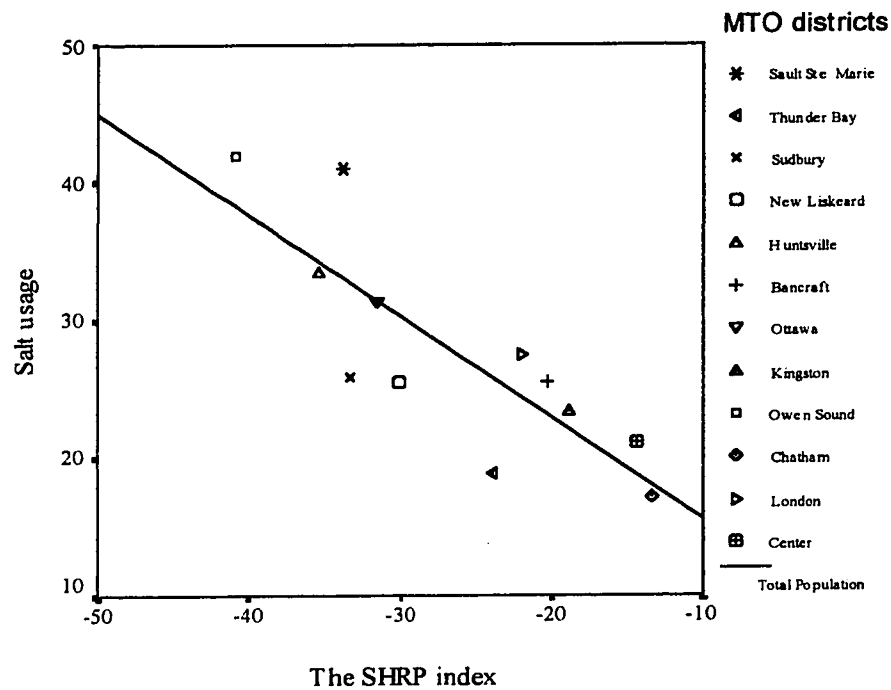


Figure 4.20, Correlation of salt usage in each district (ton per saltable 2-lane km) with seasonal SHRP winter index.

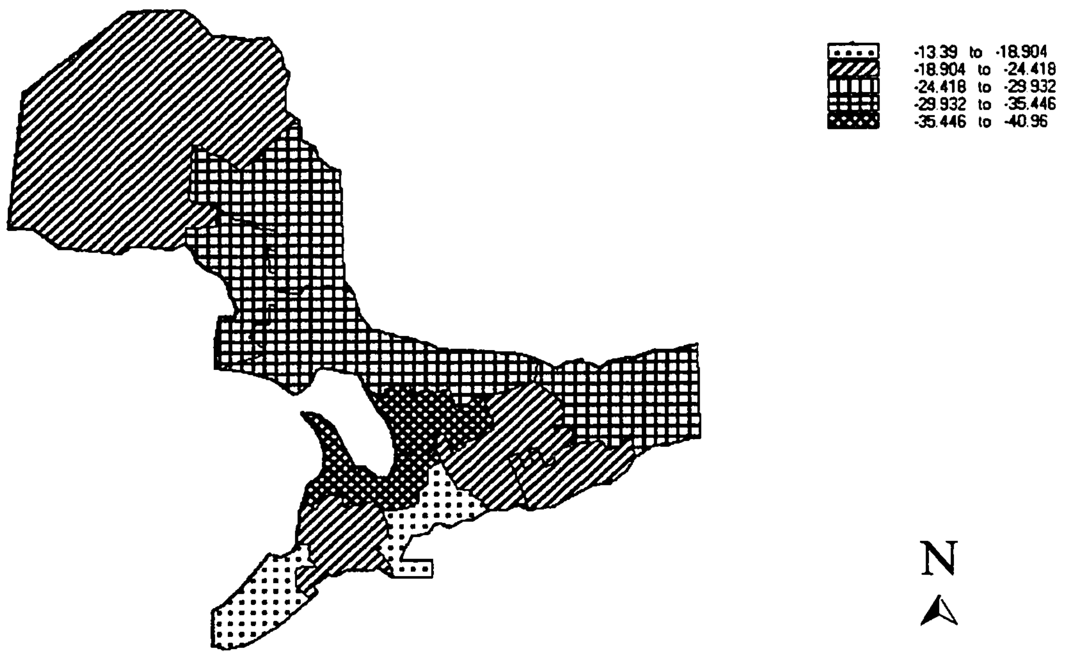


Figure 4.21 Spatial distribution of seasonal SHRP index across Ontario, averaged from 1993/94 to 1997/98

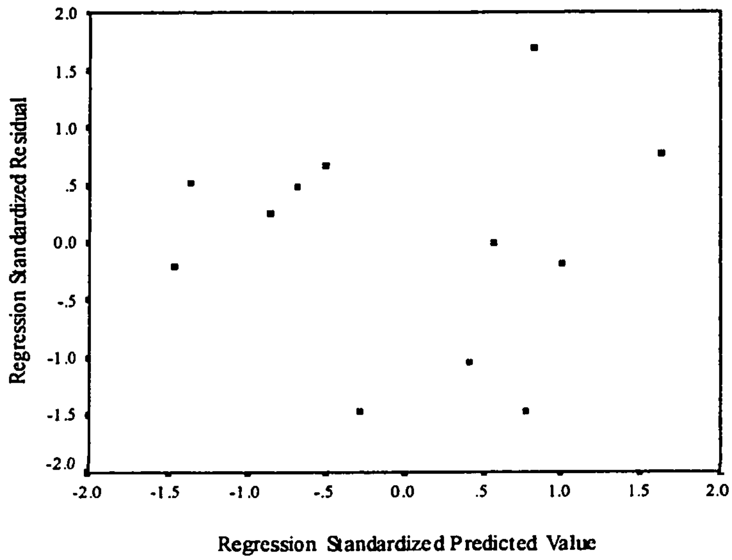


Figure 4.22 Scatter plots of standardized residuals vs. predicted salt usage

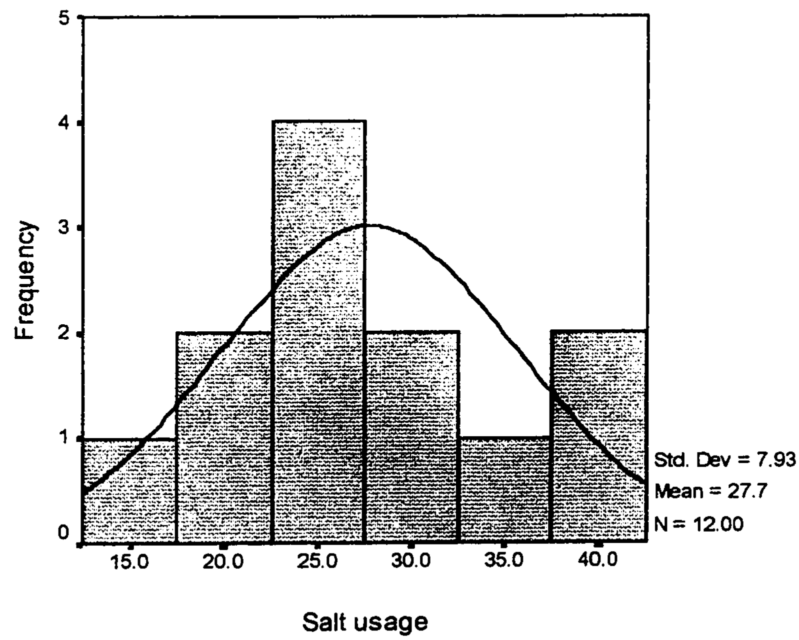


Figure 4.23 Annual regional salt usage (ton per saltable 2-lane km) averaged from 1993/94 to 1997/98 histogram with normal curve

Validation and error

Figure 4.22 is the standardized error vs. predicted salt usage plot. Figure 4.23 is salt usage histogram with normal curve from frequencies. Most errors randomly fill in the band of ± 1. So the independent and normality assumption is not violated and this model is validated.

Among the 3 winter indices concerned, the SHRP index provides relatively high explanation of both the temporal and spatial variation in salt usage on provincial roads in Ontario. Given these results, it was decided to investigate the SHRP index further. The next part of the work will focus on modification of this index.

4.3 Modification of the SHRP winter index

This part of the work is to modify the SHRP index so as to make it more suitable to Ontario's climate and road maintenance conditions. This is necessary for several reasons. First, the SHRP index's performance is not quite as good in Canada as in the US. Secondly, the developers of this index indicated that it can be adjusted to local climate, but they don't give a very convincing argument for why certain climate elements are included and for why certain weights are used. The previous analysis in my thesis uses the US SHRP formula. By adjusting the weights and climate elements involved, it is possible that the performance of the SHRP index will be improved.

In order to identify an appropriate time scale, a comparison between salt usage vs. monthly and biweekly SHRP index will be made. Relationship between salt usage and climate variables for each district will be examined. Modification of the SHRP index will be made based on the regression and correlation results of salt usage vs. climate variables. A regression model of salt usage vs. temperature and precipitation variables will be identified for every district.

4.3.1 Biweekly analysis

The original salt usage were biweekly data, so the climate data were used at exactly the same time-interval as the salt data this time. The potential advantage of the biweekly analysis is tied to the fact that this is the time scale used by the MTO for recording salt data. It would make the index more user-friendly. The biweekly SHRP index was calculated for every MTO district for the recent 5 winters. Detailed results are summarized in Appendix 5. Correlation of salt usage and the biweekly SHRP winter index was done for every district separately and for the province as a whole. The results are shown in Table 4.4. The correlation coefficient of salt usage vs. the biweekly SHRP index is lower than that of salt usage vs. the monthly SHRP index for most of the MTO districts, and for the whole area. Only at Windsor, Huntsville and Wawa are the correlation coefficients slightly higher for the biweekly analysis. The overall result is not as good as the original monthly SHRP index. This might be due to the fact that the SHRP index was designed as a seasonal winter index based on monthly data. The monthly time scale is better than the biweekly one.

Table 4.4 Results of regression model of salt usage vs. monthly and biweekly SHRP indices

Station Name	MTO districts	r-value salt vs. biweekly SHRP	r-value salt vs. monthly SHRP	Number of cases
Ottawa Int'l A	Ottawa	-0.762	-0.863	50
London A	London	-0.737	-0.782	44
Kingston A	Kingston	-0.716	-0.782	20
Toronto Pears. Int'l A	central	-0.635	-0.719	50
Windsor A	Chatham	-0.887	-0.877	50
Peterborough	Bancroft	-0.440	-0.556	48
Owen Sound MOE	Owen Sound	-0.663	-0.729	46
Huntsville WPCP	Huntsville	-0.664	-0.620	44
Sudbury A	Sudbury	-0.718	-0.793	50
Wawa A	Salt Ste. Marie	-0.605	-0.581	46
Iroquois Falls	New Liskeard	-0.212	-0.580	38
Kenora A	Thunder Bay	-0.461	-0.484	50
All 12 districts		-0.654	-0.693	536

4.3.2 The relationship between salt usage and climate variables

In order to explore opportunities to improve the SHRP index, the relationship between salt usage and a wide range of climate variables was assessed using the Pearson correlation coefficients. These correlations between salt usage (ton per saltable 2-lane km) and different climate variables are summarized in Table 4.5. The analysis covers 5 winters from Nov. 1993 to Mar. 1998, totaling 25 winter months for every district.

Within the temperature subgroup (*TI* – temperature index, *Tmax* – monthly mean maximum temperature, *Tmn* – monthly mean temperature, *Ngf* – days with ground frost, which is actually decided by minimum temperature, and temperature range - *R*), the temperature index, *TI* is highly correlated with salt usage at most northern districts. Temperature range *R* is poorly correlated with salt usage at most of the stations. In the precipitation subgroup (*S* – snowfall, *Nsd* – days with measurable snowfall, and *frz* – days with freezing rain), salt usage is highly correlated with snowfall, *S* in the whole area. But at some stations, snow days *Nsd* is also highly correlated with salt usage.

The manner in which climate variables reflect salt usage is quite different among different districts. For the province as the whole, salt usage is highly correlated with the SHRP index; temperature index and snowfall are relatively highly correlated with salt usage in the temperature and precipitation subgroups. In southern districts (upper portion in Table 4.5), days with freezing rain correlated with salt usage better than air frost, *N* and temperature range, *R*; while in northern districts (middle portion in Table 4.5), the salt usage is almost similarly correlated with days with freezing rain, *frz* and air frost, *N*.

Table 4.5 Pearson correlation coefficients between salt usage and climate variables and winter indices

station	SHRP	Hulme	saltdy	TI	Tmax	Tmn	Ngf	S	Nsd	frz	N	R	No. of cases
Ottawa	-0.863	-0.682	0.554	0.723	-0.675	-0.646	0.496	0.807	**0.876**	0.782	0.461	0.032	25
London	-0.782	-0.723	0.629	0.702	-0.716	-0.722	0.604	**0.783**	0.772	0.696	0.587	0.163	22
Kingston A	-0.782	-0.894	0.452	0.800	**-0.902**	-0.886	0.624	0.735	0.864	0.654	0.611	0.429	10
Toronto	-0.719	-0.717	0.256	0.677	-0.713	-0.744	0.569	0.650	**0.826**	0.567	0.534	0.482	25
Windsor	**-0.877**	-0.752	0.846	0.786	-0.731	-0.747	0.763	0.864	0.790	0.743	0.721	0.116	25
Peterborough	-0.556	-0.561	Miss	0.554	**-0.563**	-0.485	0.288	0.475	0.546	0.524	0.319	-0.203	24
Owen Sound	-0.729	-0.535	**0.827**	0.612	-0.495	-0.488	0.643	0.658	0.744	0.130	0.652	0.192	23
Huntsville	-0.620	-0.399	0.679	0.508	-0.387	-0.302	0.279	0.548	**0.699**	0.448	0.325	-0.167	22
Sudbury	**-0.793**	-0.622	0.095	0.682	-0.611	-0.571	0.463	0.759	0.787	0.448	0.508	0.113	25
Wawa A	-0.581	-0.522	0.251	0.662	-0.515	-0.461	0.369	0.509	**0.707**	0.406	0.466	0.150	23
Iriquois Falls	-0.580	-0.070	0.354	-0.168	-0.066	0.275	-0.050	0.036	0.446	**0.597**	-0.402	-0.420	19
Kenora A	-0.484	-0.312	0.181	0.424	-0.303	-0.236	0.266	0.377	**0.549**	0.410	0.391	-0.411	25
All 12 districts	**-0.693**	-0.319	0.592	0.418	-0.302	-0.301	0.345	0.676	0.656	0.285	0.349	0.025	268

Note: the maximum of every row is in **bold** type.

4.3.3 Modification of the SHRP winter index

1) Attempts to modify the weights

The original SHRP winter index is given as

$$WI = a(TI)^{0.5} + b\ln\left[\frac{S}{10} + 1\right] + c\left[\frac{N}{R + 10}\right]^{0.5} + d \qquad (1)$$

where *TI, S, N, R* are four climate variables, and *a, b, c, d* are constants which can be assign a particular weight for suitable climate conditions. For US data, percentages of 35, 35 and 30 were assigned to *TI, S* and *N*, respectively. $WI = -50$ when $TI = 1.87$, $S = 16.5$, $N = 1$, and $R = 1$, solving a set of equations such that

$-50 = -35-35-30 + d,$ $\quad d = 50;$

$-35 = a\,(TI)^{0.5}$, when $TI = 1.87$, $\quad a = -25.58;$

$-35 = b\ln(S/10 + 1)$, when $S = 16.5$, $\quad b = -35.68;$

$-30 = c\,(N/(R+10))^{0.5}$, when $N = 1$ and $R = 1$, $\quad c = 99.5.$

Substitution of *a, b, c* and *d* into Equation (1), we got

$$WI = -25.58(TI)^{0.5} - 35.68\ln\left[\frac{S}{10} + 1\right] - 99.5\left[\frac{N}{R+10}\right]^{0.5} + 50 \qquad (2)$$

This is the formula applied in the previous analysis.

As Thornes mentioned, the coefficients of equation (1) can be adjusted to a particular climate (Thornes, 1993). Equation (2) is suitable for the US climate. In general, Ontario has more snowfall and is colder than the US. Applying the original SHRP index to our Ontario data, when the index is around -50, the winter in the most severe, *TI* is equal to 1.9, $N = 1$, but *S* is around 35, and *R* is around 8. By assigning the same weight percentages of 35, 35 and 30 to *TI*, *S* and *N*, respectively, *WI* can be derived by solving a new set of equations such that

$-50 = -35-35-30 + d$, $d = 50$;

$-35 = a\,(TI)^{0.5}$, when $TI = 1.9$, $a = -25.39$;

$-35 = b\ln(S/10 + 1)$, when $S = 35$, $b = -23.27$;

$-30 = c(N/(R+3))^{0.5}$, when $N = 1$ and $R = 8$, $c = -99.5$.

(Note: R + 10 was adjusted to R + 3 based on our data set)

Substitution of *a, b, c* and *d* into Equation (1), we get

$$WI = -25.39(TI)^{0.5} - 23.27\ln\left[\frac{S}{10}+1\right] - 99.5\left[\frac{N}{R+3}\right]^{0.5} + 50 \qquad (3)$$

Using this formula, the results (in Table 4.6, Case1) of correlation of salt usage vs. the new SHRP index expressed by (3) are not very different from the original one expressed by (2), although the fit is improved slightly for 6 of 12 districts.

The weights might be a problem. As shown in Table 4.5, for the whole area, the correlation coefficients of salt usage vs. *TI, S, N, R* are 0.418, 0.676, 0.349 and 0.025, respectively. The original SHRP index assigned weight of 35%, 35%, and 30% to the *TI*, *S*, and the *N/R* terms. Based on the correlation results, the weight of snowfall, *S* was increased, and the weight of the third term that deals with frost, *N*, and temperature range, *R*, was decreased. Several different weights to *TI, S, N* have been tested; the results are summarized in Table 4.6. In case 1, the same weight as the original SHRP index are used, but the *TI, S, N,* and *R* are based on Ontario's data values, and the coefficients in the original SHRP index are changed. In case 2 and 3, both the weights and the coefficients are changed. The *TI, S, N,* and *R* are also based on Ontario's data values so that the modified SHRP index is limited from –50 and +50 in Ontario.

Table 4.6 Correlation coefficients of salt usage vs. modified SHRP index

Station name	MTO districts	Original SHRP	Case1	Case2	Case3	No. of cases
Ottawa Int'l A	Ottawa	-0.863	-0.860	**-0.867**	-0.864	25
London A	London	**-0.782**	-0.749	-0.775	-0.776	22
Kingston A	Kingston	-0.782	-0.780	**-0.787**	-0.785	10
Toronto Pears. Int'l A	central	**-0.719**	-0.690	-0.716	-0.712	25
Windsor A	Chatham	**-0.877**	-0.853	-0.872	-0.874	25
Peterborough	Bancroft	-0.556	**-0.600**	-0.577	-0.564	24
Owen Sound MOE	Owen Sound	-0.729	**-0.734**	-0.729	-0.728	23
Huntsville WPCP	Huntsville	-0.620	**-0.659**	-0.634	-0.628	22
Sudbury A	Sudbury	-0.793	**-0.813**	-0.803	-0.798	25
Wawa A	Salt Ste. Marie	-0.581	**-0.618**	**-0.597**	-0.585	23
Iroquois Falls	New Liskeard	**-0.580**	0.008	0.026	0.012	19
Kenora A	Thunder Bay	-0.484	**-0.541**	-0.506	-0.493	25
All 12 districts		-0.693	-0.681	-0.694	**-0.700**	268

In which

Case1: assign weights 35, 35, 30 to *TI, S, N*, respectively;
Case2: assign weights 35, 45, 20 to *TI, S, N*, respectively;
Case3: assign weights 30, 50, 20 to *TI, S, N*, respectively.

On the whole, these modifications of coefficients and weights did not improve the correlation between salt usage and the winter index. The following analysis will consider the variables involved in the SHRP index.

2) Introducing a new variable in the SHRP index

Another alternative is to adjust the variables in the model. The correlations between salt usage and climate variables (Table 4.5) indicate that in southern Ontario, freezing rain, *frz,* is better correlated with salt usage than air frost, *N,* and temperature range, *R.* So, to improve the winter index, the term with *N* and *R* was replaced with days with freezing rain (*frz*) and the weights were re-estimated based on the Ontario's climates.

Table 4.7 Standardized coefficients of regression model of *TI, S, frz* on salt usage

Station name	*TI*	*S*	*frz*	No. of cases
Ottawa Int'l A	0.266	0.561	0.286	25
London A	-0.035	0.731	0.357	22
Kingston A	0.629	0.026	0.221	10
Toronto Pears. Int'l A	0.325	0.354	0.470	25
Windsor A	0.317	0.557	0.098	25
Peterborough	0.387	0.091	0.325	24
Owen Sound MOE	0.272	0.461	0.075	23
Huntsville WPCP	0.204	0.355	0.304	22
Sudbury A	-0.104	0.917	0.348	25
Wawa A	0.518	0.118	0.174	23
Iroquois Falls	-0.140	-0.033	0.592	19
Kenora A	0.271	0.242	0.282	25
All 12 districts	0.067	0.626	0.197	268

Table 4.7 shows the regression coefficients (standardized). The result shows that on the whole area, the salt usage is best correlated with *S,* and then with *frz* , and *TI.* But at

individual stations, the coefficients are quite different. For most stations, the salt usage is best correlated with *S*. The ratio of *S/frz* is roughly 2:1. Based on this result, different weights were assigned to *TI*, *S*, and *frz*. Several sets of weights have been tested. The results are summarized in Table 4.8.

The maximum r value in every row is in the bold type in Table 4.8. The best set of weights comes out as Case 9, 20% to *TI*, 50% to *S*, and 30% to *frz*. Compared with the original SHRP index, it performs better. The *r* value of salt usage vs. the modified SHRP index is higher than the original SHRP index for most stations, especially in London, where the *r* value improved from 0.782 to 0.851. Only in Windsor, Owen Sound, Iroquois Falls, and in all 12 MTO districts together, the correlation coefficients of the modified SHRP index are slightly lower than the original one. The formula of the modified SHRP index is

$$WI = -14.51(TI)^{0.5} - 33.24\ln\left[\frac{S}{10}+1\right] - 9.49(frz)^{0.5} + 50 \qquad (4)$$

The detailed results of the modified SHRP index are shown in Appendix 6.

3) Attempts on *TI* modification

TI in the original model is a simple temperature index determined by daily maximum and minimum temperatures. It is reasonable for one to think that the winter index's performance should be improved by adding some thresholds related to salt effective critical temperature to this index. Efforts were made to modify the *TI* accordingly. The results with the *TI* modification are also summarized in Table 4.8 (case 9a, and case 9b). The same weights and coefficients as in case 9 were used in case 9a and case 9b, but in case 9a, *TI* is decided as

TI = 0	Tmin > 0°C or	no need of salt
	Tmax < -12°C	temperature is too cold to salt use
TI = 1	Tmin < 0°C and Tmax > 0°C	mild weather, averaged salt
TI = 2	-12°C < Tmax < 0°C	cold weather, salt is the most effective

Case 9b is the same as case 9a except the salt effective critical temperature changed to –18°C.

The result shows that, not as expected, case 9a and 9b get slightly lower r values than case 9 in most of the southern districts, and get slightly higher r values than case 9 only in 4 districts and for all 12 districts together. The overall results of case 9a and 9b are not very different from those in case 9.

This is reasonable since *TI* only has a 20% weight of the *WI*, there are little impacts of the r value changes when changing *TI*. The results of case 9a and case 9b show that in northern districts, add salt effective critical values to *TI* might slightly improve the correlation coefficients. But the improvement is not obvious in our results. More work needs to be done to better understand the relationship between *TI* and salt usage and why the original *TI* performs well.

Table 4.8 Correlation coefficients of salt usage vs. modified SHRP index

Station name	Original SHRP	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 9a	Case 9b	No. of cases
Ottawa Int'l A	-0.863	-0.887	-0.890	-0.896	-0.906	-0.914	**-0.919**	-0.914	-0.918	25
London A	-0.782	**-0.866**	-0.865	-0.865	-0.864	-0.856	-0.851	-0.851	-0.851	22
Kingston A	-0.782	-0.823	-0.822	-0.824	-0.829	-0.830	**-0.831**	-0.819	-0.828	10
Toronto Pears. A	-0.719	-0.737	-0.751	-0.763	-0.771	-0.775	**-0.783**	-0.760	-0.779	25
Windsor A	**-0.877**	-0.859	-0.871	-0.875	-0.871	-0.866	-0.868	-0.866	-0.867	25
Peterborough	-0.556	-0.558	-0.566	-0.577	-0.591	-0.600	**-0.609**	-0.601	-0.612	24
Owen Sound MOE	**-0.729**	-0.712	-0.717	-0.719	-0.717	-0.713	-0.713	-0.722	-0.714	23
Huntsville WPCP	-0.620	-0.630	-0.630	-0.636	-0.649	-0.660	-0.666	**-0.670**	**-0.670**	22
Sudbury A	-0.793	-0.810	-0.819	**-0.824**	**-0.824**	-0.814	-0.814	-0.754	-0.793	25
Wawa A	-0.581	-0.585	-0.589	-0.598	-0.610	-0.618	-0.626	-0.629	**-0.630**	23
Iroquois Falls	-0.580	-0.412	-0.349	-0.357	-0.444	-0.514	-0.522	**-0.584**	-0.575	19
Kenora A	-0.484	-0.487	-0.492	-0.502	-0.518	-0.528	**-0.537**	-0.504	-0.519	25
All 12 districts	-0.693	-0.718	**-0.720**	-0.718	-0.710	-0.695	-0.687	-0.695	-0.691	268

Case4: assign weights 0, 75%, 25% to *TI, S, frz*, respectively;
Case5: assign weights 10%, 70%, 20% to *TI, S, frz*, respectively;
Case6: assign weights 15%, 65%, 20% to *TI, S, frz*, respectively;
Case7: assign weights 15%, 60%, 25% to *TI, S, frz*, respectively;
Case8: assign weights 15%, 55%, 30% to *TI, S, frz*, respectively;
Case9: assign weights 20%, 50%, 30% to *TI, S, frz*, respectively.

4.3.4 Regional results

Considering the result of temporal difference of salt usage and winter severity with each district, the SHRP index is a good indicator of winter severity. But in Northern Ontario, the correlation result of salt usage vs. the SHRP index is not ideal. When testing other climate variables, the result comes out that temperature index, *TI*, air frost *N*, (included in the SHRP index), days with snowfall, *Nsd* and freezing rain, *frz* all together can explain quite a large proportion of the salt usage. These 4 variables are identified due to the following two reasons. First, in most districts, the temperature index, *TI*, is more highly correlated with salt usage than other temperature variables such as mean temperature or maximum temperature; days with snowfall correlated better with salt usage than total snowfall in most districts (refer back to Table 4.5); *N* is an indicator of frost information; and *frz* is an indicator of freezing precipitation, which occurs in most regions of Ontario. Secondly, when constructing a regression model with all the climate variables (in Table 4.5, exclude the winter indices) versus the salt usage for every district, using stepwise method to select variables, *TI*, *N*, *Nsd* and *frz* are selected in most of the districts. Comparisons among the r-value of the regional regression model, the original SHRP index and the modified SHRP index are summarized in Table 4.9. Coefficients of the regression model results of regional salt usage vs. those climate variables are shown in Table 4.10. Although their own regression models are different from each other, the salt usage is sensitive to those climate variables in all districts. Especially in northern Ontario, such as Iroquois Falls, the correlation coefficient of salt usage vs. the SHRP index is only 0.580; but its own regression model has a r value of 0.786. In terms of explaining the regional salt usage, results from their own regression models are better than the modified SHRP index and the original SHRP index. This suggests that the relationship between regional salt usage and climate variables is quite site-specific.

Table 4.9 Results of regression model of salt usage vs. several winter indices

Station name	MTO districts	r salt vs. SHRP	r salt vs. mSHRP	r salt vs. *TI, N, N sd, frz*	No. of cases
Ottawa Int'l A	Ottawa	-0.863	-0.919	**0.947**	25
London A	London	-0.782	-0.851	**0.908**	22
Kingston A	Kingston	-0.782	-0.831	**0.951**	10
Toronto Pears. Int'l A	central	-0.719	-0.783	**0.870**	25
Windsor A	Chatham	**-0.877**	-0.868	0.858	25
Peterborough	Bancroft	-0.556	-0.609	**0.713**	24
Owen Sound MOE	Owen Sound	-0.729	-0.713	**0.774**	23
Huntsville WPCP	Huntsville	-0.620	-0.666	**0.735**	22
Sudbury A	Sudbury	-0.793	-0.814	**0.871**	25
Wawa A	Salt Ste. Marie	-0.581	-0.626	**0.811**	23
Iroquois Falls	New Liskeard	-0.580	-0.522	**0.786**	19
Kenora A	Thunder Bay	-0.484	-0.537	**0.641**	25
All 12 districts		**-0.693**	-0.687	0.660	268

Table 4.10 Coefficients of the regression model

Station name	Constant	*TI*	*N*	*Nsd*	*frz*	r-value	Std. error
Ottawa Int'l A	1.118	5.482	-10.311	0.371	0.305	0.947	1.105
London A	-1.761	-2.812	5.588	0.367	0.871	0.908	1.152
Kingston A	2.207	4.548	-9.137	0.382	-0.509	0.951	0.785
Toronto Pears. Int'l A	1.513	4.611	-7.398	0.354	0.168	0.870	1.398
Windsor A	0.256	2.704	-1.694	0.121	0.436	0.858	1.185
Peterborough	5.394	4.332	-9.531	0.124	0.337	0.713	1.656
Owen Sound MOE	-0.561	-1.439	6.900	0.338	0.347	0.774	2.341
Huntsville WPCP	1.172	2.073	-3.044	0.345	0.532	0.735	2.068
Sudbury A	1.916	4.143	-7.838	0.244	0.244	0.871	1.214
Wawa A	6.703	6.050	-14.152	0.252	0.321	0.811	1.676
Iroquois Falls	10.494	2.415	-13.725	0.141	0.400	0.786	1.101
Kenora A	-0.818	0.095	1.494	0.106	0.147	0.641	0.888
All 12 districts	1.646	0.841	-2.526	0.370	0.033	0.660	2.084

Dependent variable: salt usage
Independent variables: temperature index TI, humidity N, days with snowfall Nsd, and days with freezing rain frz.
Std. error represents standard error of the estimate.

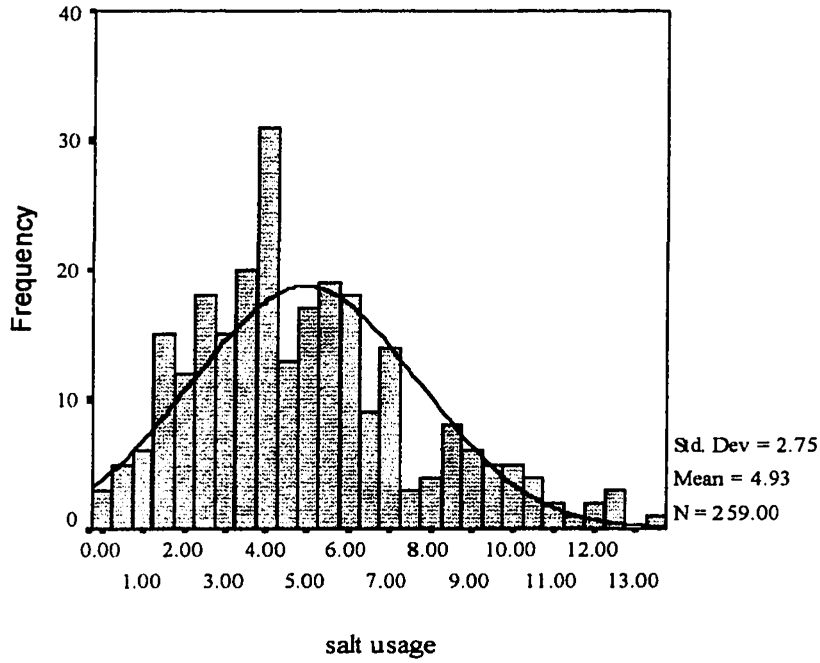


Figure 4.24 Histogram of regional salt usage with a normal curve for all 12 districts

5 Discussion and Conclusions

5.1 General conclusions and contributions

This thesis provides several important contributions to our understanding of relationships between winter weather severity and winter road maintenance activities. To the best of our knowledge, a winter weather index that is oriented to road maintenance has not been applied to Canadian data. This study provides insight into the appropriateness of established indices to the climate of Ontario. Knowledge of the spatial and temporal variation of winter road maintenance operations is limited at present. This thesis provides detailed information for winter weather severity and salt usage on provincial roads in Ontario. The results of the regression model of winter index and salt usage have wide applications for monitoring the salt usage and budget planning. More specifically, the analysis of the winter index to Ontario climate and winter road maintenance activities has allowed for the following conclusions to be drawn.

1. Both the spatial and temporal variation of winter weather severity in Ontario is quite large. Winter mean temperature (from Nov. to March) ranges from –8.4°C at Sudbury to above –1°C at Windsor. Annual winter snowfall (averaged from 1978/79 to 1997/98) ranges from 404.6 in the lee of Great Lakes area, at Owen Sound to less than 150 cm in Toronto and Kingston. The winter snowfall variation from year to year is quite large in heavy snowfall areas, and is relatively low in areas of light snowfall.

2. Among the three winter indices concerned, the SHRP winter index is most suitable for benchmarking winter road maintenance activities in Ontario. It can be used at the district level to interpret temporal differences of regional salt usage and winter severity. This index can also be used to indicate the spatial distribution of winter severity and road salt usage across the province.

   In different regions of Ontario, road salt usage on Provincial highways is related to the SHRP winter index in different ways. Generally, in districts of southern Ontario the temporal variability of salt usage is more sensitive to the SHRP index, and districts in northern Ontario are less sensitive. The correlation coefficients of salt usage vs. the SHRP index range from -0.877 in Windsor to –0.484 at Kenora.

   Weather severity is an important factor in explaining the spatial variation of salt consumption. But there are other factors as well, such as road mixture, which will affect winter salt usage. The SHRP winter index can explain 68.3% of the spatial distribution of annual salt usage for MTO districts; with a road mixture factor added, the explanation increases to 76%.

3. In terms of different time scales, our analysis indicates that monthly SHRP index works better than biweekly time scale in interpreting the temporal difference of salt usage in regional analysis. The monthly SHRP index is also easy to calculate since we can use some climate variables from the monthly archives.

4. After assigning particular weights to certain climate variables and adding a freezing precipitation variable, the modified SHRP index correlated better with salt usage than the original SHRP index did in most MTO districts. But the improvement is not very large. And for Ontario as a whole, the correlation between salt usage and modified SHRP index is slightly lower than for the original SHRP index.

5. Certain weather variables (temperature index *TI*, frosts *N*, days with snowfall *Nsd*, and days with freezing rain *frz*) can explain quite a large proportion of the temporal variation of salt usage for all the MTO districts. Especially in northern districts, their own regression models including temperature and precipitation variables are better than the models only using SHRP index in the estimation of regional salt usage. Given the very local snowfall patterns, the regression models are especially useful in estimations of the salt usage.

5.2 Practical applications of the research

The significance of the results is realized when applied to winter road maintenance planning and management procedures. Temporally, the SHRP index and the modified SHRP index can be used to monitor climatic variability and salt usage over time. The winter index can be used to assess the effectiveness and efficiency of road maintenance planning and management procedures by plotting the index vs. salt usage over years. It can be used to assess the cost-benefit of new technology (such as road weather information system) for snow removal operation by comparison of the salt usage vs. the index before and after the implementation of this new technology.

The regression model for each MTO district can be used to estimate the salt usage in the coming winter. Together with the long range climate forecast results, it can be used to estimate the "severity level" of the coming winter weather, and to help decide the salt purchases.

Spatially, it allows us to monitor the cost saving of salt usage and to compare different winter severity. Some regions have similar winter index values but quite different salt usage values. Also some regions have the same salt usage but different weather index values. This difference may due to many factors such as maintenance policy, traffic density, and topography. The SHRP index and the modified SHRP index can also be used to allocate the maintenance resources to different regions based on winter weather severity.

5.3 Limitations and Recommendations for future research

The SHRP index provides a means of assessing a winter's severity. This winter index is very useful for the managers of winter maintenance as they can compare salt usage with winter severity. It allows the maintenance practices of different time and different places comparable. This is extremely convenient for cost/benefit studies for instance to assess the benefits of the RWIS. The modified SHRP index is more suitable for Ontario's climate and road maintenance situation. It has the same application value as the SHRP index in Ontario. The regional regression model can be used to monitor the temporal difference of salt usage within each district, it is especially suitable for northern districts where the SHRP index and the modified SHRP index do not work well.

There are differences between regions; each region reacts to changes in the SHRP index in a different way. In some regions, the salt usage is more sensitive to the SHRP index than in others. In implementation, before the SHRP index is used, whether this region is sensitive to the SHRP index needs to be ascertained.

The limitations associated with the research involve using the station climate data to represent the whole district area. This can be a problem in large districts, e.g. using Peterborough for the Bancroft District. To remedy this problem, several stations in this district should be used in the analysis of the winter index. But unfortunately, the climate data of most stations located in northern Ontario for recent winters are not available.

Further research should use several stations in a relative large area and calculate the area average.

It seems that future work could concentrate upon two aspects. Firstly, there is the need to improve the estimation of the meteorological variables, such as temperature, with more road sensors. Road surface temperature can be used in future analysis instead of air temperature, and the meteorological average should be based on several stations for a relative large area. Secondly a long time period would be required for analysis or, a larger spatial scale and a more reliable system of monitoring regional salt usage. This would facilitate improved analysis of the relationship between salt usage on winter road maintenance activities and climate.

Appendices

Appendix 1 Source codes for calculation

Many calculation was done for this thesis. Included in this appendix are only the main source codes for the early-stage calculations. Much more invisible (manual) calculation was done for the post-processing by using MS EXCEL and SPSS. Each routine listed here has its own description and also summarized in table A1. Calculation was first conducted for most stations which have their data available earlier than others. Data at Peterborough arrived later, therefore it has its own source codes.

Figure A1 is a tree of most source code files. To avoid repeating, here listed are just the principle codes. Only one sample routine will be listed if there are many similar routines, the matching routines, for instance, I have 21 matching routines for data quality control but I only listed one of them. Only the codes for most stations are listed here. Codes for other special stations mentioned above are similar with these and not listed.

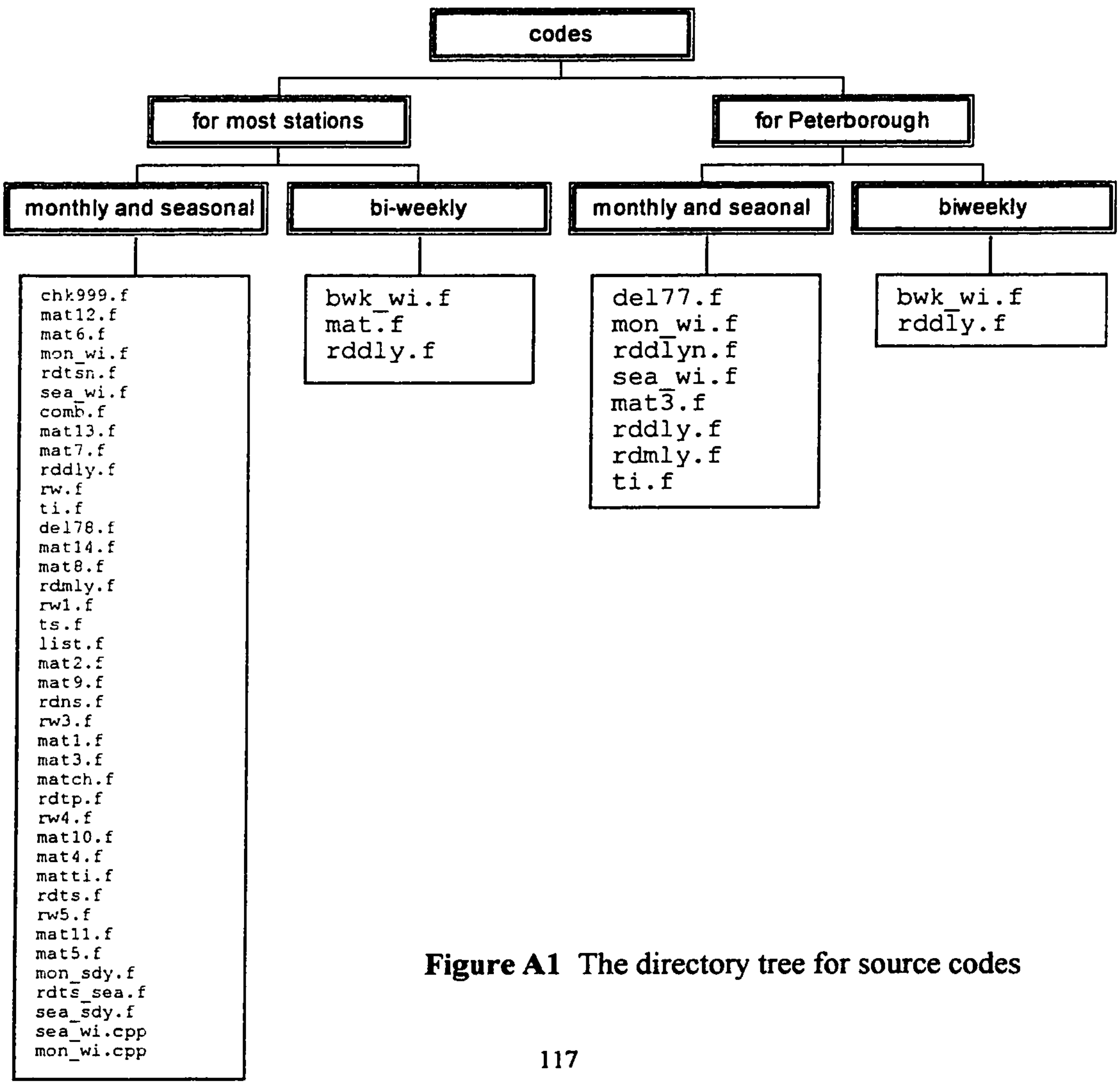


Figure A1 The directory tree for source codes

Table A1 Descriptions of principal routines for calculation

Routine name	Function
Rddly.f	Read daily archives
Rdmly.f	read monthly archives
Rdns.f	read # of snow days from monthly archive
Rdts.f	read total snowfall
Del77.f	Delete the unnecessary data in 1977.
chk9999.f	a sample code for removing missing data
match .f	match different files to insure all the variables used are associated with the same time period.
mon_wi .f	to calculate monthly winter index (coded in FORTRAN)
sea_wi .f	to calculate the seasonal winter index (coded in FORTRAN)
mon_wi .cpp	to calculate monthly winter index (coded in C++)
sea_wi .cpp	to calculate the seasonal winter index (coded in C++)
biweek_wi.f	to calculate the biweekly winter indices and other related climatological variables

Appendix 2 Seasonal winter indices

Seasonal SHRP winter index from 1978/79 to 1997/98

Station name	dis.	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	mean
Ottawa Int'l A	42	-29.67	-21.89	-24.9	-29.65	-15.6	-33.91	-30.76	-27.29	-25.25	-28.84	-28.42	-30.64	-26.1	-33.31	-38.5	-34.56	-21.12	-36.06	-38.79	-27.25	-29.13
London A	31	-22.24	-16.38	-24.77	-30.32	-12.6	-30.29	-30.7	-29.49	-23.1	-23.69	-18.97	-27.11	-23.5	-27	-27.2	-20.45	-17.36	-24.35	*	*	-23.86
Kingston A	41	-27.19	-11.49	-15.79	-22	-6.04	-25.43	-25.3	-29.23	-15.2	-16.81	-15.85	-22.16	-16.33	-20.32	-29.5	-25.91	-9.65	*	*	*	-19.66
Toronto Pear. A	20	-15.58	-11.71	-10.57	-18.22	-6.68	-19.4	-20.58	-13.84	-14.83	-10.06	-8.5	-10.59	-10.38	-12.41	-18.96	-14.97	-8.19	-20.38	-19.27	-8.98	-13.71
Windsor A	32	-11.08	-9.63	-10.47	-21.97	1.51	-17.05	-17.56	-20.61	-12.95	-12.55	-7.28	-11.16	-7.36	-15.8	-16.37	-15.77	-7.7	-17.62	-19.8	-6.08	-12.87
Peterborough	43	-20.09	-16.77	-17.05	-24.91	-5.45	-25.9	-21.97	-22.38	-19.13	-20.54	-17.9	-19.54	-21.41	-22.32	-29.55	-19.84	-16.83	*	-26.33	-18.33	-20.33
Owen Sound	33	-46.62	-28.15	-41.55	-39.24	-16.79	-43.78	-41.09	*	-28.44	-34.68	-38.04	-40.03	-24.39	-30.8	-31.09	-40.83	-31.23	-47.84	-48.63	*	-36.29
Huntsville WPCP	52	*	*	-39.26	*	-24.08	-45.3	*	*	-32.03	-33.45	-39.61	*	-36.46	-34.24	-32.49	-30.67	*	-38.87	-37.13	*	-35.30
Sudbury A	54	-39.61	-30.89	-39.43	-37.02	-29.32	-35.61	-40.96	-33.97	-32.55	-39.77	-34.82	-34.85	-32.43	-36.56	-28.96	-32.52	-23.43	-38.35	-42.89	-29.7	-34.87
Wawa A	62	*	*	*	-35.38	-35.21	*	-37.69	-40.61	-34.5	-39.36	-47.5	-39.6	-31.7	-36.79	-37.08	-38.64	-26.84	*	*	-30.76	-36.54
Iroquois Falls	53	*	-24.71	-28.29	-24.16	-25.02	-25.68	-26.69	-23.26	*	-32.36	-31.72	-35.24	-28.41	-27.72	-25.49	-24.31	*	-34.05	-35.82	*	-28.31
Kenora A	61	-28.09	*	-13.32	-20.44	-20.87	-24.08	-23.9	-28.33	-25.49	-23.85	-29.65	-22.44	-22.31	-25.48	-24.21	-16.59	-20.32	-29.14	-34.18	-19.65	-23.83

Seasonal modified HULME winter index from 1978/79 to 1997/98

Station name	dis.	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	mean
Ottawa Int'l A	42	-51.06	-37.66	-52.14	-54.68	-22.58	-54.89	-44.15	-50.05	-36.95	-39.89	-41.62	-51.12	-30.46	-56.37	-51.14	-65.52	-22.14	-62.54	-49.75	-31.29	-45.30
London A	31	-25.42	-21.1	-23.77	-32.35	10.45	-29.05	-11.69	-21.35	-10.58	-7.59	-7.72	-13.19	1.25	-11.75	-18.95	-34.88	3.86	-35.12	*	*	-16.05
Kingston A	41	-34.3	-16.72	-29.02	-32.5	6.62	-35.28	-17.25	-30.42	-12.16	-13.66	-17.82	-22.5	-2.02	-24.86	-27.05	-39.46	-0.95	*	*	*	-20.55
Toronto Pearson A	20	-21.65	-15.13	-19.06	-28.18	7.4	-28.5	-10.77	-19.72	-3.9	-5.26	-6.65	-10.05	8.34	-7.95	-16.86	-29.78	9.54	-33.61	-13.29	9.31	-11.79
Windsor A	32	-10.06	0.74	-1.21	-12.69	27.74	-13.02	7.55	-0.48	11.04	10.9	14.64	8.45	22.89	7.47	-1.69	-10.22	22.68	-15.68	1.7	24.59	4.77
Peterborough	43	-35.01	-27.7	-32.37	-39.26	-2.16	-40.26	-23.94	-34.09	-17.73	-18.72	-21.94	-26.88	-9.39	-29.48	-32.79	-46.62	-4.33	*	-30.02	-8.9	-25.35
Owen Sound MOE	33	-28.72	-21.37	-24.4	-27.79	7.38	-30.09	-15.08	*	-11.26	-10.22	-14.35	-19.86	-2.3	-17.18	-21.88	-39.79	1.1	-39.89	-20.23		-18.66
Huntsville WPCP	52	*	*	-49.42	*	-19.69	-51.99	*	*	-27.7	-31.61	-35.68	*	-24.45	-41.28	-39.06	-58.18	*	-54.22	-43.05	*	-39.69
Sudbury A	54	-85.58	-68.02	-74.86	-77.25	-51.01	-78.92	-69.52	-78.03	-48.52	-62.91	-68.2	-75.71	-54.25	-74.05	-71.72	-95.75	-50.18	-93.48	-77.88	-50.99	-70.34
Wawa A	62	*	*	*	-79.83	-58.74		-72.4	-80.69	-48.57	-70.09	-75.71	-72.92	-57.48	-68.77	-72.59	-95.57	-49.41	*	*	-50.92	-68.12
Iroquois Falls	53	*	-82.46	-80.06	-85.3	-75.14	-96.1	-89.86	-100.02	*	-90.54	-96.05	-90.35	-76.21	-92.25	-91.5	-114.18	*	-112.45	-104.68	*	-92.32
Kenora A	61	*	*	-81.01	-109.48	-80.66	-103.12	-103.86	-109.98	-72.32	-94.79	-109.83	-98	-95.37	-88.89	-99.32	-114.48	-77.17	-133.95	-122.23	-67.35	-97.88

Seasonal salt days winter index from 1978/79 to 1997/98

Station name	dis.	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	mean
Ottawa Int'l A	42	19	10	20	13	12	20	18	19	15	17	24	14	15	11	16	14	16	18	26	20	16.9
London A	31	19	18	22	12	10	18	23	23	16	17	18	16	18	17	18	12	16	23	*	*	17.6
Kingston A	41	9	16	17	12	8	17	17	22	11	8	23	13	12	15	13	10	11	*	*	*	13.8
Toronto Pearson A	20	11	11	13	9	5	14	13	15	9	5	10	10	11	9	11	11	12	13	14	11	10.9
Windsor A	32	11	14	11	12	5	12	11	15	6	9	8	13	9	11	7	10	10	17	18	6	10.8
Owen Sound MOE	33	26	23	21	18	16	25	22	*	21	23	34	23	21	20	25	18	18	34	33		23.4
Huntsville WPCP	52	*	*	18	*	16	16	*	*	13	15	23	*	21	16	17	8		23	26	*	17.7
Sudbury A	54	13	21	20	15	21	18	17	16	21	19	18	14	21	17	16	11	10	12	18	18	16.8
Wawa A	62	*	*	*	19	16	*	8	16	18	18	16	20	17	21	18	12	13	*	*	19	16.5
Iroquois Falls	53	*	9	12	8	8	4	10	6	*	11	6	8	9	13	6	15	*	6	10	*	8.8
Kenora A	61	8	*	5	16	10	12	7	11	13	11	11	13	9	13	13	7	7	9	14	11	10.5

*NOTE: * represents missing data in all tables.*

Appendix 3 Monthly winter indices and climate variables

Monthly SHRP index and climate variables from Nov.1993 to Mar.1998.

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-01	96-02	96-03	96-11	96-12	97-01	97-02	97-03	97-11	97-12	98-01	98-02	98-03
Ottawa Int'l A	42	-5.6	-29.58	-47.09	-46.4	-34.79	1.1	-20.14	-41.58	-33.05	-1.6	-44.12	-50.79	-37.74	-22.41	-14.82	-10.85	-37.78	-49.28	-40.48	-45.78	-26.53	-26.94	-46.74	-6.5	-19.77
London A	31	4.9	-10.38	-33.81	-31.2	-23.9	4.6	-19.9	-24.0	-38.89	0.7	-22.0	-29.63	-25.86	-15.53	-27.37	-20.39	-25.34	-35.0	•	-23.06	-7.9	-21.49	-27.9	•	•
Kingston A	41	5.9	-12.27	-40.74	-42.0	-28.2	13.5	-5.7	-18.56	-28.89	-1.6	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Toronto Pearson A	20	9.6	-3.0	-30.06	-24.2	-18.87	8.4	-11.5	-19.12	-16.29	2.4	-17.0	-27.62	-20.11	-9.3	-25.39	-0.2	-16.33	-32.75	-14.63	-25.7	-5.2	-7.3	-18.41	4.1	-13.8
Windsor A	32	15.3	-5.14	-38.52	-33.2	-1.7	27.8	-13.9	-26.44	-18.28	5.1	0.4	-22.08	-19.76	-11.55	-30.23	-11.7	-18.42	-38.13	-20.1	-4.7	-3.0	-12.89	-16.32	13.8	-7.1
Peterborough	43	7.8	-13.24	-35.21	-23.4	-25.64	-2.2	-19.58	-32.76	-23.38	-0.4	•	-32.33	-22.33	-5.3	-24.0	-17.6	-16.52	-40.71	-16.09	-34.43	-16.7	-16.36	-31.71	-1.2	-20.0
Owen Sound	33	-1.1	-46.59	-62.17	-47.8	-26.33	1.1	-2.8	-52.18	-62.3	-7.2	-44.39	-71.61	-44.47	-32.35	-33.0	-35.78	-34.21	-69.0	-43.42	-51.0	-9.8	-24.8	-48.53	•	•
Huntsville	52	-10.68	-29.81	-51.75	-36.9	-12.5	-16.2	•	-47.77	-43.47	-4.9	-47.57	-56.51	-36.17	-15.42	-26.74	-20.3	-33.15	-49.31	-40.32	-38.36	-29.31	-22.26	-45.23	•	•
Sudbury A	54	-33.44	-31.41	-41.5	-32.0	-22.3	-2.7	-25.31	-28.6	-30.86	-25.38	-43.37	-42.93	-38.5	-43.87	-18.77	-16.63	-50.54	-57.14	-49.75	-29.31	-19.83	-28.57	-44.35	-19.47	-31.1
Wawa A	62	-24.86	-41.18	-54.14	-31.78	-35.24	-12.73	-16.17	-30.13	-47.16	-20.06	•	-37.8	-59.68	-50.8	-30.66	-12.26	-60.07	-53.24	-30.03	•	-31.87	-36.19	-45.94	-21.54	-12.0
Iroquois Falls	53	-22.64	-25.77	-23.0	-14.2	-33.45	•	-27.26	-29.42	-38.36	-24.54	-39.2	-29.88	-39.84	-36.42	-22.2	-18.89	-44.84	-50.99	-21.59	-34.17	•	•	•	•	•
Kenora A	61	-18.62	-21.67	-19.83	-8.9	-12.85	-9.3	-27.45	-35.9	-19.0	-5.0	-38.0	-33.0	-23.76	-26.0	-23.32	-52.81	-44.12	-19.58	-16.06	-25.0	-31.36	-15.08	-30.01	-11.51	-6.07

Temperature range (TI)

Station name	district	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-03
Ottawa Int'l A	42	0.93	1.35	1.9	1.79	1.19	0.7	1.42	1.68	1.75	0.94	1.27	1.87	1.71	1.59	1.32	1.27	1.26	1.81	1.79	1.45	1.13	1.74	1.74	1.29	1
London A	31	0.67	1.19	1.81	1.64	1.19	0.57	1.06	1.35	1.64	0.9	0.93	1.65	1.52	1.24	1.35	1.07	1.06	1.39	•	1.13	0.77	1.16	1.26	•	•
Kingston A	41	0.7	0.9	1.84	1.79	1.29	0.53	0.97	1.32	1.64	0.84	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Toronto Pears. A	20	0.63	1.1	1.71	1.71	1.1	0.53	0.84	1.35	1.61	0.87	0.93	1.68	1.48	1.34	1.39	0.9	0.97	1.48	1.36	1.13	0.7	1.03	1.23	1	0.9
Windsor A	32	0.5	1.03	1.71	1.57	0.77	0.23	0.87	1.35	1.5	0.77	0.8	1.52	1.52	1.21	1.35	0.83	0.97	1.42	1.32	0.77	0.53	0.94	1.03	0.61	0.68
Peterborough	43	0.83	1.32	1.87	1.79	1.23	0.67	1.26	1.58	1.68	1	•	1.77	1.58	1.41	1.39	1.1	1.03	1.71	1.5	1.29	1	1.39	1.32	1.04	1.06
Owen Sound	33	0.67	1	1.81	1.75	1.26	0.5	0.87	1.39	1.71	1	1.03	1.71	1.65	1.55	1.52	0.97	0.84	1.55	1.54	1.32	0.7	1	1.35	•	•
Huntsville	52	0.97	1.35	1.94	1.79	1.19	0.73	•	1.45	1.75	1.16	1.33	1.94	1.68	1.55	1.42	1.17	1.39	1.77	1.75	1.52	1.07	1.58	1.71	•	•
Sudbury A	54	1.47	1.55	2	1.86	1.52	0.93	1.39	1.9	1.93	1.19	1.7	1.97	1.81	1.79	1.58	1.33	1.65	1.97	1.89	1.58	1.27	1.81	1.94	1.5	1.29
Wawa A	62	1.43	1.52	2	1.86	1.55	1.03	1.1	1.94	1.89	1.23	•	1.94	1.94	1.83	1.58	1.47	1.87	1.94	1.86	•	1.3	1.74	1.9	1.36	1.39
Iroquois Falls	53	1.7	1.77	2	1.86	1.68	•	1.55	1.97	1.96	1.42	1.03	1.68	1.52	1.31	1.39	0.97	1	1.45	1.46	1.16	•	•	•	•	•
Kenora A	61	1.63	2	2	1.89	1.39	1.03	1.74	1.97	1.96	1.1	1.8	2	1.97	1.86	1.74	1.8	2	1.97	1.89	1.71	1.7	1.84	2	1.32	1.42

Snowfall (S, is the mean daily value in millimeters)

Station name	Distr.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	4.6	13.68	24.26	24.21	19.29	4.53	7.68	20.06	13.71	3.55	27.13	26.26	17.81	8.41	6.06	4.2	19.55	26.9	19.07	27.16	14.4	9.48	24	2.79	11.42
London A	31	2.6	4.71	13.61	13.64	11.1	3.93	10.19	10.84	18.36	3.1	12.47	11.29	10.9	7.48	13.1	10.53	13.03	18.58	•	11.61	7.2	8.84	13.29	•	•
Kingston A	41	2.27	8.71	19.68	20.29	12.84	1.13	4.52	8	11.64	4.19	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Toronto Pearson A	20	1.27	2.84	12.19	8.86	9.35	3.07	8.71	7.94	5.21	2.58	9.07	9.87	8.06	3.66	11.1	2.27	9.1	15.74	5.86	13.42	6.4	3.94	7.74	0.5	9.03
Windsor A	32	0.53	3.81	17.35	15.29	4.45	0	8.84	11.81	6.29	2.45	2.8	7.87	7.16	5.93	14.39	7.53	9.35	20.45	7.93	5.81	6.73	6.94	8.52	0	7.61
Peterborough	43	0.53	5.48	15.68	8.93	12.52	6.27	9.29	14.77	9	2.84	•	12.71	9.39	2.41	10.65	8.87	8.26	20.23	6.18	18.58	9.07	5.68	15.87	2.43	11.1
Owen Sound MOE	33	4.7	34.77	41.45	26.07	12.48	7	4.35	35	42.32	5.1	29.13	56.13	23.19	14.28	14.52	22.37	23.74	59.19	22.43	33.39	8	11.97	29.29	•	•
Huntsville WPCP	52	6.13	13.74	30.13	17.86	6.23	13.13	•	29.71	23.21	3.35	30.23	33.06	17.65	5.76	12.42	9.77	14.65	28.19	19.57	20.1	15.67	8.03	23.06	•	•
Sudbury A	54	15.2	13.35	19.35	12.93	8.77	3.4	10.84	9.48	12.04	13.23	21.07	19.03	18.19	22.69	6.97	6.87	27.9	35.1	28.07	13.06	8.57	10.42	20.9	6.93	16.68
Wawa A	62	10.2	22.13	33.16	14	16.77	8.07	8.58	10.77	26.21	9.87	•	16.13	41.1	31.14	14.39	4.2	37.03	31.94	12.43	•	15.87	15.16	23.23	8.93	5.48
Iroquois Falls	53	7.9	9.55	8.19	4.57	15.16	•	10.65	11.32	18.11	12.03	9.13	7.55	11.97	7.52	19.16	6.73	10.84	15.48	6.14	9.55	•	•	•	•	•
Kenora A	61	5.77	5.61	5.35	1.79	4.9	5.43	9.55	13.84	5.64	3.74	15.83	11.71	7.26	9	8.65	28.9	19.48	5.19	4.5	9.32	11.17	3.42	9.55	4	2.52

Appendix 3 (continued)

Number of air frosts (N)

Station name	district	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	0.77	0.94	1	0.96	0.94	0.53	0.94	0.94	1	0.74	0.87	1	0.97	0.97	0.97	0.93	0.9	1	1	0.94	0.73	0.97	0.97	0.93	0.74
London A	31	0.6	0.81	1	0.93	0.97	0.5	0.81	0.77	1	0.71	0.77	0.94	0.9	0.76	0.9	0.77	0.81	0.84	*	0.87	0.6	0.9	0.81	*	*
Kingston A	41	0.57	0.61	0.97	0.96	1	0.5	0.74	0.81	1	0.68	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toronto Pearson A	20	0.6	0.74	1	0.96	0.87	0.47	0.61	0.81	1	0.71	0.8	0.97	0.9	0.86	0.97	0.77	0.71	0.9	0.93	0.84	0.6	0.84	0.87	0.82	0.71
Windsor A	32	0.5	0.68	1	0.89	0.68	0.23	0.68	0.81	1	0.61	0.73	0.94	0.94	0.72	0.97	0.73	0.81	0.87	0.96	0.65	0.53	0.74	0.71	0.57	0.58
Peterborough	43	0.77	0.94	1	0.96	0.97	0.57	0.9	0.9	1	0.84	*	1	0.94	0.86	1	0.83	0.81	1	0.96	0.97	0.83	1	0.87	0.86	0.81
Owen Sound	33	0.57	0.68	1	0.93	0.9	0.33	0.58	0.74	0.96	0.74	0.87	0.97	0.97	0.93	0.97	0.73	0.58	0.9	1	0.9	0.6	0.87	0.9	*	*
Huntsville	52	0.8	0.97	1	0.96	0.9	0.53	*	0.84	0.96	0.94	0.87	1	0.97	0.97	1	0.8	0.94	1	1	0.97	0.87	0.97	0.97	*	*
Sudbury A	54	0.97	0.97	1	0.96	1	0.77	0.87	1	1	0.87	1	1	0.97	1	0.97	0.83	0.97	1	1	0.97	0.87	1	0.97	1	0.84
Wawa A	62	0.97	0.94	1	0.96	1	0.67	0.77	1	1	0.87	*	1	1	1	1	0.87	1	1	1	*	0.9	1	1	0.93	0.87
Iroquois Falls	53	1	1	1	0.96	1	*	1	0.97	0.96	0.9	0.8	0.97	0.9	0.83	0.97	0.77	0.74	0.9	0.82	0.87	*	*	*	*	*
Kenora A	61	1	0.97	1	1	1	0.77	1	1	1	0.77	1	1	1	1	0.97	0.97	1	1	1	1	1	1	1	0.89	0.9

Temperature range (R)

Station name	district	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	8.2	8	10.2	9.1	9.3	8.9	7.5	7.3	9.6	10.5	7.8	7.1	10.1	9.3	9.7	7.5	5.7	9.7	9.9	9.4	6.8	7.4	7.5	8.7	8.2
London A	31	7.5	6.4	8.9	9.6	8.5	8.1	7	6.3	8.9	10.9	6.5	6.4	8.8	7.8	9.6	6.5	5.9	8.9	*	8.4	6.8	4.7	5.8	*	*
Kingston A	41	7.3	7.6	10.9	9.1	8.5	8.7	7.9	6.9	9.5	9.7	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toronto Pearson A	20	7.7	7.5	10.1	9.4	8.3	8.9	7.7	6.3	9.1	10.6	5.9	6.7	9.1	7.4	9.4	6.4	5.8	9.1	9.1	8.1	6.9	6.2	6.3	7.4	8.5
Windsor A	32	7.3	5.5	8.4	8.4	9	7.8	6.2	5.8	8.2	10.1	7	6.6	7.9	7.6	9.3	6.2	5.5	8.5	7.4	8.5	5.8	4.8	5.2	6.3	7
Peterborough	43	9.3	9.5	12.9	12.6	10.3	10.9	10.5	8.3	11.8	13	*	8.5	12.2	9.6	11.3	8.1	6.2	10.8	10.9	10.9	8.4	7.5	7.9	10.3	9.5
Owen Sound MOE	33	5.7	5.8	8	8.5	8.2	6.6	6.1	5.2	6.8	8.4	6.4	5.6	8.5	7.9	7.7	5.4	4.1	8.6	7.9	7.2	4.8	4.7	6.1	*	*
Huntsville	52	7.2	8.4	12.8	13.2	10.9	8.2	*	8	11.9	12.3	7.8	8.6	12.3	11.3	12.2	6.9	5.5	11.3	10.7	11.1	7.1	8.2	7.9	*	*
Sudbury A	54	7.8	7.9	11.9	10.2	10.3	7.9	6.9	7.5	11.6	10	7.8	8.2	11.2	11.4	10.5	7	6.5	10.8	12.2	11.3	7.1	9	8.5	8.5	9.7
Wawa A	62	8.3	9.5	14.4	14.2	10.3	8.7	8.3	9.2	14	10.3	*	10.1	14.4	15	13.4	7	7.1	13	13.5	*	7.9	7.8	10.3	8.1	11.9
Iroquois Falls	53	9.5	10.6	15.3	13.7	11.7	*	8.1	12.1	13.9	13.4	6.3	6.5	9.3	8.1	9	7.5	5.6	8.7	8.8	8.4	*	*	*	*	*
Kenora A	61	7.7	6.7	9.2	10.3	10.3	7.2	7.4	8.2	11.3	9.1	7.3	7.9	9.2	9.8	10.9	6.4	7.6	8.6	10.7	10.3	5.5	7.1	6.8	5.8	9.8

Note: * is missing data.

Appendix 3 (continued)

Monthly modified Hulme index from Nov.1993 to Mar.1998.

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	18.5	-59.7	-166.7	-105.4	-13.9	59.2	-41.5	-68.7	-90.2	30.9	-17.5	-97.1	-102.7	-76.7	-18.5	-7.9	-30.9	-107.4	-67.5	-34.8	1.6	-60.9	-77.9	-24.8	5.9
London A	31	42.5	-30.7	-107.7	-70.9	-7.2	73.8	2.7	-31.2	-65.7	40.5	8.8	-57.5	-60.1	-45.7	-21.1	8.8	-12.8	-51.1	•	8.3	27.1	-26.2	-20.5	•	•
Kingston A	41	43.7	-16.1	-119.8	-85.5	-18.5	74.5	-1.2	-35.1	-70.2	28.2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
TorontoPears.A	20	47.7	-17.3	-111.1	-68.7	1.7	79.8	12.9	-29.9	-60.9	46.7	9.1	-54.1	-55.2	-51.1	-16.7	13.2	-3.2	-53.1	-17.5	-5.4	36.2	-9.3	-23.2	7.7	36.1
Windsor A	32	58.7	-15.1	-88.1	-43.9	38.8	102	19.8	-24.7	-38.3	58.2	24.7	-36.2	-38.7	-24.5	-3.5	21.5	-5.9	-40.5	-5.5	39.3	37.9	-0.1	-0.1	37.0	51.7
Peterborough	43	29.2	-37.2	-131.8	-87.1	-5.4	67.8	-8.1	-48.1	-74.5	42.2	•	-77.2	-70.7	-59.5	-16.7	-2.5	-15.1	-75.7	-35.7	-21.1	19.7	-30.9	-41.5	-6.3	15.6
Owen Sound	33	35.8	-19.2	-116.2	-85.2	-13.3	77.2	11.8	-26.4	-73.9	18.2	1.9	-54.3	-57.9	-58.2	-30.7	11.1	-7.7	-52.4	-34.1	-17.9	28.9	-17.2	-30.8	•	•
Huntsville	52	9.5	-53.5	-149.7	-90.7	-6.1	53.5	•	-46.1	-82.5	27.8	-17.1	-84.2	-81.1	-66.8	-21.5	-8.1	-32.9	-89.7	-55.2	-29.1	8.5	-37.7	-55.5	•	•
Sudbury A	54	-33.4	-83.4	-196.2	-131.2	-34.5	17.8	-44.5	-93.4	-114.9	-15.5	-59.8	-118.7	-126.2	-102.1	-60.5	-27.2	-73.5	-144.5	-90.7	-53.2	-18.7	-66.9	-102.2	-40.8	-25.9
Wawa A	62	-32.7	-79.7	-193.8	-126.9	-44.7	19.5	-22.5	-104.5	-110.5	-28.5	•	-114.1	-138.5	-111.8	-65.5	-35.7	-90.7	-127.7	-91.1	•	-26.5	-63.7	-107.5	-27.3	-29.3
Iroquois Falls	53	-56.5	-103.9	-221.5	-149.3	-39.7	•	-62.1	-123.9	-148.5	-33.1	-68.7	-128.4	-165.1	-125.5	-74.1	-53.5	-99.5	-169.9	-124.5	-75.3	•	•	•	•	•
Kenora A	61	-59.1	-121.7	-227.4	-147.5	-16.7	-2.9	-86.9	-137.8	-133.8	-24.1	-95.2	-153.8	-205.2	-130.4	-85.1	-98.3	-165.3	-177.5	-108.4	-61.5	-66.9	-72.3	-127.7	-40.5	-28.8

Mean maximum temperature (Tmax)

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	4.6	-2.4	-12.9	-7.2	2.1	8	-0.7	-3.3	-5.6	5.9	1.5	-5.9	-6.6	-4.3	1.7	2.6	0.4	-6.9	-3.3	0.1	3	-2.5	-4.1	0.6	3.5
London A	31	6.5	0	-7	-3.9	2.9	9.3	3.3	-0.1	-3.1	6.7	3.8	-2.2	-2.6	-1.8	1.3	3.8	1.9	-1.8	•	4.1	5.1	0.8	1.1	•	•
Kingston A	41	6.4	0.8	-8.3	-5.3	1.8	9.4	2.6	-0.4	-3.6	5.3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
TorontoPears.A	20	6.9	1.1	-7.3	-3.6	3.4	9.8	3.7	0.1	-2.7	7.2	3.9	-1.8	-2.1	-2.1	1.9	4.1	2.5	-1.8	1.4	2.7	5.9	2.2	1	3.4	6.4
Windsor A	32	7.7	1.2	-5	-1.3	6.4	10.9	4.5	0.6	-0.5	8.1	5.2	-0.1	-0.4	0.2	3.3	4.8	2.5	-0.7	2.7	6.5	5.9	2.8	2.8	5.3	7.5
Peterborough	43	5.6	-0.2	-9.4	-5.4	3.1	8.9	2.5	-1.4	-4	7.2	•	-4	-3.6	-2.9	2	2.8	1.6	-3.8	-0.3	1.5	5	0.6	-0.8	2.1	4.7
Owen Sound	33	5.7	0.8	-7.8	-5.3	2	9.1	3.4	0.3	-4	4.6	3.5	-1.7	-2.1	-2.5	0.5	3.9	1.7	-1.7	0	1.6	5.2	-1.6	0.4	•	•
Huntsville	52	3.8	-1.8	-11.2	-5.8	2.7	7.4	•	-1.4	-5	6.1	1.6	-4.7	-4.5	-3.4	1.5	2.1	0.3	-5.2	-2.1	0.7	4	-0.2	-1.9	•	•
Sudbury A	54	0.2	-4.7	-15.9	-9.8	0.2	4.5	-1.2	-5.6	-8.1	1.7	-2.3	-8.1	-9	-6.7	-2.5	0.4	-3.6	-10.6	-5.6	-1.7	1.3	-3	-6.5	-0.8	0.6
Wawa A	62	0.3	-4.4	-15.6	-9.4	-0.8	4.4	0.7	-6.7	-7.6	0.4	•	-7.7	-10.1	-7.6	-2.9	-0.4	-5.2	-8.9	-5.7	•	0.7	-2.7	-7	0.4	0.3
Iroquois Falls	53	-2.1	-6.7	-18.5	-11.7	-0.3	•	-2.5	-8.8	-11.6	0	-3.7	-9.8	-13.4	-9.5	-3.8	-1.9	-6.2	-13.2	-9.2	-3.9	•	•	•	•	•
Kenora A	61	-2.3	-8.6	-19	-11.4	2	2.6	-4.9	-10	-9.9	0.5	-5.8	-11.6	-16.8	-9.5	-4.9	-6.2	-12.7	-14	-7.4	-2.4	-3	-3.6	-9	-1	0.4

Number of ground frosts (Ngf)

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	23	29	31	27	29	16	29	29	28	23	26	31	30	28	30	28	28	31	28	29	22	30	30	26	23
London A	31	18	25	31	26	30	15	25	24	28	22	23	29	28	22	28	23	25	26	31	27	18	28	25	•	•
Kingston A	41	17	19	30	27	31	15	23	25	28	21	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Toronto Pears.A	20	18	23	31	27	27	14	19	25	28	22	24	30	28	25	30	23	22	28	26	26	18	26	27	23	22
Windsor A	32	15	21	31	25	21	7	21	25	28	19	22	29	29	21	30	22	25	27	27	20	16	23	22	16	18
Peterborough	43	23	29	31	27	30	17	28	28	28	26	•	31	29	25	31	25	25	31	27	30	25	31	27	24	25
Owen Sound	33	17	21	31	26	28	10	18	23	27	23	26	30	30	27	30	22	18	28	28	28	18	27	28	•	•
Huntsville	52	24	30	31	27	28	16	•	26	27	29	26	31	30	28	31	24	29	31	28	30	26	30	30	•	•
Sudbury A	54	29	30	31	27	31	23	27	31	28	27	30	31	30	29	30	25	30	31	28	30	26	31	30	28	26
Wawa A	62	29	29	31	27	31	20	24	31	28	27	•	31	31	29	31	26	31	31	28	•	27	31	31	26	27
Iroquois Falls	53	30	31	31	27	31	•	31	30	27	28	25	24	25	26	31	30	31	31	27	31	•	•	•	•	•
Kenora A	61	30	30	31	28	31	23	31	31	28	24	30	31	31	29	30	29	31	31	28	31	30	31	31	25	28

Appendix 3 (continued)

Number of snow days (Nsd)

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	5	16	16	14	11	6	9	16	13	7	15	19	16	10	9	11	18	22	15	17	14	11	18	6	12
London A	31	5	10	16	11	13	4	8	13	16	5	13	15	12	10	12	13	17	19	*	10	11	13	15	*	*
Kingston A	41	2	7	17	9	9	5	4	12	13	3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toronto Pears.A	20	2	8	19	10	8	4	7	11	11	2	11	12	13	7	10	6	13	19	9	14	6	8	13	2	11
Windsor A	32	2	12	19	11	4	0	4	10	8	3	8	13	10	9	15	5	11	15	9	10	7	7	12	0	8
Peterborough	43	3	13	17	12	14	4	7	12	15	3	*	13	10	9	10	9	12	16	10	12	8	11	15	2	14
Owen Sound	33	4	13	20	13	8	3	4	14	18	6	19	21	18	13	10	11	16	22	12	11	7	13	17	*	*
Huntsville	52	5	9	16	10	7	5	*	12	9	4	19	13	12	6	9	7	18	16	13	12	9	10	15	*	*
Sudbury A	54	14	14	13	13	9	4	9	14	11	9	17	16	13	12	9	13	23	23	16	13	10	11	20	6	11
Wawa A	62	16	16	17	11	10	5	9	15	15	9	*	12	15	17	9	10	25	25	12	*	15	10	15	8	8
Iroquois Falls	53	9	11	9	8	10	*	12	11	9	7	12	13	12	9	13	10	12	17	6	11	*	*	*	*	*
Kenora A	61	12	10	14	9	10	11	18	17	17	7	20	17	13	14	12	21	21	15	14	15	18	8	16	9	6

Monthly salt days index from Nov.1993 to Mar. 1998.

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	1	3	2	1	7	1	4	6	2	3	7	6	1	2	3	2	7	5	7	5	6	6	7	1	4
London A	31	0	1	2	4	5	1	3	5	4	3	7	2	4	3	7	*	*	*	*	*	*	*	*	*	*
Kingston A	41	1	3	2	3	3	1	2	2	5	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toronto Pears.A	20	2	0	1	3	5	2	2	2	4	2	1	3	3	1	6	1	2	7	2	4	3	2	3	0	4
Windsor A	32	0	1	3	5	2	0	2	5	2	1	1	4	3	4	5	1	3	9	4	1	1	0	4	0	1
Owen Sound	33	0	6	6	3	4	0	2	7	6	3	7	9	7	3	8	3	8	11	7	7	*	*	*	*	*
Huntsville	52	0	1	3	1	3	*	*	*	*	*	10	4	3	4	4	3	7	5	8	5	*	*	*	*	*
Sudbury A	54	5	2	0	0	4	2	3	4	2	0	4	3	3	1	2	4	7	3	0	4	5	6	4	2	3
Wawa A	62	5	3	0	0	4	2	2	3	5	1	*	*	*	*	*	*	*	*	*	*	6	5	2	3	3
Iroquois Falls	53	6	5	0	0	5	*	*	*	*	*	3	0	1	1	1	4	5	1	1	0	*	*	*	*	*
Kenora A	61	2	2	0	0	3	1	3	4	0	1	3	0	0	3	4	6	4	0	1	4	5	4	1	1	0

Monthly salt usage (ton per saltable 2-lane km) from Nov.1993 to Mar.1998.

Station name	Dis.	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	0.60	5.35	8.94	5.77	3.58	1.24	9.07	5.06	7.09	5.05	7.09	8.65	6.82	4.89	1.21	2.03	6.27	11.84	10.44	5.85	5.64	6.16	10.30	1.67	5.44
London A	31	1.29	3.59	6.64	4.79	1.51	3.65	8.01	5.64	4.12	6.85	6.94	6.19	6.82	*	*	3.60	6.66	11.33	7.49	4.86	2.30	4.23	5.63	1.23	4.04
Kingston A	41	0.55	3.95	5.86	4.02	2.04	0.86	2.50	4.77	4.05	*	5.45	4.58	5.29	5.38	*	1.90	3.76	9.62	6.11	4.21	3.66	4.42	9.70	2.54	4.69
Toronto Pears.A	20	0.42	2.47	12.46	6.20	3.06	4.51	4.21	4.48	5.30	*	4.46	5.15	5.57	5.86	4.26	2.19	4.22	9.83	6.40	3.90	2.60	3.01	6.54	1.20	3.15
Windsor A	32	0.31	2.78	7.15	2.82	0.10	2.48	6.07	2.68	3.76	1.55	2.29	5.10	3.40	*	*	2.70	3.85	8.10	5.82	1.68	2.03	3.33	4.46	0.23	3.06
Peterborough	43	1.46	3.93	4.89	6.87	2.09	2.13	2.57	3.98	2.63	5.09	8.25	5.09	5.05	5.48	1.49	4.24	5.86	10.03	3.98	4.50	5.86	5.48	7.25	2.37	3.78
Owen Sound	33	2.51	4.76	9.46	6.45	4.25	4.30	11.03	8.58	5.35	12.40	14.84	9.67	8.27	*	*	5.19	8.29	12.25	13.74	10.17	4.71	7.57	10.66	3.55	6.24
Huntsville	52	1.53	3.09	3.96	3.96	1.87	3.11	2.79	7.08	5.40	7.46	6.28	5.73	7.44	7.52	1.46	2.98	8.19	11.01	8.77	5.84	5.89	6.03	9.76	2.93	5.58
Sudbury A	54	4.73	5.46	6.96	5.23	3.81	2.85	3.35	8.28	5.42	1.94	5.93	4.52	5.27	5.81	1.42	2.44	8.70	9.40	8.09	3.68	4.15	4.22	9.50	4.13	4.84
Wawa A	62	6.55	5.01	6.76	5.50	5.57	4.80	4.96	9.20	9.44	4.50	8.26	8.74	7.11	9.22	0.84	5.81	10.18	12.26	10.61	7.19	6.09	6.87	9.15	5.49	4.25
Iroquois Falls	53	4.69	2.61	1.26	1.63	3.13	3.30	3.29	6.07	4.54	1.50	5.73	3.52	4.02	4.01	0.63	3.38	6.51	5.00	4.85	3.93	4.75	6.28	5.29	5.24	5.58
Kenora A	61	2.47	1.98	2.41	1.15	1.79	1.84	3.11	3.01	3.42	1.30	3.40	2.58	2.57	4.01	0.24	3.74	3.87	4.06	3.49	2.32	4.03	4.02	4.02	3.54	1.36

Note: * means missing data

Appendix 4 Five year averaged winter indices and salt usage (ton per saltable 2-lane km) for different districts

Station name	MTO districts	Hulme	SHRP	salt days index	salt usage
Ottawa Int'l A	Ottawa	-46.25	-31.56	18.8	31.38
London A	London	-19.65	-21.98	17.22	27.53
Kingston A	Kingston	-20.42	-18.91	12.46	23.34
Toronto Pearson A	Central	-11.57	-14.36	12.2	21.16
Windsor A	Chatham	4.61	-13.39	12.2	17.12
Peterborough	Bancroft	-31.04	-20.33	*	25.45
Owen Sound MOE	Owen Sound	-23.49	-40.96	25.03	41.96
Huntsville WPCP	Huntsville	-46.97	-35.45	18.47	33.43
Sudbury A	Sunbury	-73.66	-33.38	13.8	25.89
Wawa A	Sault Ste. Marie	-66.43	-33.87	15.4	41.04
Iroquois Falls	New Liskeard	-103.19	-30.16	9.73	25.47
Kenora A	Thunder Bay	-103	-23.98	9.6	18.93

*NOTE: * represent missing data.*

Appendix 5 Biweekly SHRP index from Nov. 5, 1993 to Mar.22, 1998

Time	Ottawa	London	Kings-ton	Toronto	Windsor	Peter-borough	Owen Sound	Hunts-ville	Sudbury	Wawa A	Iroquois Falls	Kenora
11/5-11/19/93	15.26	11.15	19.5	15.52	18.77	12.23	17.51	7.79	-47.01	-29.99	-17.56	-9.79
11/19 - 12/3/ 93	-1.91	-1.89	6.36	3.19	11.82	3.02	-18.4	-26.99	-17.71	-23.52	-28.35	-28.15
12/3 - 12/17/ 93	-4.21	7.27	11.33	11.98	14.33	1.64	2.64	-1.43	-13.92	-4.27	-26.66	-19.36
12/17 - 12/31/ 93	-46.99	-25.16	-28.98	-17.22	-21.7	-26.99	-74.79	-46.86	-46.27	-55.34	-27.62	-22.14
12/31/93 -1/14/94	-48.28	-44.53	-43.17	-26.21	-47.01	-32.13	-56.65	-48.07	-42.47	-68.31	-30.57	-26.78
1/14 - 1/28/94	-50.08	-24.77	-41.89	-35.64	-28.8	-40.79	-70.67	-57.99	-38.66	-51.62	-19.13	-13.67
1/28 - 2/11/94	-31.99	-32.05	-41.68	-26.16	-43.36	-19.33	-58.08	-45.35	-37.35	-42.86	-7.84	-13.29
2/11 - 2/25/94	-57.79	-25.87	-45.61	-21.36	-10.33	-28.59	-39	-35.28	-35.96	-12.44	-19.88	-4.62
2/25 - 3/11/94	-26.96	-31.2	-33.71	-23.88	-26.86	-29.55	-12.96	-6.4	-4.59	-13.73	-3.66	-16.06
3/11 -3/25/94	-42.1	-23.06	-16.89	-9.96	2.5	-15.47	-27.32	-18.02	-37.45	-52.61	-53.68	-11.77
11/18 - 12/2/94	-18.99	-14.36	2.8	-7.8	17.58	-21.72	-24.69	*	-15.58	-32.69	*	-20.67
12/2 -12/16/94	-25.36	-34.91	-15.31	-27.26	-32.83	-31.72	-12.99	*	-30.39	-32.49	-32.42	-35.51
12/16 - 12/30/94	-13.17	1.31	4.99	9.59	10.18	-5.9	13.87	*	-20.99	6.08	-23.85	-14.47
12/30/94 -1/13/95	-58.14	-33.84	-33.69	-31.65	-29.26	-43.26	-79.55	*	-34.13	-32.99	-37.2	-35.75
1/13 -1/27/95	-22.2	-15.48	1.66	-8.72	-23.45	-24.86	0.81	-0.77	-24.01	-28.44	-8.66	-40.57
1/27 - 2/10/95	-31.92	-49.27	-28.73	-7.28	-9.48	-18.16	-41.63	-35.19	-24.96	-33.47	-30.4	-20.2
2/10 - 2/24/95	-27.41	-17.96	-16.2	-11.04	-3.09	-20.07	-72.39	-52.3	-38.43	-55.59	-52.24	-20.7
2/24 - 3/10/95	-29.53	-28.38	-32.69	-26.94	-31.02	-25.37	-34.77	-18.51	-51.49	-46.1	-44.93	-17.62
3/10 -3/25/95	14.2	19.12	16.41	19.96	21.46	14.39	14.63	5.65	5.06	3.06	-3.62	4.42
11/3 - 11/17/95	-39.39	-29.76	*	-14.57	-4.44	*	-51.15	-42.59	-52.52	*	-44.44	-32.49
11/17 - 12/1/95	-51.46	-19.58	*	-25.01	1.15	*	-44.47	-57.39	-35.44	*	*	-32.13
12/1 - 12/15/95	-60.02	-34.8	*	-36.54	-22.69	-46.82	-88	-75.59	-57.23	-47.27	*	-47.14
12/15 -12/29/95	-36.35	-26.86	*	-19.18	-24.24	-10.92	-48.13	-19.87	-21.91	-29.98	*	-13.79
12/29/95 -1/12/96	-39.97	-19.94	*	-19.11	-30.69	-23.69	-48.64	-27.06	-13.37	-5.77	*	-14.24
1/12 -1/26/96	-19.59	-14.88	*	-13.16	-1.44	-8.15	-22.67	-18.27	-28.73	-64.52	*	-31.07
1/26 - 2/9/96	-47.6	-30.22	*	-17.96	-11.68	-23.58	-50.08	-46.89	-54.25	-63.52	*	-11.89
2/9 - 2/23/96	-23.46	-22	*	-16.64	-25.03	-9.09	-27.05	-17.72	-50.04	-42.21	-3.69	-37.31
2/23 -3/8/96	-19.96	-39.88	*	-29.82	-23.27	-22.27	-49.17	-41.86	-44.48	-57.62	-58.99	-12.33
3/8 - 3/22/96	-13.9	-14.21	*	-20.04	-33.4	-28.32	-22.09	-8.76	-1.19	-1.15	-6.41	-16.9
11/3 - 11/17/96	-5.61	-15.73	*	11.52	12.36	-8.2	-23.12	-5.84	-8.53	-6	-8.12	-47.43
11/17 -12/1/96	-16.74	-24.02	*	-9.85	-30.15	-25.32	-23.64	-8.06	-23.52	-18.03	-24.39	-60.27
12/1 -12/15/96	-38.19	-17.14	*	-5.28	-8.74	-0.47	-0.78	-24.16	-40.63	-45.48	-36.02	-54.19
12/15 - 12/29/96	-35.15	-30.61	*	-10.35	-30.23	-19.03	-47.73	-35.56	-58.69	-74.65	-55.46	-34.22
12/29/96 -1/12/97	-46.61	-31.65	*	-42.65	-31.21	-47.79	-71.8	-52.4	-64.06	-47.28	-40.5	-20.07
1/12 - 1/26/97	-44.76	-37.37	*	-22.56	-32.04	-33.4	-66.1	-51.09	-51.91	-61.3	-61.2	-12.31
1/26 -2/9/97	-57.85	*	*	-28.87	-31.83	-32.53	-45.73	-35.44	-50.75	-26.89	-19.58	-27.55
2/9 - 2/23/97	-35.38	*	*	-22.06	-30.19	-19.52	-53.32	-41.25	-51.59	-36.88	-24.96	-18.72
2/23 - 3/9/97	-45.44	*	*	-26.22	-9.02	-26.17	-29.35	-32.88	-25.42	*	-22.98	-22.15
3/9 - 3/23/97	-49.58	-24	*	-33.82	2.5	-42.13	-74.47	-53.78	-43.1	*	-44.94	-18.85
11/2 - 11/16/97	-17.28	-5.95	*	-8.19	-7.85	-26.2	-11.46	-24.62	-9.9	-31.76	*	-34.07
11/16 - 11/30/97	-34.19	-13.56	*	-3.23	-0.07	-6.47	-9.52	-36.99	-31.29	-36.6	*	-20.48
11/30 - 12/14/97	-27.38	-21.38	*	-6.35	-21.9	-17.85	-13.26	-30.64	-37.7	-36.9	*	-19.89
12/14 - 12/28/97	-21.72	-14.54	*	-3.25	3.32	-16.47	-12.53	-14.85	-3.51	-8.65	*	-8.25
12/28/97 -1/11/98	-42.55	-0.39	*	-0.34	16.77	-6.75	-46.72	-42.11	-53.57	-57.42	*	-41.1
1/11 - 1/25/98	-55.33	-50.99	*	-33.91	-40.32	-42.81	-61.14	-48.11	-40.44	-52.04	*	-19.63
1/25 - 2/8/98	-22.66	*	*	-6.99	-3.07	-22.11	*	*	-23.99	-33.93	*	-10.94
2/8 - 2/22/98	-10.97	*	*	6.45	15.08	-3.91	*	*	-26.46	-7.77	*	-10.69
2/22 - 3/8/98	-3.93	*	*	6.84	11.41	-8.41	*	*	-19.6	-20.76	*	-13.25
3/8 - 3/22/98	-38.24	*	*	-37.02	-26.17	-31.26	*	*	-51.11	-19.23	*	-13.48

*Note: * is missing data.*

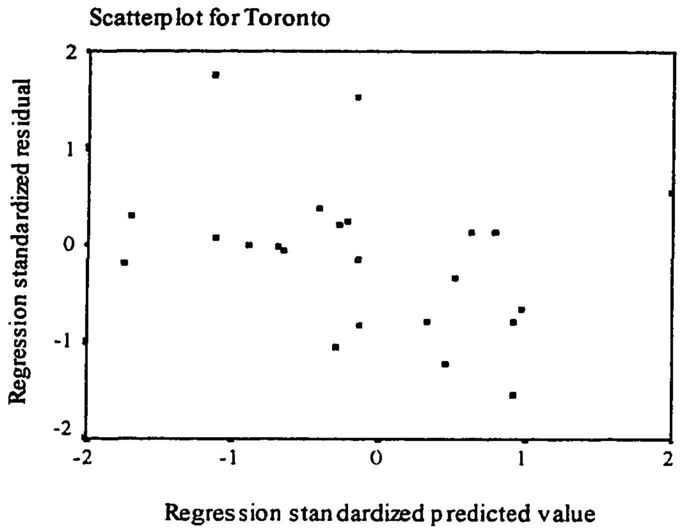
Appendix 6 Modified SHRP index

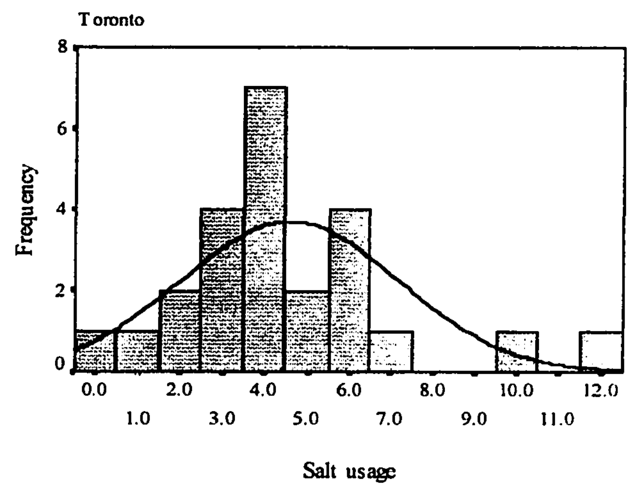
Modified monthly SHRP index from Nov. 1993 to Mar. 1998.

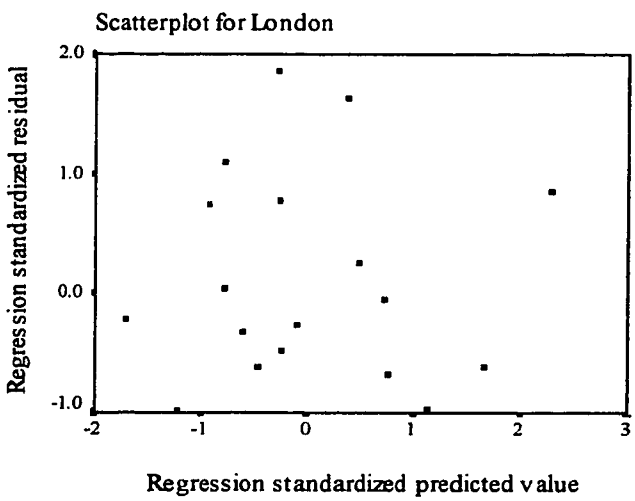
Station name	Dis	93-11	93-12	94-1	94-2	94-3	94-11	94-12	95-1	95-2	95-3	95-11	95-12	96-1	96-2	96-3	96-11	96-12	97-1	97-2	97-3	97-11	97-12	98-1	98-2	98-3
Ottawa Int'l A	42	10.0	-8.9	-32.2	-23.7	-15.0	16.0	0.4	-24.4	-11.3	9.4	-23.4	-37.8	-26.2	-7.6	8.1	5.6	-25.6	-39.76	-30.0	-24.5	-4.6	-4.7	-39.83	15.9	-8.8
London A	31	30.4	11.9	-19.3	-16.2	9.4	14.6	2.2	-7.7	-16.7	13.8	9.1	-10.2	-11.4	5.8	5.3	11.1	-6.1	-23.23	*	9.0	19.2	13.3	5.6	*	*
Kingston A	41	31.1	15.4	-27.1	-15.7	6.1	26.4	23.3	4.3	-10.7	15.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toronto Pears.A	20	34.5	26.5	-11.9	0.5	3.4	21.1	2.5	-9.5	4.2	12.4	1.1	-5.1	-3.7	13.4	8.1	29.4	14.2	-18.06	8.3	-3.2	11.9	14.7	-8.4	33.9	14.9
Windsor A	32	38.0	24.5	-21.4	-12.4	25.0	43.0	5.9	-2.3	-0.4	20.5	28.8	-3.6	4.7	5.1	-6.0	8.6	-2.7	-25.52	0.5	8.6	12.8	18.4	1.4	38.7	5.8
Peterborough	43	25.6	18.8	-20.2	-4.1	6.9	12.5	-1.6	-11.8	-3.6	13.8	*	-10.0	-3.7	9.2	8.8	13.7	5.8	-29.0	-0.2	-26.5	14.0	1.5	-21.51	18.5	-6.2
Owen Sound	33	25.3	-14.3	-37.4	-11.8	6.8	8.7	24.5	-17.1	-33.5	8.4	-10.1	-41.3	-8.5	-7.0	2.3	-3.3	-3.7	-32.36	-16.6	-15.5	18.3	9.3	-28.78	*	*
Huntsville	52	19.8	4.4	-16.4	-3.5	18.1	9.7	*	-26.7	-9.1	24.8	-13.0	-28.2	-19.1	16.8	5.9	11.7	-10.5	-13.85	-14.7	-4.5	3.7	2.7	-22.14	*	*
Sudbury A	54	-17.3	-9.7	-15.8	2.6	-7.8	16.8	-4.9	-23.6	3.6	6.2	-27.8	-15.3	-20.4	-27.8	0.8	2.5	-34.2	-39.42	-23.9	-9.4	-8.2	-14.5	-34.55	-8.5	-15.5
Wawa A	62	-7.2	-6.7	-19.13	1.1	-17.23	15.6	14.2	-7.9	-12.72	11.1	*	-21.12	-40.87	-26.13	2.1	11.3	-34.73	-31.29	3.36	*	1.9	0.2	-26.35	2.4	18.4
Iroquois Falls	53	-1.7	8.4	9.6	17.7	0.5	*	7.8	-16.8	-4.7	6.5	13.7	3.0	-7.5	5.3	-2.7	9.1	1.6	-19.78	3.1	-6.9	*	*	*	*	*
Kenora A	61	-2.7	-12.2	15.2	15.1	6.2	7.4	-7.9	-22.5	-1.6	10.8	-24.26	-21.4	-1.9	-12.34	0.7	-33.6	-19.88	-0.7	-3.52	-9.8	6.2	-0.7	-11.78	0.9	25.2

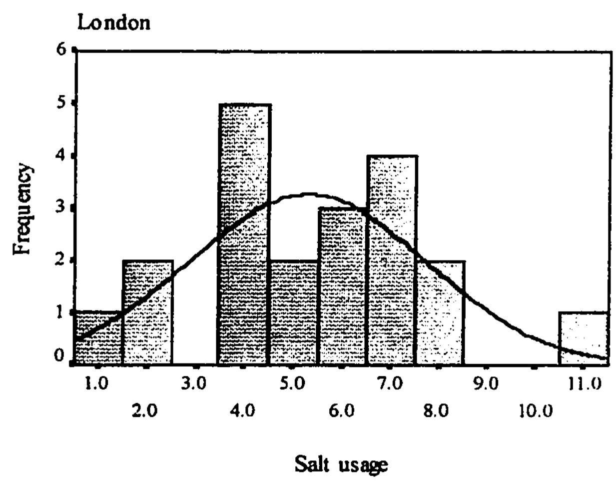
Note: * is missing data

Appendix 7 Regression residual plots and histograms for salt usage

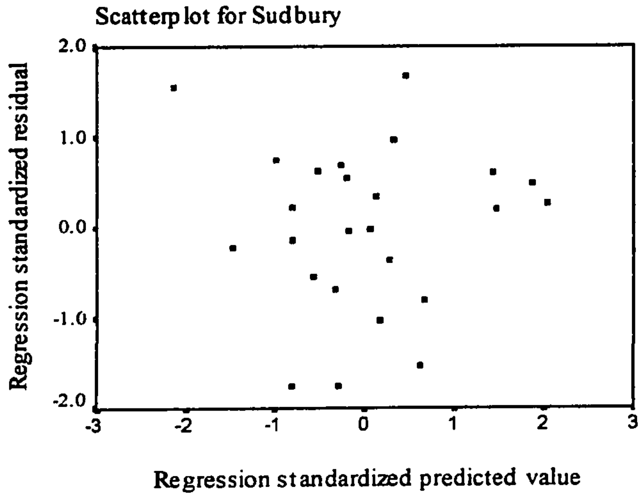


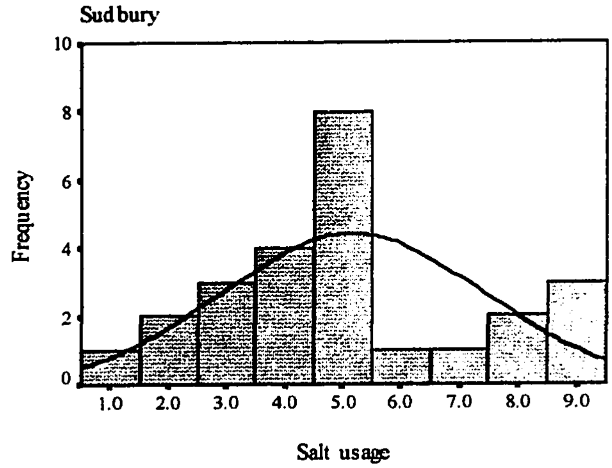


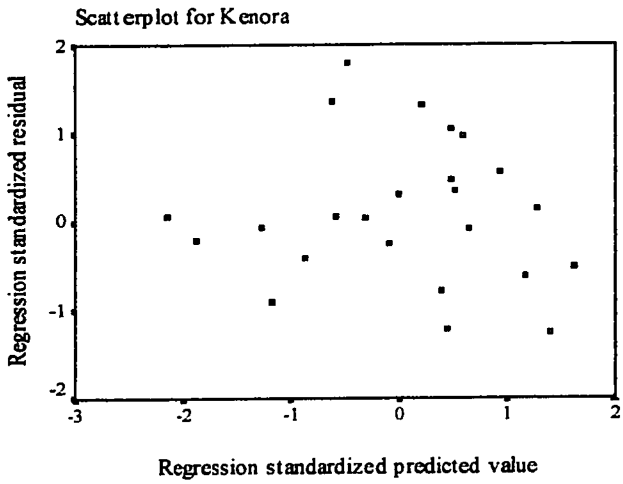


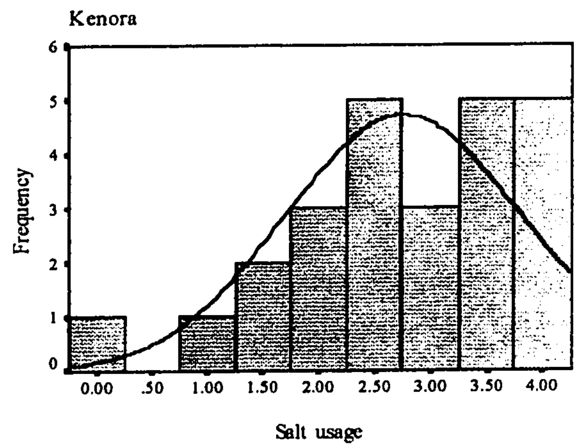


Appendix 7 (Continued)









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