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16. Abstract

Road authorities rely on accurate and timely road weather and surface condition information provided by road weather information systems (RWIS) to optimize winter maintenance operations and improve the safety and mobility of the traveling public. However, RWIS stations are costly to install and operate and therefore must be placed strategically to accurately monitor the entire highway network. Few guidelines are available for optimizing RWIS networks and thus maximizing return on investment.

This project developed several approaches for determining the optimal location and density of RWIS stations over a regional highway network. To optimize locations, three approaches were developed: surrogate measure–based, cost-benefit–based, and spatial inference–based. The surrogate measure–based method prioritizes locations that have the highest exposure to severe weather and traffic. The cost-benefit–based method explicitly accounts for the potential benefits of an RWIS network in terms of reduced collisions and maintenance costs. The spatial inference–based method maximizes the use of RWIS information to optimize the configuration of an RWIS network. To optimize network density, a cost-benefit–based method and a spatial inference–based method were developed.

To demonstrate the applications of the proposed approaches and evaluate existing RWIS networks, four case studies were conducted using data from one Canadian province (Ontario) and three US states (Minnesota, Iowa, and Utah). It was found that all approaches can be conveniently implemented for real-world applications. The approaches provide alternative ways of incorporating key road weather, traffic, and maintenance factors to optimize the locations and density of RWIS stations in a region; the alternative to use can be decided based on the data and resources available.

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RWIS NETWORK PLANNING: OPTIMAL DENSITY AND LOCATION

Final Report
June 2016

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EXECUTIVE SUMMARY

Accurate and timely information on road weather and surface conditions in winter seasons is a necessity for road authorities to optimize their winter maintenance operations and improve the safety and mobility of the traveling public. One of the primary tools for acquiring this information is road weather information systems (RWISs), which include various environmental and pavement sensors for collecting real-time data on precipitation, pavement temperature, snow coverage, etc. Many transportation agencies have invested millions of dollars in establishing their current RWIS network and continue expanding their network to better support winter maintenance decisions and provide more accurate traveler information.

While effective in providing real-time information on road weather and surface conditions, RWIS stations are costly to install and operate and, therefore, can only be deployed at a limited number of locations. Considering the vast road network that often needs to be monitored and the varied road conditions that are possible during winter events, a sufficient number of RWIS stations must be installed over a given region, and they must be placed strategically so that they are collectively most informative in providing the inputs required for accurate estimation of the road weather and surface conditions of the entire highway network. Despite the significance of RWIS networks, few guidelines and tools are available for transportation agencies to optimize their RWIS network and thus maximize the return on their investment. This project attempted to address this gap by investigating various important factors that need to be considered in the RWIS network planning process and developing alternative approaches for determining the optimal location and density of RWIS stations over a regional highway network.

Alternative Approaches to RWIS Location Optimization

This first problem that we attempted to address in this project is how to optimize the location of a given number of RWIS stations in a region. We started by examining various important factors that need to be considered in the RWIS network planning process and subsequently developed and evaluated three alternative approaches for solving the underlying location optimization problem. The three approaches differ in basic assumptions, data needs, and computational complexity; however, each is formulated as a discrete optimization problem in which the candidate RWIS locations constitute a grid of cells defined over the region of interest and its highway network. The main ideas of the three approaches are summarized as follows:

- *Surrogate measure–based method*: This method formalizes the various RWIS network planning processes currently being followed by many transportation agencies, with the basic assumption that priority should be given to those locations that have the highest exposure to severe weather and traffic. Two types of surrogate measures are used for ranking the candidate locations (i.e., grid cells): (1) weather-related factors such as variability of surface temperature (VST), mean surface temperature (MST), and snow water equivalent (SWE) and (2) traffic-related factors such as winter average daily traffic (WADT), winter accident rate (WAR), and highway type (HT). The candidate locations can be ordered by each measure individually or using a weighted total, and the top locations can then be selected as the final solution. In order to apply this approach, values for each selected measure at all candidate locations either must be available directly or able to be estimated using a model. In this project, as described later in this report, we showed that the generalized linear regression technique can be effectively applied to build empirical models of the relationship between measures of interest and some locational and topological descriptors using data from the existing weather and/or RWIS monitoring networks. The models can then be used to generate reliable estimates of weather-related measures such as temperature and snowfall.

- *Cost-benefit–based method*: This method gives an explicit account of the potential benefits of an RWIS network. The approach assumes that the benefits of an RWIS station at any given candidate location can be defined and estimated. Using these benefit estimates and the costs of installing and maintaining RWIS stations, the life cycle net benefits can be estimated for all candidate locations, and the locations with the highest net benefits can then be selected. The main challenge of this approach is defining and quantifying the benefits of installing an RWIS station at a given location. In this project, as described later in this report, we demonstrated through a case study that when detailed data related to weather, traffic, collisions, and the costs of winter road maintenance operations are available for the region of interest, it is possible to build empirical models for quantifying the main benefit components of RWIS, namely, improvements in safety (i.e., reduction in collisions) and a reduction in maintenance costs. It should be noted that in order to apply this approach to any given region, empirical benefit models must first be calibrated on the basis of the differences in collision frequency and maintenance costs between highways covered by RWIS and those without RWIS coverage. Local data on installation and maintenance costs also need to be collected. The life cycle net benefit of each candidate location can then be determined and used to prioritize it.

- *Spatial inference–based method*: A more comprehensive and innovative framework is based on the idea of maximizing the use of RWIS information in determining the optimal configuration of an RWIS network. The basic premise is that data from individual RWIS stations in a region are collectively used by a weather or maintenance decision support model to estimate and forecast the conditions over the whole region. This premise suggests that the objective of RWIS network planning should focus on maximizing the overall monitoring capability of an RWIS network or, more specifically, minimizing the spatial inference (i.e., estimation) errors. In order to model the monitoring capability of an RWIS network, a popular geostatistical approach called kriging is utilized. Without loss of generality, hazardous road surface condition (HRSC) frequency is considered to be the monitoring target (or variable). In addition to spatial inference errors, traffic exposure (e.g., annual average daily traffic [AADT]) is also incorporated into the objective function to capture the need for maximizing user coverage. The spatial simulated annealing (SSA) algorithm is employed to solve the formulated optimization problem. A case study was used in this project to exemplify two distinct scenarios: redesign and expansion of the existing RWIS network. The method developed in this project is the first in the literature targeted at simulating and optimizing RWIS station locations under any given settings and can provide decision makers with the freedom to balance the respective needs and priorities of the traveling public with those of winter road maintenance operations in locating RWIS stations. Likewise, this approach requires much less data than the first two approaches and can be conveniently generalized and applied to other regions.

Alternative Approaches to Optimal RWIS Density

In this project, we also attempted to address another important question: the optimal or minimum number of RWIS stations for a given region. The two approaches used in this project are summarized below:

- The first approach follows the same cost-benefit–based optimization framework described above for determining the optimal locations of a given number of RWIS stations. The approach is based on the fact that, as part of the cost-benefit–based optimization process, the total benefit (i.e., total reduction in maintenance and collision costs) is obtained along with the optimal location solution. By repeatedly running the optimization process with different numbers of RWIS stations (or densities), the relationship between the benefits of an RWIS network and the number of RWIS stations can be established. To make the analysis more complete, this approach adopts a life cycle cost framework, in which the costs associated with an RWIS network are estimated on the basis of various nominal cost statistics reported in the literature, including sensor, installation, maintenance, and operating costs. The annualized net present value (NPV) of the benefits and costs over the life of any given project can be calculated. By examining the relationship between the net benefit (i.e., the difference between the annualized benefits and costs) and the number of RWIS stations, the optimal number of RWIS stations can be identified as that corresponding to the highest projected net benefit.

- The second approach follows the spatial inference–based optimization framework described above and has the objective of minimizing the total inference or estimation errors for the conditions in a region. In this approach, the spatial inference process is repeated with different numbers of RWIS stations (or densities), and the optimal RWIS density is identified by examining the total estimation error curve and locating the knee point at which the rate of reduction in estimation errors reaches a pre-specified threshold. The approach makes use of information on spatial characteristics and correlations; as a result, the optimal density identified for a region is expected to be dependent on the spatial variability of the road weather conditions of the region. The relationship between the optimal RWIS density of a region and a measure of the variability of the conditions in the region was examined in this project. Based on several case studies, it was confirmed that there is indeed a well-correlated relationship between the optimal density of a region and the spatial correlation range of the road weather conditions in the region.

Case Studies and Findings

To demonstrate the applications of the proposed approaches, four case studies were conducted using data from one Canadian province (Ontario) and three US states (Minnesota, Iowa, and Utah). The main findings of the case studies are summarized as follows:

- *Surrogate measure–based method*: A total of three location selection criteria were evaluated. Alternative 1 accounts for weather-related factors only, while Alternative 2 includes traffic-related factors only. Alternative 3 is a combination of Alternatives 1 and 2. These alternatives were used to evaluate the current Ontario RWIS network. The findings revealed that the locations generated using Alternative 1 generally covered the northern region, which experiences highly varying weather conditions, while the locations generated using Alternative 2 covered the southern region, which experiences heavy traffic loads. The high percent of matching (POM) rate (79%) of Alternative 2 indicates that the current RWIS network has been set up in such a way that it predominantly considers the need to cover the road network. Likewise, the large difference between the traffic- and weather-related criteria suggests that the RWIS stations may not have been located optimally. Alternative 3 seems to address some of the limitations of the first two alternatives, yielding a solution in which the RWIS stations are located across the whole province. While the research did not attempt to answer the question of how much weight to give to each objective component, the proposed model allows RWIS planners to set these weights according to their local policies and needs.

- *Cost-benefit–based method*: A case study based on the current RWIS network in northern Minnesota was used to test the applicability of the proposed cost-benefit–based method. It was found that data are readily available from the Minnesota Department of Transportation (MnDOT) that allow winter road maintenance costs and collisions for highway sections with and without RWIS coverage to be modeled as a function of certain weather attributes. A life cycle cost–based analysis was performed to determine the optimal locations of a range of RWIS networks of different sizes. As a result, the highest projected 25-year net benefit was found to be approximately $6.5 million when a network of 45 RWIS stations was assumed. The corresponding cost-benefit ratio was found to be approximately 3.5. The optimal station density was found to be similar to the current density of 42 in northern Minnesota. The optimal station density was used as a threshold for selecting only the top 45 cells for all three criteria: maintenance costs, collision costs, and combined benefits. The corresponding POM values were found to be 80.0%, 75.6%, and 77.8%, respectively, compared to the existing network. Similar yet high POM values indicate that the current RWIS network is able to provide reasonably good coverage in terms of all three criteria.

- *Spatial Inference–based method*: This approach was applied to all four regions. Each optimization problem was solved using the SSA algorithm with a fixed number of iterations for generating a single solution. Findings from the case studies of the four study areas indicate that optimally redesigned RWIS networks are, on average, 13.85% better than the existing RWIS networks. The findings further reveal that the deployment of 20 additional RWIS stations would improve the current networks, on average, by 15.13%. Additional analyses were conducted to determine the spatial continuity of road weather conditions and their relationship to desirable RWIS density. Road surface temperature was selected as the variable of interest, and its spatial structure for each region was quantified and modelled via semivariogram. The number of RWIS stations per unit area (10,000 km^2) required to provide adequate coverage was found to be 2.0, 2.2, 2.9, and 4.5 for Iowa, Minnesota, Ontario, and Utah, respectively. Similarly, the number of RWIS stations per unit highway length (100 km) required was found to be 0.7, 0.8, 1.0, and 1.6 for Iowa, Minnesota, Ontario, and Utah, respectively. The findings suggest that there is a strong dependency between RWIS density and the spatial correlation parameter of range. Regions with less varied topographies tend to have longer spatial correlation ranges than regions with more varied topographies. The density analysis conducted in this project provided valuable information, particularly for highway authorities initiating a statewide RWIS implementation plan. Furthermore, with help of simple density analysis charts, it should be possible to estimate the number of stations required to provide adequate coverage for a region.

- The proposed approaches provide alternative ways of incorporating key road weather, traffic, and maintenance factors in the planning of an optimal and sufficiently dense RWIS network in a region. The decision regarding which alternative to use depends on the availability of data and resources. Nevertheless, all approaches can be conveniently implemented for real-world applications.

LIST OF ABBREVIATIONS AND ACRONYMS

AADT	Annual Average Daily Traffic
BPTRT	Bare-Pavement Target Regain Time
CPU	Central Processing Unit
DOT	Department of Transportation
ESS	Environmental Sensor Stations
FHWA	Federal Highway Administration
GIS	Geographic Information System
HRSC	Hazardous Road Surface Conditions
HT	Highway Type
MST	Mean Surface Temperature
MVKT	Million Vehicle Kilometers Travelled
NPV	Net Present Value
POM	Percent of Matching
RPU	Remote Processing Unit
SSA	Spatial-Simulated Annealing
SWE	Snow Water Equivalent
VST	Variability of Surface Temperature
WADT	Winter Average Daily Traffic
WAR	Winter Accident Rate
WRM	Winter Road Maintenance

1. INTRODUCTION

1.1 Background

During winter months, many regions in the US and Canada often experience a high frequency of inclement weather events, which can have a detrimental impact on the safety and mobility of motorists. Generally, road collision rates increase dramatically during inclement weather conditions due to the degradation of visibility and traction on the roadway. A study by Goodwin (2002) indicated that in the United States more than 22% of total collisions occurred during severe winter weather conditions, while a study by Qiu and Nixon (2008) revealed that snow storms could increase the collision rate by 84%. Ontario Road Safety Annual Reports for 2001 through 2010 (MTO 2016) showed that vehicle collisions occurring during wet, slushy, snowy, and icy conditions account for up to 27.5% of total collisions. Wallman (2004) found that the average collision rate during a winter season could be 16 times higher in black ice conditions than in dry road conditions.

There is also extensive evidence showing that inclement winter events can significantly affect traffic mobility. A study by Liang et al. (1998) found that snow events could reduce the average operating speed by 18.13 km/hr, while Kyte et al. (2001) showed that snow could cause up to a 50% reduction in traffic speed. A comprehensive analysis by Agarwal et al. (2005) found that snow at various severity levels caused 4.29% to 22.43% and 4.17% to 13.46% reductions in capacity and average operating speed, respectively. More recently, Kwon and Fu (2012a) and Kwon et al. (2013) confirmed that winter weather events negatively affect the mobility of road users; these studies established an empirical relationship between road conditions on the one hand and the capacity and free-flow speed of urban highways on the other. The findings from these studies also showed that slippery roads can reduce capacity and free-flow speed by 44.24% and 17.01%, respectively. In general, snow storms that typically result in poor road conditions are strongly related to high collision rates, reduced roadway capacity, and reduced vehicle speed (Wallman and Åström 2001, Datla and Sharma 2008).

To minimize the safety and mobility impacts caused by winter weather events, it is crucial that snow and ice control be controlled systematically by integrating various winter road maintenance operations, including snow plowing, sanding, and salting. Efficient and effective winter road maintenance programs can not only reduce the risk of vehicle collisions but can also facilitate better traffic movement. Fu et al. (2006) and Usman et al. (2012) showed with strong statistical evidence that lower rates of collisions on roads are associated with better road surface conditions that result from improved winter maintenance operations such as anti-icing, pre-wetting, and sanding. Qiu and Nixon (2008) explored the direct and indirect causal effects of adverse weather and winter maintenance actions on mobility in the context of traffic speed and volume. Their findings confirmed that plowing and salting operations have significant positive effects on increasing the speed at which it is safe to drive.

While winter road maintenance is indispensable, it entails substantial financial costs and environmental damage. North American transportation authorities, for instance, expend more than $3 billion annually on winter road maintenance activities such as removing snow and applying salt and other chemicals for ice control (Ye et al. 2009, FHWA 2007). Use of these chemicals has become an increasing environmental concern because they could contaminate the ground and surface water, damage roadside vegetation, and corrode infrastructure and vehicles. To reduce the costs of winter road maintenance and the use of salts, many transportation agencies are seeking ways to optimize their winter maintenance operations while improving the safety and mobility of the traveling public.

One approach to improving the decision making process for road maintenance is to use real-time information (i.e., for monitoring current road conditions) and forecasts (i.e., for predicting near-future road conditions) provided by innovative technologies such as road weather information systems (RWIS). This research is particularly concerned with selecting the locations of RWIS stations in such a way that the benefits to maintenance personnel and road users can be maximized.

1.2 Road Weather Information Systems (RWIS)

RWIS can be defined as a combination of advanced technologies that collect, transmit, process, and disseminate road weather and condition information to help winter road maintenance (WRM) personnel make timely and proactive winter maintenance decisions. The system collects data using environmental sensor stations (ESS) and provides real-time and forecast roadway-related weather and surface conditions. Implementation of this information not only enables the use of cost-effective WRM but also helps motorists make more informed decisions for their travel.

There are two types of RWIS ESS (hereafter referred to as RWIS station because the terms can be used interchangeably), namely, stationary and mobile. A stationary RWIS station is installed in situ within or along a roadway and collects data at a fixed location, while a mobile RWIS station is installed on a patrol vehicle and collects data as it travels along the road network. Due to their different data collection mechanisms, the two types of stations yield different data: the stationary system provides high temporal but low spatial coverage, while the mobile system provides low temporal but high spatial coverage. Therefore, the information collected on road conditions between RWIS stations must be interpolated and/or generated using other sources (Ye et al. 2009). An RWIS station discussed in this report connotes a stationary station, which typically consists of atmospheric, pavement, and/or water-level monitoring sensors. Figure 1 presents the major components of an RWIS station, including the following:

- Pavement and atmospheric sensors
- Remote processing units (RPUs)
- Central processing units (CPUs)
- Communication hardware (e.g., wired and wireless)

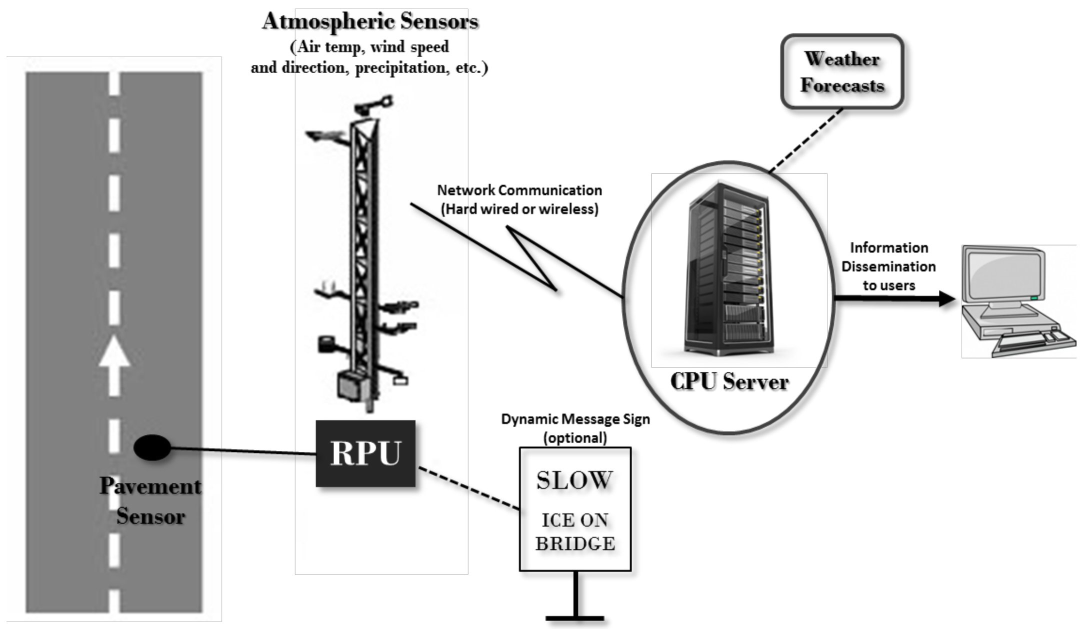


Figure 1. Major components of an RWIS station

The most visible components of stationary RWIS stations are roadside towers equipped with an RPU, to which pavement and atmospheric sensors are connected. Measurements from a typical RWIS station include but are not limited to air and pavement temperatures; wind speed and direction; (sub)surface temperature and moisture; precipitation type, intensity, and accumulation; visibility; dew point; relative humidity; and atmospheric pressure (Garrett et al. 2008). While not commonly included as part of an RWIS station, water level sensors are deployed in flood-prone areas to monitor site-specific characteristics and conditions. Some stations are also equipped with live webcams to provide information on conditions at the sensor location. These measurements from the RPU can be made available directly via a dynamic message sign to alert road users of any hazardous road conditions and/or transmitted to a server where all data from remote locations are processed, compiled, and sent to the end users. Forecasting services from external sources may be combined with the RWIS data to generate short-term road surface temperature and condition forecasts. RWIS data can also be accessed directly by maintenance personnel via, for instance, a web interface for monitoring and analyzing real-time site-specific road conditions and trends and acquiring the latest forecasts.

Since the advent of sensor-based RWIS technologies in European counties between the late 1970s and early 1980s, these systems have gradually earned recognition for being the primary tool to aid and improve WRM operation decisions. Subsequently, these systems have been extensively adopted and used across Europe and North America as a means to enhance road weather and condition monitoring and prediction capabilities. For instance, there are more than 2,700 RWIS stations across North America, with plans to continually expand the RWIS networks in the future (Kuennen 2006).

1.3 Current Practices on RWIS Network Planning

Transportation agencies that are interested in installing RWIS stations often face two relevant questions: how many RWIS stations should be installed to cover their road network and where the new RWIS stations should be placed. Answering the first question requires determining the optimal density and spacing of RWIS stations, i.e., determining the number of stations that are required to provide adequate coverage of a region of interest. Despite of the importance of this problem, there are very few guidelines currently available providing such information. The single most widely adopted reference is the RWIS siting guideline made available by Federal Highway Administration (FHWA) in 2008, which recommends an average spacing of 30 to 50 km along a roadway (Garrett et al. 2008). However, this recommendation appears to have originated from existing practice and experience with little scientific justification. Intuitively, the number of RWIS stations required for a region depends on the spatiotemporal variability of the region. Regions with winter weather conditions of high spatial variability would require a higher number of RWIS stations than those with uniform weather conditions. Currently, the authorities responsible for RWIS planning have no reference available to assist them in deciding the optimal density for their regions. Their decisions are primarily dictated by the available budget, without information on the adequacy of their RWIS network and thus the cost effectiveness of their investment.

In comparison, the problem of selecting suitable locations for a given number of RWIS stations has received relatively more attention recently because of its critical role in governing the overall effectiveness of the sensor suite and the representativeness of its observations in various weather events and road conditions. As part of an FHWA study, Manfredi et al. (2005) proposed a heuristic process for choosing the location of RWIS stations. First, weather zone maps that show regions exhibiting similar weather characteristics or patterns (i.e., areas having regional representativeness) are examined with the support of meteorologists. In this context, an area has regional representativeness if it experiences uniform and stable road weather and surface conditions such that the possibility of adverse local weather effects and influences from other non-weather factors, including heat, moisture, and wind barriers, is minimized. Once the regions are determined in accordance with regional site guidelines, local maintenance personnel are consulted to identify the unique characteristics of each region and provide a general assessment of potential candidate locations. In this stage, planners ensure that the station is located to satisfy road weather information requirements. The following are examples of sites that should be prioritized as the locations of RWIS stations:

- Areas with poor road surface conditions, such as historically cold spots that are likely to create slippery conditions or spots likely to experience significant drifting snow
- Low-lying road segments where surface flooding may occur
- Areas with low visibility due to, for instance, a large local moisture source
- High-wind areas with frequent occurrences of hurricanes along a confined valley or ridge top

In addition, other local siting considerations include aesthetics, safety, security, and ensuring the resilience of the power grid and communication networks. Thermal mapping is a technique that has been applied to determine the locations of RWIS stations at some of the hotspots described above (Gustavsson 1999). Thermal mapping is the process of identifying variations in the pattern of pavement surface temperatures along roadways by creating road surface temperature profiles. Thermal mapping makes it possible to precisely identify cold trouble spots (i.e., potential locations for RWIS stations) that may require more frequent monitoring and additional maintenance treatments (Zwahlen et al. 2003). Nevertheless, thermal mapping requires a substantial amount of time and effort, particularly for cities that are in need of large-scale implementation, which poses a significant limitation on its applicability at the regional level.

Kwon and Fu (2012b) conducted a survey (see Appendix A) to review and examine the current best practices for locating RWIS stations. In this survey, most of the North American participants stated that they would consider requirements similar to those mentioned above (i.e., hotspots where ice and frost are a concern) when there was a need to install an RWIS station. The survey also revealed that participants would consider other non-weather-related requirements, including highway class, collision rate, traffic volume, and frequency of winter maintenance operations, including salting and plowing. These results indicate that in locating RWIS stations transportation agencies would consider not only meteorological representativeness but also the potential number of users (i.e., travelers) who would be served. The survey further showed that deciding where to locate a station generally entails a series of discussions and interviews with many individuals, including meteorologists, traffic engineers, regional/local maintenance personnel, and other industry experts. Despite such efforts, there are always tradeoffs in choosing one location over another because a location that satisfies one site condition may not be optimal for another site condition. For example, an area with high winds may not experience significant snow accumulation. Another important factor to consider when installing an RWIS station is the proximity of power and communication utilities to ensure that data can be obtained and processed in real time. Furthermore, RWIS station deployments are always constrained by tight budgets (Buchanan and Gwartz 2005).

1.4 Objectives

While effective in providing real-time information on road weather and surface conditions, RWIS stations are expensive to install and operate and, therefore, can only be deployed at a limited number of locations. Considering the vast road network that often needs to be monitored and the varied road conditions that could develop during winter, RWIS stations must be placed strategically to ensure that they are collectively most informative in providing the inputs required for accurate estimation of the road weather and surface conditions of the whole highway network. Currently, however, there are significant gaps in the knowledge and methodology for effectively planning the locations of RWIS stations over a regional road network. Road authorities currently follow a laborious yet ad hoc process when deciding RWIS station locations. Furthermore, decisions about suitable RWIS locations and network density can often become challenging, given that multiple factors must be considered.

The primary goal of this project, therefore, is to develop and evaluate alternative approaches for determining the optimal locations and density of RWIS stations over a regional highway network. The project has the following specific objectives:

- Formalize various heuristic approaches for determining the candidate RWIS station locations by incorporating criteria being considered in practice and evaluate the implications of alternative location selection criteria
- Construct a cost-benefit–based approach to the problem of finding the optimal location of RWIS stations by taking explicit account of the benefits of RWIS information such as reduced maintenance costs and collisions
- Develop a spatial inference–based approach such that the resulting RWIS network provides the optimal sampling pattern by considering the spatial variability of key road surface condition variables (i.e., hazardous road surface conditions) and interactions between candidate RWIS station locations
- Evaluate the existing RWIS network, recommend new potential RWIS station locations using the proposed methodology, and demonstrate the effectiveness and applicability of the proposed methods through case studies
- Develop guidelines for determining the optimal RWIS network size (density or spacing) based on the spatial variability of road weather conditions for a region

2. LITERATURE REVIEW

2.1 RWIS Station Location Selection Strategies

As previously discussed, the existing guidelines and current best practices that most transportation agencies have adopted for deciding where to locate RWIS stations may not be optimal and can often be challenged. Despite these challenges, very few studies have been conducted to address RWIS location problems.

Eriksson and Norrman (2001) undertook a study on optimally locating RWIS stations in Sweden in which they identified conditions hazardous to road transport as a criterion for locating RWIS stations at the regional level. In their study, the authors identified 10 different types of slipperiness using one winter season of RWIS data and linearly regressed each type with location attributes including latitude, longitude, elevation, distance to the coast, etc. With the resulting regression model, they mapped out the occurrences of each slipperiness type over the entire study area. Candidate RWIS sites were recommended based on the estimated slipperiness counts and four different land use groups. Although their proposed method seems to provide a good reference for the analysis of station locations with respect to various locational attributes and land use types, their method is a heuristic approach that considers only one location criterion: road weather condition. In addition, the authors did not provide much explanation/justification as to how their four land use groups—forest/water, open/water, forest, and open areas—were determined. Such a categorization scheme is subjective and thus scientifically unpersuasive.

A climatological study was conducted by World Weather Watch (2009) to determine RWIS station locations. Focusing on the general guidelines adopted by many transportation agencies, this study reviewed micrometeorological variations by investigating local physiography, topography, temperature, and snow precipitation amount in a small study area. The study also took into account hotspots that require regular monitoring, as identified by maintenance personnel. By combining all these factors, a list of high-risk sites was identified as the recommended locations for new RWIS stations in the region. The Alberta Department of Transportation conducted a similar but more inclusive study, in which a new approach was proposed to determine the location of RWIS stations by identifying and analyzing RWIS-deficient regions and following general budget guidelines, respectively (Mackinnon and Lo 2009). Similar to what the general guidelines suggest, their approach consisted of two parts: macro or regional assessments and micro or local assessments. In the macro assessment phase, the authors took into account several factors when determining RWIS-deficient regions, such as traffic loads, accident rates, climatic zones, availability of meteorological information, and discussions with regional road maintenance personnel and key stakeholders. In the micro assessment phase, a final site among the selected subsets of new potential RWIS locations was selected by conducting detailed field visits to ensure site suitability and project feasibility, for example, by ensuring appropriate sensor selection and configuration, conformance with budget, and access to power.

Two recent studies by Jin et al. (2014) and Zhao et al (2015) attempted to address the RWIS station location problem using a mathematical programming approach. Jin et al. (2014) used weather-related crash data to develop a safety concern index using the locations providing good spatial coverage as optimal locations. Zhao et al. (2015) applied the concept of influencing area to capture the effects of RWIS station location on weather severity and traffic volume and delineated a list of potential RWIS station locations with the distance to existing RWIS stations considered explicitly. While the spatial variability is partially accounted for in these two studies, the effect of distance and spatial patterns associated with a particular region are not fully utilized. Furthermore, the models presented do not account for the use of RWIS information for spatial inference.

Currently, a majority of provincial and municipal transportation agencies rely heavily on the experience of regional/local maintenance personnel for determining potential RWIS station locations. All of the information (e.g., historically icy spots) is put together through a series of face-to-face meetings with key stakeholders and field experts to narrow down various candidate locations to a manageable size and decide the locations based on the budget availability. Finding a solution through this process is laborious and time-consuming. Therefore, a method that formalizes all of these heuristics to locate candidate RWIS stations is a high priority.

2.2 RWIS Benefits and Costs

As stated briefly above, the information available from RWIS, for instance, detailed and tailored weather forecasts, can provide substantial benefits to users. Before RWIS technology was introduced, highway maintenance agencies reacted to current road conditions or forecasts obtained only from publicly available weather sources. Road patrollers were typically sent out to check road weather conditions, and when roads became icy or snow-covered, maintenance personnel were notified. This type of reactive response was inefficient and expensive in both time and materials (Boselly et al. 1993). In contrast, RWIS provides information that offers proactive ways of doing business, and, therefore, more efficient and cost-effective WRM operations can be realized to promote faster and safer road conditions. Table 1 identifies and summarizes the benefits of using RWIS-enabled winter maintenance practices.

Table 1. RWIS-enabled winter maintenance practices and associated benefits

RWIS-enabled Practices	Associated Benefits
Anti-icing	• Lower material costs • Lower labor costs • Higher level of service (improved road conditions), travel time savings, and improved mobility • Improved safety (fewer crashes, injuries, fatalities, property damage) • Reduced equipment use hours and cost • Reduced sand cleanup required • Less environmental impact (e.g., reduced sand/salt runoff, improved air quality) • Road surfaces returned to bare and wet more quickly • Safe and reliable access, improved mobility
Reduced Use of Routine Patrols	• Reduced equipment use hours and cost • Improved labor productivity
Cost-effective Allocation of Resources	• Reduced labor pay hours • Reduced weekend and night shift work • Improved employee satisfaction • Reduced maintenance backlog • More timely road maintenance • Increased labor productivity • Overall higher level of service • More effective labor assignments
Provide Travelers Better Information	• Better prepared drivers • Safer travel behavior • Reduced travel during poor conditions • Fewer crashes, injuries, fatalities and property damage • Increased customer satisfaction • Improved mobility / reduced fuel consumption • Safer, more reliable access
Additional Benefits	• Share weather data for improved weather forecasts • Support the development of road weather forecast models • Insurance companies by determining risks of potential weather impacts • Use for long-term records and climatological analyses

Adapted from Boon and Cluett 2002

When tailored road weather forecast information is available from RWIS, it becomes possible to predict near-future road weather conditions. With such information, anti-icing chemicals can be applied before a snow storm to prevent or minimize the formation of the bonded snow and ice layers (C-SHRP 2000). When snow and ice are prevented from bonding to the road surface, the surface becomes less slippery, thus increasing traffic safety and mobility. Because the treatment is done proactively, a smaller amount of chemical is required to prevent the bonding than when applied to existing snow and ice layers, which thus reduces the environmental impact. According to more than 100 case studies, anti-icing in conjunction with RWIS can result in substantial cost savings, particularly from reduced material/labor/equipment usage (Epps and Ardila-Coulson 1997).

Another potential benefit of implementing RWIS technology is the reduction of the need for routine patrols for monitoring road conditions (Boselly et al. 1993). With the availability of RWIS information, the number of routine patrols can be reduced significantly because the site conditions can be observed directly without in-person site visits; the camera sensor becomes the eyes of the road maintenance supervisors, who can monitor the current situation of the site in a remote area without using road patrols. Having a smaller number of patrols results in reduced equipment usage and improved labor productivity (Boon and Cluett 2002).

Cost-effective allocation of WRM resources is also possible by using site-specific road weather and condition information available from individual RWIS stations. Road maintenance supervisors can better mobilize the available crew and equipment in terms of time and location. This efficiency can lead to more effective labor assignments and thus increase labor productivity and improve employee satisfaction (Ye et al. 2009).

RWIS makes it possible to disseminate information on current and near-future road conditions via a website and dynamic message signs so that travellers can make better decisions as to when, where, and how to travel. A recent study on RWIS and vehicle collision rates showed that a well-maintained RWIS network significantly reduces collision rates (Greening et al. 2012).

Implementing RWIS technology can also improve weather forecasts through the sharing of weather data available from RWIS. Use of weather information from individual RWIS stations can enhance future weather prediction capability by generating more accurate forecasts than would otherwise be available. Insurance companies can also benefit from using RWIS data to help determine the risks of potential impacts from foreseeable weather events. Furthermore, state climatologists and other organizations such as government agencies and universities can use RWIS data for long-term climatological analyses and the development of road weather forecast models (Manfredi et al. 2005).

Some of the abovementioned benefits, particularly the foreseeable savings from anti-icing techniques, have been evaluated quantitatively through cost-benefit analyses in a limited number of past studies. The Strategic Highway Research Program of the National Research Council initiated a research project in 1991 to evaluate the cost-benefit effectiveness of RWIS (SHRP 1994). The authors investigated the potential for reducing collisions and minimizing material, equipment, and labor costs when anti-icing operations were done before an anticipated adverse weather event. The study concluded that under certain conditions, the implementation of RWIS and anti-icing strategies could result in cost savings to highway agencies and reduce collisions by up to 15 percent. The study also claimed that areas not under RWIS coverage would have ice-and snow-covered pavements for approximately 50 percent of the time during an adverse weather event, compared with about 40 percent of the time for areas under RWIS coverage.

A more recent study by McKeever et al. (1998) introduced a systematic method for highway agencies to evaluate the costs and benefits of implementing RWIS technology based on a synthesis of the preceding results. The authors developed a life cycle cost-benefit model to account for direct costs (e.g., RWIS installation as well as operating and maintenance costs), direct savings (e.g., patrol, labor, equipment, and material savings), and social cost savings (e.g., collision cost savings). The findings suggested that the net benefit of RWIS installation would be $923,000 over a 50-year life cycle.

As noted above, one of the main benefits of RWIS is its ability to allow an agency to transition with confidence to an anti-icing strategy. From the late 1980s to the early 1990s, many US transportation agencies documented the benefits of RWIS-driven anti-icing operations. Although the approaches undertaken to quantitatively assess and/or estimate the benefits are largely vague, they provide a good indication of the RWIS benefits associated with anti-icing operations. Table 2 summarizes the findings reported by individual agencies.

Table 2. Cost savings resulting from anti-icing

Agency	Reported Cost Savings
Colorado DOT	• Sand use decreased by 55%. All costs considered, winter operations now cost $2,500 per lane mile versus $5,200 previously.
Kansas DOT	• Saved $12,700 in labour and materials at one location in the first eight responses using an anti-icing strategy.
Oregon DOT	• Reduced costs for snow and ice control from $96 per lane mile to $24 per lane mile in freezing rain events.
Washington DOT	• Saved $7,000 in labour and chemicals for three test locations.
ICBC (Insurance Corporation of British Columbia)	• Accident claims reduced 8% on snow days in Kamloops, BC: estimated savings to ICBC $350,000–$750,000 in Kamloops. • Potential annual savings of up to $6 million with reduced windshield damage.

Adapted from Boselly 2001

While the aforementioned studies provide some quantitative evidence that implementing RWIS is cost-effective relative to having no RWIS, especially through the use of RWIS-enabled anti-icing operations, the methods used in these studies are limited in several ways, with the inability to quantify the sole benefits of RWIS being the primary limitation. This is a challenging task because, in practice, many other sources of information in addition to the RWIS information are often used in the maintenance decision making process. Therefore, there is a need to develop an approach for determining the benefits associated exclusively with RWIS that can be incorporated into a cost-benefit–based model for finding the most beneficial RWIS location.

2.3 Kriging for Spatial Inference

In designing an environmental or meteorological monitoring network, the development of efficient planning procedures is a fundamental task for accurately understanding the spatial variations of, for instance, hazardous road surface conditions, which can be readily estimated using RWIS information. The problem can then be formulated as an optimal monitoring network design, where the primary concern is to locate a given set of RWIS stations such that the best possible estimation results are ensured. Such a formulation of the problem can be justified with the reasonable assumption that the more accurate the RWIS estimation measurements, the more benefits that are likely to be obtained by utilizing various efficient winter maintenance operations (e.g., anti-icing).

Kriging is a geostatistical technique widely used for optimizing monitoring networks. The main idea behind kriging is that the predicted outputs are weighted averages of sample data, and the weights are determined by considering the spatial interaction between the observed locations and the location where data is to be predicted. In addition, kriging provides estimates and estimation errors at unknown locations based on a set of available observations by characterizing and quantifying spatial variability over the area of interest (Goovaerts 1997).

In order to use kriging, the underlying spatial structure of the measurements to be monitored must be identified and quantified. In geostatistics, this problem is addressed by assuming that the correlation (covariance) between any two locations is a function of separation and orientation delineated by the two locations. The underlying functional relationship is called a semivariogram, which can be calibrated in advance using available data. The semivariogram model used for capturing spatial autocorrelation is expressed as follows:

$$\hat{\gamma}(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} \left[z(x_i + h) - z(x_i) \right]^2 \quad (1)$$

where $\hat{\gamma}(h)$ is the sample semivariogram; $z(x_i)$ is a measurement taken at location x_i, with i being a location index; and $n(h)$ is the number of pairs of observations separated by distance h. An example of a sample variogram is illustrated in Figure 2.

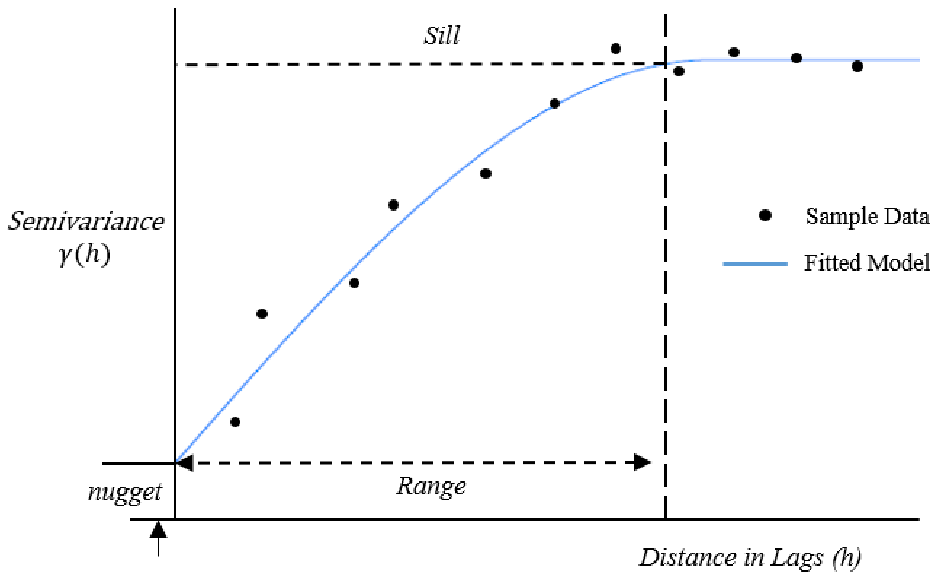


Figure 2. An example of a typical semivariogram.

In Figure 2, range, sill, and nugget are parameters representing the distance at which the measurements are no longer correlated, the level of the plateau, and the micro scale variation and measurement errors, respectively. Typically, a functional model is fit to the sample semivariograms. The three most commonly employed models considered in this study are exponential, Gaussian, and spherical. For more information on semivariogram modelling, readers are referred to a comprehensive guide made available by Olea (2006).

3. PROPOSED METHODOLOGY

Recognizing the complexity of the RWIS location planning problem and the variation and limitations in data availability, three distinct approaches were proposed in this project. The first method is a surrogate measure–based approach intended to formalize the current best practices for locating RWIS stations using various heuristic rules capturing not only weather-related factors (e.g., snowy roads) but also traffic-related factors (e.g., traffic volume). The second method is a cost-benefit–based approach based on the assumption that historical maintenance costs and collision data are available that allow cost-benefit modeling at a patrol route level. The third approach, also the most sophisticated, is a spatial inference–based approach that incorporates the spatial interactions between RWIS stations such that the use of RWIS information or the system's monitoring capability can be maximized.

Figure 3 provides an overview of the proposed location selection methods discussed herein.

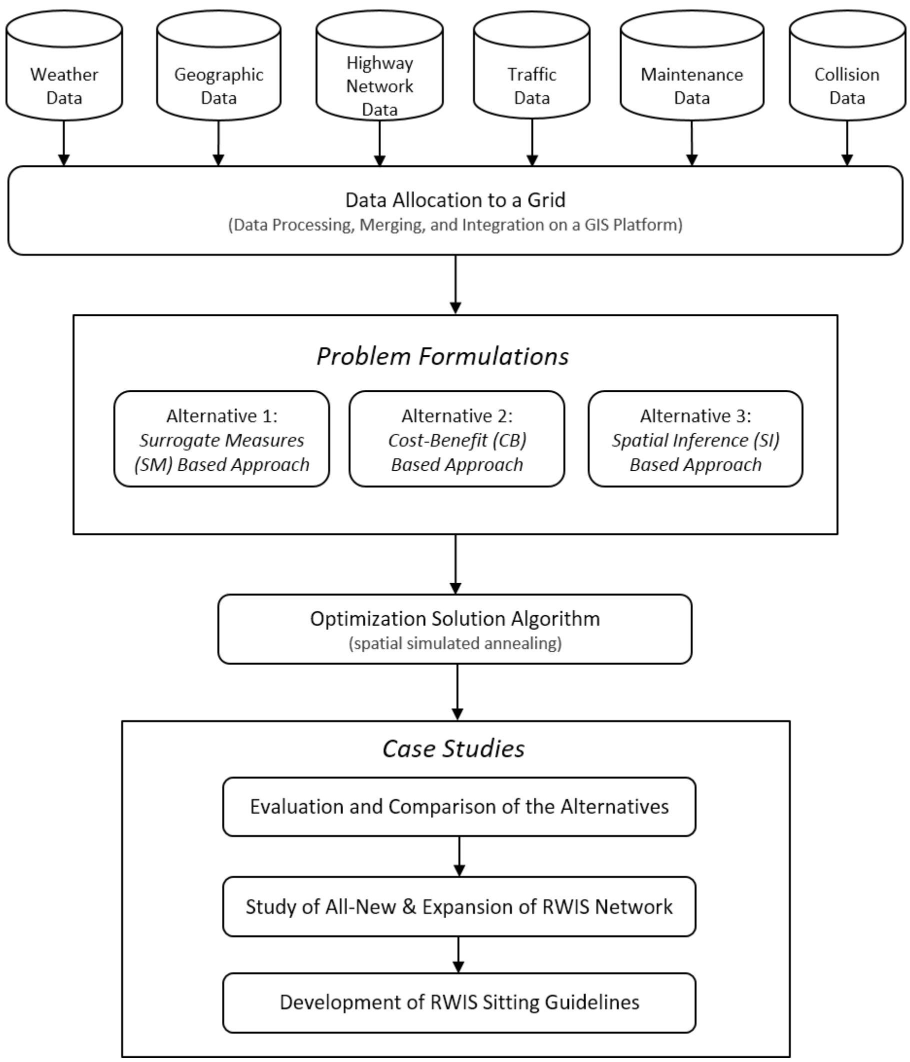


Figure 3. Overview of proposed methodology

As shown in Figure 3, various types of data were required to tackle the objectives, such as weather (e.g., RWIS), geographic, highway network, traffic volume, vehicle collision, and winter maintenance data (to be discussed in more details in Sections 4.2 and 4.3). Because large amounts of data were to be assimilated, a geographical information systems (GIS)–based platform was used for effective data handling. In order to reduce the mathematical complexity of the proposed approaches, the region under investigation was discretized and divided into a grid of equal-sized zones or cells. Using the appropriate size, a grid covering the entire study area was created, and then major road segments were superimposed onto the grid in such a way that only the cells containing the road segments could be selected for further analysis.

Case studies were then conducted to evaluate the three alternative approaches and their solution sets and to describe the unique features of the individual solution sets accordingly. For each solution set, an existing RWIS network (if available) was used to evaluate the model outputs and recommend new locations and density. A summary of the assessments is made available for use as general guidelines to improve decision support for RWIS installation and siting. A comprehensive description of each component of the proposed method is provided in the following sections.

3.1 Alternative 1: Surrogate Measures–Based Approach

As emphasized earlier, the current RWIS deployment schemes are inconsistent, heavily dependent on the subjective opinions of maintenance personnel, and lack quantitative rationales for choosing one location over another when determining RWIS sensor sites. Therefore, it is of high interest to investigate the feasibility of formalizing the various heuristic approaches being adopted in practice so that the process of locating RWIS becomes more transparent, consistent, and justifiable. Figure 4 shows a flowchart of the surrogate measures–based approach for choosing provisional RWIS station locations.

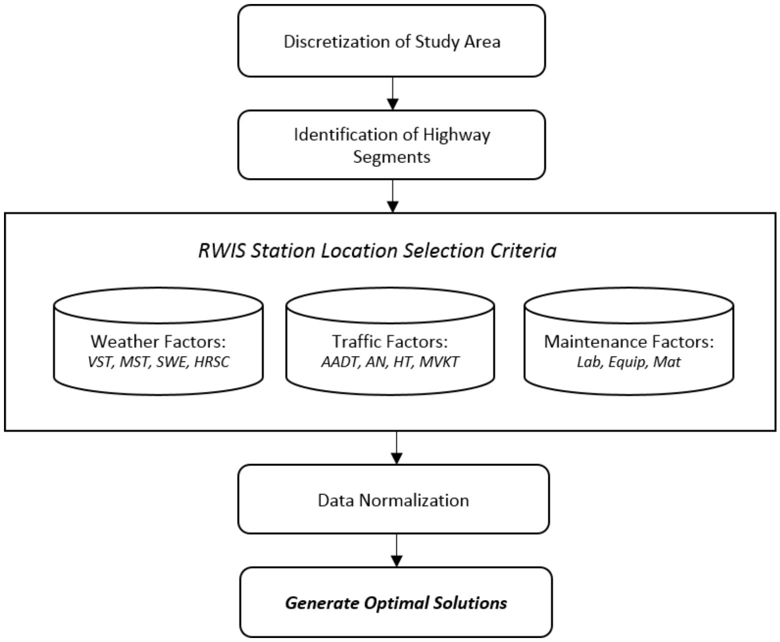


Figure 4. Flowchart of surrogate measures-based approach

Three different groups of criteria, which include but are not limited to weather, traffic, and maintenance factors, were processed and normalized to calculate the total average score in each cell of the grid. Subsequently, a set of solutions for each individual criterion and combined criteria was generated for further evaluation.

As discussed above, RWIS stations are installed to collect road weather and surface condition data, and their value is reflected in the use of these RWIS data, including improved mobility and safety (i.e., benefits for motorists) and reduced WRM costs and salt usage (i.e., benefits for agencies and the environment). Therefore, it is critical to clearly define the criteria that can be used to measure the "goodness" of a location for installing an RWIS station. The following is a list of surrogate location selection measures representing the main criteria considered by maintenance personnel in planning RWIS installation:

- **Weather-related Factors:** Intuitively, RWIS stations should be placed in locations that experience severe yet less predictable weather patterns and therefore are in need of real-time monitoring. Therefore, it is important to analyze the spatial distribution patterns of critical weather variables such as temperature and precipitation. For example, the variability of surface temperature (VST) and mean surface temperature (MST) are important factors to consider because they can provide a quantitative measure of how much the surface temperature varies over time and space. Late November to early December is the time of year with the highest probabilities of black ice or frost. Higher elevations and greater distances from large bodies of water can both contribute to generating colder surface temperatures. Locations with these characteristics generally have longer winters that produce a higher likelihood of frost on road surfaces, which thus poses risks to motorists. Note that VST is the standard deviation calculated using all available surface temperature observations. The amount of snow water equivalent (SWE) at a location is another important factor, in that RWIS stations need to be situated in areas where snowfall occurs frequently. This is particularly true when better monitoring capability can intuitively increase mobility and safety by enabling prompter WRM operations (Ye et al. 2009). Other factors, such as hazardous road surface conditions (HRSC), for example, frost and ice, can also be considered because locations with high probabilities of such conditions are most likely to experience mobility and safety problems. The abovementioned weather factors are proposed to be included in the analysis for selecting a candidate location for an RWIS station.

- **Traffic-related Factors:** Intuitively, greater benefits can be obtained from RWIS stations when they are placed in locations with a greater number of travelers. A recent study conducted by Greening et al. (2012) showed that a well-maintained RWIS network can reduce accident rates by a significant amount, which in turn would bring huge savings. Notwithstanding the fact that other factors such as vehicle technology and weather severity could cofound the effect of real-time information provided by RWIS stations, Greening et al. (2012) clearly demonstrated that the use of RWIS information can potentially prevent accidents. Furthermore, the authors' survey of agencies' current RWIS deployment practices showed that more than 60% of participating departments of transportation (DOTs) consider highway class along with collision rate and traffic volume when selection the locations of RWIS stations. The reason for taking highway class into account is similar to the reason for considering traffic volume, namely to provide the most benefits to a higher number of road users. As such, traffic-related factors such as collision frequency or rate, traffic volume, and highway class are included as location selection criteria.

- **Maintenance-related Factors:** As discussed, one of the primary reasons for installing an RWIS station is to reduce the maintenance costs. Intuitively, the benefits of utilizing the information received from RWIS stations can increase by situating them in locations where the demand for maintenance operations and thus costs are high. For instance, many case studies (Ketcham et al. 1996, Parker 1997) have found that implementing anti-icing operations reduces total maintenance costs. The three dominant groups of maintenance operation costs include labor, equipment, and material costs. The costs from these three sources can be included in the analysis as goodness criteria for locating RWIS stations.

In order to consider all three types of surrogate location selection factors within one systematic framework, a weighting scheme was proposed to combine them into a single measure. The RWIS station location problem can thus be formulated to maximize the weighted total score of the three location selection factors, subject to budget constraints. Consider the problem that a total of M RWIS stations are to be located over a region. Let sw_k, st_k, and sm_k denote the scores of weather, traffic, and maintenance, respectively, at station *k*; the associated weights are represented by $\omega_w, \omega_t,$ and ω_m. Therefore, the problem for the surrogate measure–based approach is formulated as follows:

$$Maximize\ \ S = \sum_{k=1}^{M} \left(\omega_w sw_k + \omega_t st_k + \omega_m sm_k \right) \tag{2}$$

where *S* is the total score function defined as the weighted sum of the scores of all selected sites. The weights associated with the location criteria may vary by region; these weights may be decided based on interviews with regional maintenance personnel. The total available budget limits the number of RWIS stations to be located. During installation, the stations may be equipped with different sensors based on various requirements. Furthermore, the annual maintenance costs for individual sites may also vary depending on their proximity to maintenance facilities. As such, individual installation costs and total available budget are used as constraints in all optimization processes.

Note that a discrete network representation is considered in all proposed methods because structuring the problem discretely helps increase the computational efficiency. Equally important, the provision of a point location of an RWIS station may not be suitable in real-world applications because there are often several other factors, such as line of sight, right of way, etc., that must also be considered prior to deciding the exact location.

3.2 Alternative 2: RWIS Cost-Benefit–Based Approach

While the heuristic approaches for choosing sensor locations are based primarily on the intuition and experience of field experts, an RWIS cost-benefit model can provide a more defensible way to prioritize candidate sensor locations. As stated above, several RWIS cost-benefit studies have been conducted; however, they do not provide evidence of sufficient granularity that can be directly used for location optimization. As such, it is necessary to develop an RWIS cost-benefit model by establishing a clear relationship between the various criteria being used in practice and their associated benefits to RWIS stations. In addition, using the cost-benefit model as a basis, an RWIS location optimization model can help RWIS planners evaluate and assess their existing RWIS network and further delineate new potential locations so as to maximize the benefits to all RWIS users.

One possible approach to estimating the expected benefits of RWIS installations is to compare the maintenance costs and safety and mobility outcomes between highways with and without RWIS stations nearby. This approach requires information from an existing RWIS network that can be used for developing cost-benefit models to estimate the benefits and costs at all demand points (i.e., potential sites).

Figure 5 shows a flowchart of the proposed cost-benefit–based approach for determining the optimal RWIS station locations at a regional level.

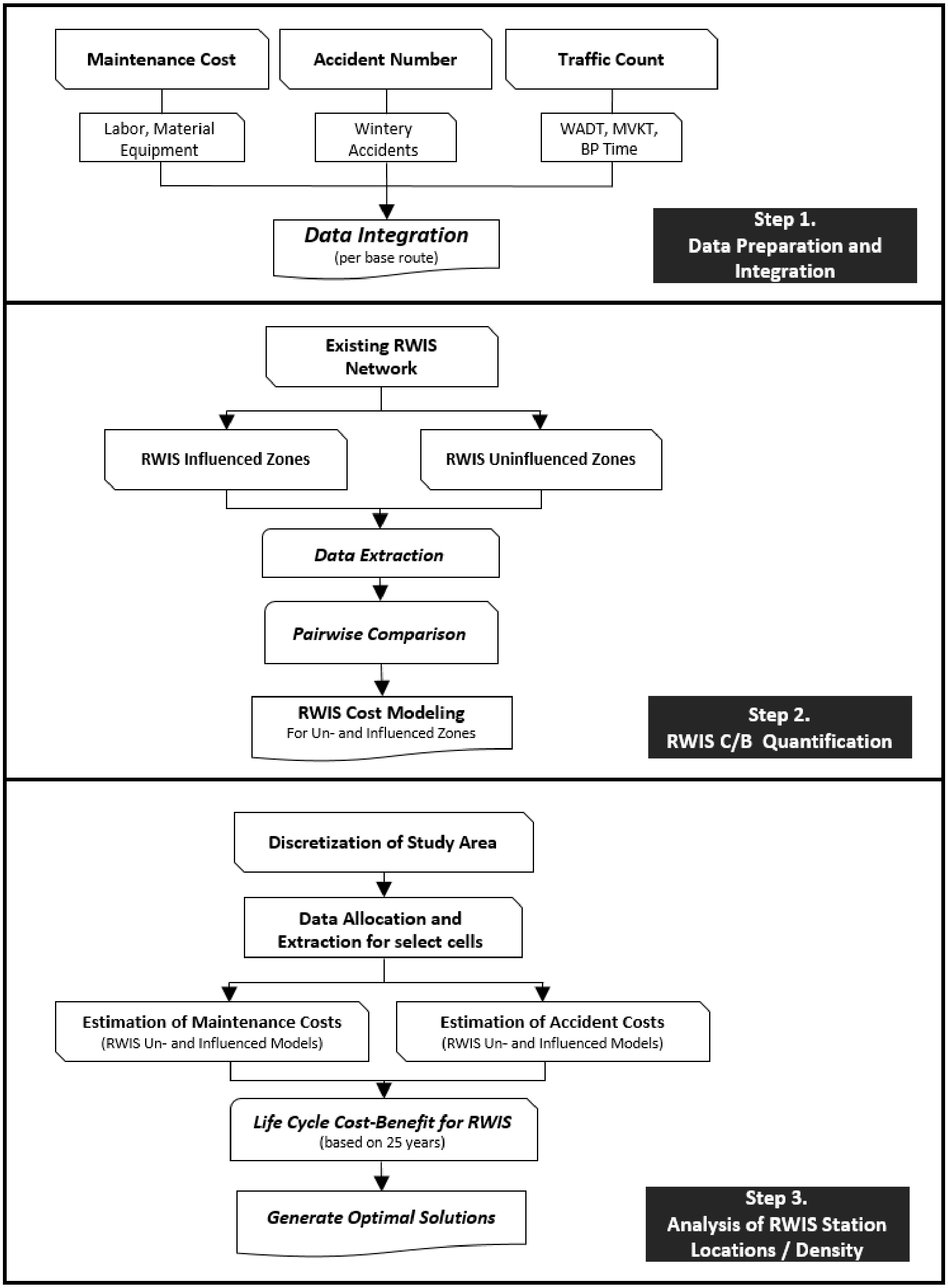


Figure 5. Flowchart of cost-benefit-based approach

The method consists of three steps: data preparation and integration, RWIS benefit and cost modeling, and analysis of RWIS station location (i.e., to generate optimal solutions).

As shown in Step 1 in Figure 5, three sources of data are needed for the intended cost-benefit analysis and location optimization of an RWIS network. Collision data are filtered in such a way that only the winter collisions derived from RWIS information are retained, including those that occur during adverse weather and surface conditions, such as on icy and slushy roads. Although collisions could occur for reasons other than inadequate maintenance operations in areas with no RWIS station, it is assumed that collisions that occur during hazardous conditions could be considered as preventable, to some extent, if information from RWIS stations is available to maintenance personnel to enable them to perform proactive and/or responsive maintenance actions. Maintenance data include labor, material (salt, sand, and brine), and equipment (plower and salter) information. Traffic count data are represented by annual average daily traffic (AADT), which can be converted to winter average daily traffic (WADT), million vehicles kilometer travelled (MVKT), and bare-pavement target regain time (BPTRT). All three types of data are integrated into one data set and expressed in terms of predefined base routes using GIS for further analysis (to be discussed in more detail in later sections).

In Step 2, models are developed to estimate the total benefit that could derive from installation of an RWIS station at a given highway section as compared to the scenario of no RWIS station. Benefits include reductions in maintenance costs, collisions, and traffic delay. For example, the first two benefit items can be defined by the following:

$$B_i^{Maintenance} = MC_i^{RWIS} - MC_i^{No\ RWIS} \quad (3)$$

$$B_i^{Safety} = AC_i^{RWIS} - AC_i^{No\ RWIS} \quad (4)$$

where $B_i^{Maintenance}$ is the expected maintenance benefit, or reduced annual maintenance costs, due to installation of an RWIS station at area *i* (i.e., demand point); B_i^{Safety} is the expected safety benefit, or reduced annual collision costs due to installation of an RWIS station, at area i; MC_i^{RWIS} is the expected total annual maintenance cost for the given area i if there is an RWIS station nearby; $MC_i^{NO\ RWIS}$ is the expected total annual maintenance cost for the given area i without an RWIS station nearby; AC_i^{RWIS} is the expected total annual collision cost for the given area i if there is an RWIS station nearby; and $AC_i^{NO\ RWIS}$ is the expected total annual collision cost for the given area i without an RWIS station nearby.

As shown in Equations 3 and 4, the two dependent variables of interest are the expected maintenance and collision costs for two distinct scenarios: one with RWIS stations and one without RWIS stations. The rationale for adopting this method is that a highway section covered by a nearby RWIS station is more likely to receive more efficient and cost-effective WRM than an area far from an RWIS station. This rationale can be justified in that information coming from RWIS stations enables maintenance staff to predict near-future road weather conditions and apply anti-icing chemicals before a snow storm hits, thus preventing or minimizing the formation of bonded snow and ice layers (C-SHRP 2000). Furthermore, because the treatment is done proactively, a smaller amount of chemical is needed to prevent bonding than when snow and ice already exist on the road (Epps and Ardila-Coulson 1997). Note that the proposed method assumes that winter maintenance personnel use RWIS station information in their WRM decision making process to reduce maintenance costs and collision frequency. This assumption is well supported by our interviews of maintenance personnel, which revealed that RWIS information is always utilized to make informed decisions whenever such information is available.

The third step is to divide the region of interest into a grid of equally sized cells, or zones, each of which is assumed to be the minimum spatial unit for allocating a candidate set of RWIS stations. Once the grid covering the entire region is constructed, the base route is superimposed onto the grid, with only the cells containing the base route selected for further analysis. This process automatically eliminates unnecessary cells and reduces the degree of complexity by removing the non-candidate cells.

Using the models developed in Step 2, the maintenance and collision costs for each cell with and without RWIS coverage can be readily estimated, which can then be used to estimate the benefit of the RWIS stations for any given year. A life cycle cost-benefit analysis is followed to determine the optimal RWIS density, in which optimality is assumed to occur when the greatest difference between the costs and benefits is observed. Once the benefits and costs are assigned to each candidate cell (i.e. the demand points), the objective function can be formulated in a similar way to the one used for Alternative 1. The goal is to maximize the total benefits calculated by the two benefit criteria, namely maintenance and accidents:

$$Maximize \;\; B = \sum_{k=1}^{M} \left(B_k^{Maintenance} + B_k^{Safety} \right) \tag{5}$$

where B is the total benefit function (objective), defined as the sum of the benefits of all selected sites. Again, the budget constraints used in the surrogate measures–based approach (Alternative 1) can be utilized for this formulation. Likewise, the cost of an RWIS station may vary depending on various requirements (e.g., number of sensors), and thus different unit costs for individual components may be used based on the study site under investigation.

Lastly, the recommended density (i.e., optimal number of RIWS stations) is used as a threshold to decide how many stations are to be deployed in a region. It should be noted that further analysis is required to pinpoint the exact locations of individual RWIS stations by considering other local siting requirements, including access to power and communication networks, obstructions, ease of access for maintenance, etc., as discussed above. Furthermore, it is important to recognize that other factors exist, such as human behavior and vehicle conditions, that may contribute to the occurrence of accidents regardless of the availability/presence of RWIS information during winter seasons. However, it is believed that these factors do not significantly affect the results because the difference in total annual collision costs between areas covered by RWIS stations and those not covered represent the benefits that are expected solely due to the presence of RWIS stations.

3.3 Alternative 3: Spatial Inference–Based Approach

While the first two proposed approaches are intuitive and easy to comprehend, they have some limitations. For example, the surrogate measures–based approach does not explicitly model the benefits of RWIS, which can only be partially captured by the traffic, weather, and maintenance parameters. For the cost-benefit–based approach, the RWIS benefit models are constructed based on empirical data (from existing RWIS stations) such that the findings may not be applicable to other areas. Likewise, it is challenging to determine all the underlying benefits (e.g., societal and environmental benefits) associated with RWIS. More importantly, both approaches do not take into consideration the fact that data from RWIS stations can be collectively used to make inferences about the conditions over a whole region, not just the areas covered by RWIS. This monitoring capability of an RWIS network is the foundation of the third method proposed to determine the optimal configuration (or spatial arrangement) of RWIS stations.

As discussed above, RWIS information makes it possible to perform proactive winter maintenance operations such as anti-icing (i.e., applying salt, mostly in liquid form, in advance of an event), which reduces the amount of time and cost required to restore the roads to a clear and dry state. When RWIS data are used to infer the conditions of the whole region, the benefits of anti-icing can be equally extended over the whole region and should be considered in location optimization. This argument remains valid under the assumption that an increase in estimation or monitoring capabilities during hazardous conditions contributes to improving the overall quality of winter road maintenance operations. In order to model the monitoring capability of an RWIS network, we proposed the application of a popular geostatistical approach called kriging, briefly described above. The monitoring capability of a given RWIS network is captured by determining the kriging estimation errors.

Therefore, the third method is based on minimizing the total spatial inference (i.e., estimation) errors to determine the optimal siting of an RWIS network. (For a detailed mathematical formulation of spatial inference–based approach, see Appendix B.) The third approach is the most refined and sophisticated method, but it requires much less data than the first two approaches and can be conveniently generalized and applied to other regions. Figure 6 shows the flowchart of the proposed spatial inference–based approach.

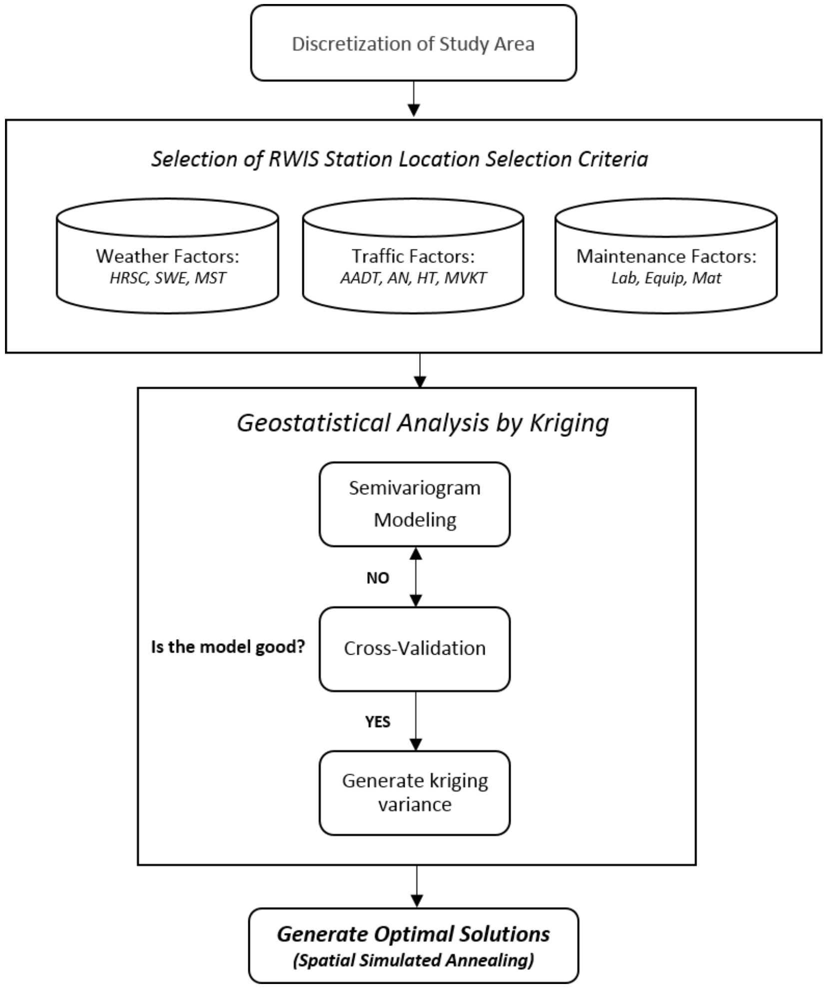


Figure 6. Flowchart of spatial inference-based approach

In the proposed method, kriging estimation errors of RWIS measurements (e.g., surface condition or surface temperature) are calculated to reflect the need for installing RWIS stations to achieve improved winter road maintenance operations. Locations with higher errors are assumed to require more attention than locations with lower errors. The sum of estimation errors should therefore be minimized. In addition, the traffic criterion should also be considered because RWIS stations should be located in areas with high travel demand. Therefore, the two aforementioned RWIS station allocation criteria are included in the objective function as follows:

$$Minimize \quad I = \sum_{k=1}^{M} \left(Crit1_k \cdot w_1 + Crit2_k \cdot w_2 \right) \tag{6}$$

where Crit1 and Crit2 represent the average kriging estimation errors of RWIS measurements and the traffic criterion, respectively. The weighting terms (w) are included so that decision makers have the freedom of choosing different weights depending on the needs of the traveling public, winter road maintenance requirements, and other priorities in locating RWIS stations. A more detailed mathematical formulation is provided in Appendix C.

Because the optimization problem considered herein is a nonlinear integer programming problem, heuristic techniques are often required to solve these problems at realistic sizes. In this research, a variant of one of the most successful techniques, spatial simulated annealing (SSA), is used to find the optimal RWIS network design by iteratively examining each possible location and accepting designs that offer the best RWIS siting plan (van Groenigen et al. 1999).

4. CASE STUDIES

4.1 Study Areas

The proposed approaches were examined via four case studies covering one Canadian province (Ontario) and three US states (Utah, Minnesota, and Iowa) using various data sets provided by each region under investigation. These four regions were considered good candidate areas because they already have well-distributed and dense RWIS networks and have distinctive and unique meteorological (lake effect) and topographical (mountainous) characteristics (see Figure 7) that allow for reliable assessments. The findings from each region were expected to provide sensible guidelines and measures as to how the optimal location and density of RWIS stations vary from one region to another.

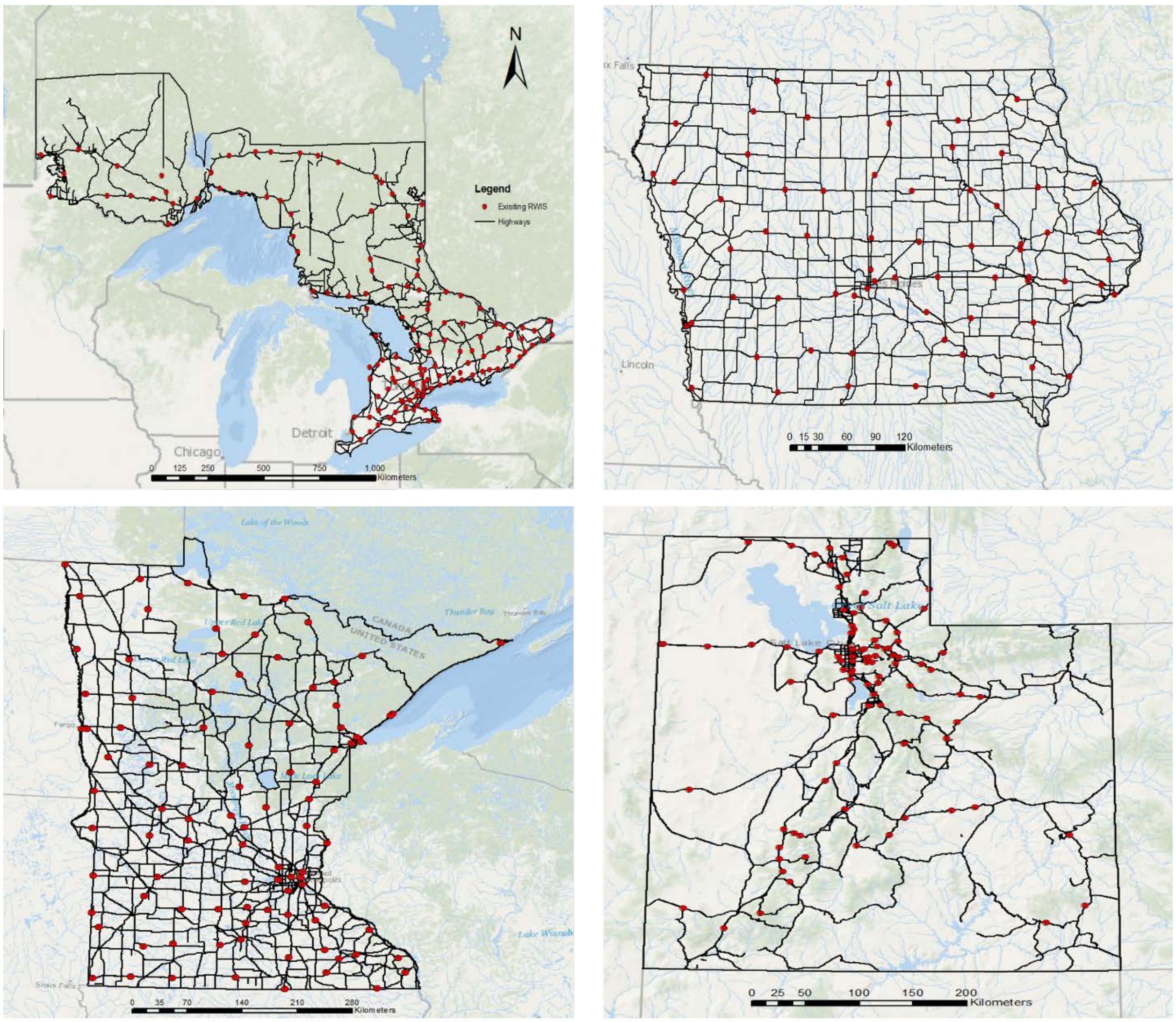


Figure 7. Study areas under investigation and the existing RWIS networks: Ontario (top left), Iowa (top right), Minnesota (bottom left), and Utah (bottom right)

Ontario, situated in east-central Canada, is the second largest Canadian province and has a continental climate like most other provinces of Canada. Northern Ontario has long, very cold winters and short summers, whereas the southern part enjoys the tempering effect of the Great Lakes. Southwestern Ontario is typically flat with many rolling hills. To its north is a mainly flat and wet area. Utah is situated in the US Mountain States region, one of the nine geographic divisions of the United States. Because of its geographic location, Utah has an extremely varied topography, with a large portion of the state being mountainous. The lowest area is in the southwestern area, with altitude of 750 m, while the highest points lie in the northeastern area and have altitudes higher than 4000 m. Utah is also known for very diverse climates; for instance, there are definite variations in temperature by altitude and latitude. Average temperature differences between the southern and northern counties at similar altitudes typically range between 6 and 8 degrees, with the northern counties having lower temperatures. The topographies of Iowa and Minnesota, in contrast, consist mainly of rolling plains and flat prairie. The differences between these states' lowest and highest altitudes are also small, ranging from low points of 183 m and 146 m to high points of 702 m and 509 m for Minnesota and Iowa, respectively. Iowa's and Minnesota's climates, because of the states' latitudes and interior continental location, are characterized by marked seasonal variations. Ontario, Iowa, Minnesota, and Utah currently have 140, 67, 97, and 96 RWIS stations in place, respectively, and RWIS network expansion initiatives are underway to deploy more stations over the next 5 to 10 years in all regions.

4.2 Data Description

This section provides a description of the different data sources used in the analyses described in subsequent sections of this report.

Weather Data

Weather data were acquired from several different sources, namely, RWIS, the National Weather Service (NWS), and Daymet. Daymet provides weather data that includes surface weather and climatological summaries at different temporal resolutions. The data come in raster format, which can be conveniently integrated into a GIS platform for extracting various weather records (Thornton et al. 2012). RWIS data in particular were a primary source for classifying the various types of hazardous road conditions due to the data's unique measurements focusing on road surface conditions. One of the limitations of RWIS data is the precipitation amount, which is frequently missing. Weather data from local weather stations (i.e., Environment Canada [EC] and NWS) were used to fill the gaps in the RWIS data. A typical RWIS station gathers air/surface temperature, visibility, wind speed, and road surface condition data, among other information, at 15- to 20-minute intervals, whereas weather stations measure common meteorological parameters (e.g., precipitation type and intensity, relative humidity, and visibility) on an hourly, daily, and monthly basis.

Geographic Data

Geographical parameters, including latitude, longitude, and altitude, provided a good measure of weather-related characteristics that vary by location. For instance, altitude can significantly affect road surface temperature variations because temperatures at high altitudes can be noticeably different from those at lower altitudes. When altitude information was not available, a digital elevation model was used to extract the said information as well as other road geometric and topographic features such as slope and relative topography, which is a measure of surface roughness.

Maintenance Data

Maintenance data included winter maintenance cost records. Each maintenance record is identified by a unique project identification number along with information on labor, equipment, sand, salt, and brine costs.

Traffic Volume Data

AADT data included a description of each location, highway type/class, geocoding information, and section length. These data were converted, where necessary, to BPTRT and MVKT as additional parameters in this study.

Collision Data

Historical collision data included individual crash records with detailed information. Each record lists time, day, month, year, data reliability, location, severity (i.e., fatality, injury, and property damage), number of vehicles involved, type of collision, surrounding weather, and surface condition information. Another form of collision data was also available that provided an annual accident number along with geocoding information for mapping onto a GIS platform.

Highway Network Data

Highway network data consisted of geocoded line features onto which traffic and collision data could be mapped. Such geocoded line features are called a linear highway referencing system which is used to identify a specific location with respect to a known point (Baker and Blessing 1974).

4.3 Data Processing

As indicated above, six main categories of data needed to be processed and merged onto corresponding road segments/grid cells. A single road segment of equal length was used as the minimum spatial unit for determining the provisional RWIS station locations. A GIS-based platform was implemented due to the need for a large amount of data sets to be processed in an efficient manner. A diagram of the steps involved in data integration and aggregation on a GIS platform is depicted in Figure 8.

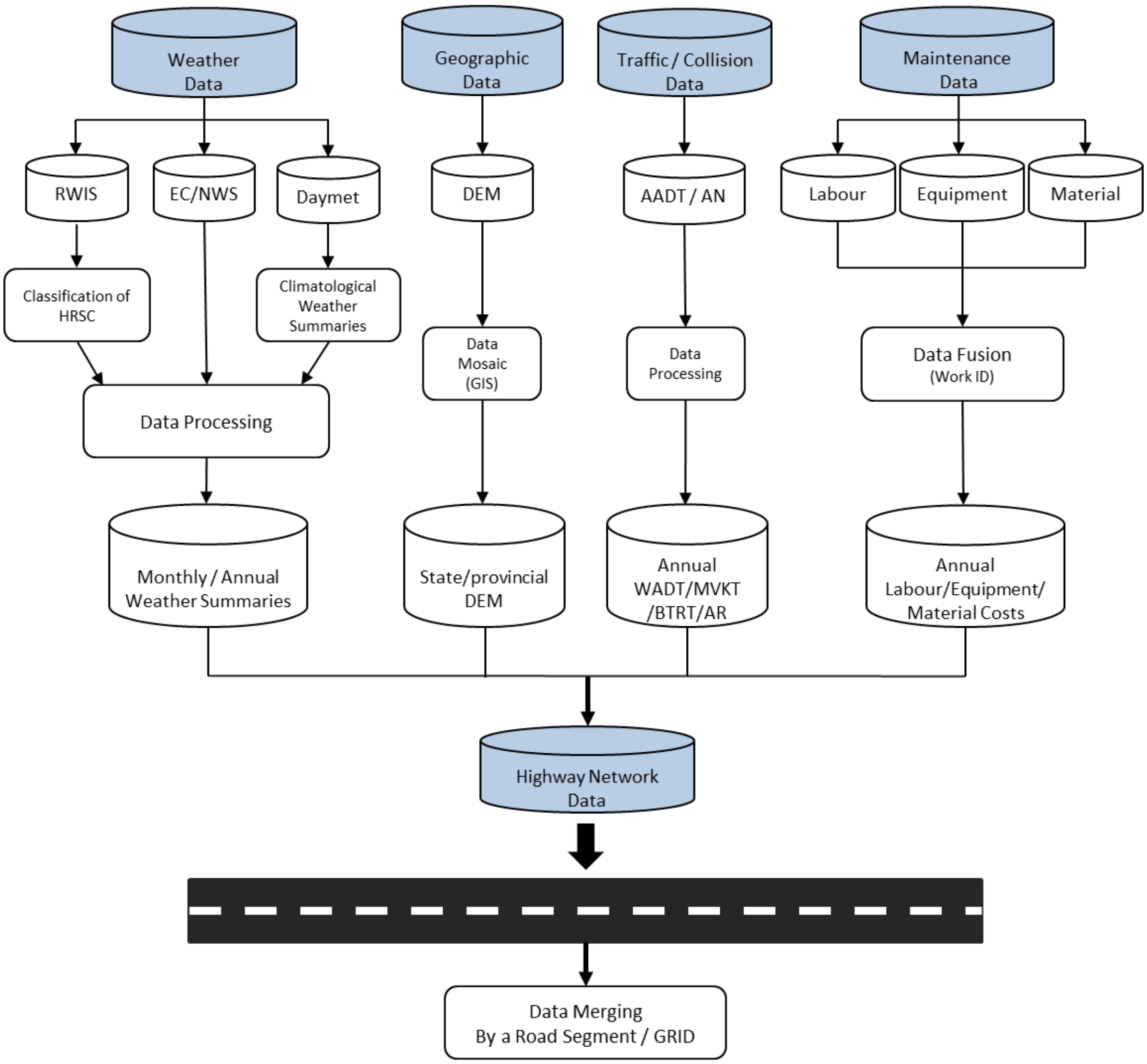


Figure 8. Diagram for data processing and merging

Weather Data Processing

As mentioned above, the weather data from three sources were utilized in this study. Different weather variables, such as precipitation amount and surface temperature, collected from RWIS, EC/NWS, and Daymet were used as surrogate measures to delineate the candidate RWIS station locations. Some select weather variables were used as predictors in the modeling phases to improve the explanatory power of target variables. Furthermore, weather data were also used to capture the spatial variability (i.e., of the weather trends) in the region of interest. RWIS data in particular were a primary source for classifying the various types of hazardous road conditions due to the data's unique measurement characteristics, which are focused primarily on road weather and surface conditions. For instance, the frequency of hazardous road surface conditions (e.g., icy or snowy roads) was calculated using RWIS measurements to obtain monthly and yearly totals. All available weather data were aggregated at two different temporal resolutions (i.e., monthly and yearly) and merged onto uniform grid cells on a GIS database platform.

Geographic Data Processing

Digital elevation models were distributed and packaged in small tiles. To keep file sizes and processing times manageable, tiles with 1-km spatial resolutions (appropriate for large-scale study) were used in this study. Because the data were stored as ASCII files, GIS software was used to convert the model results to raster files for display on a GIS platform. A set of converted tiles were mosaicked to a single raster tile to increase computational efficiency.

Traffic and Collision Data Processing

Traffic data were received in the form of AADT. A few derivatives of AADT, such as WADT, MVKT, and BPTRT, were calculated for analysis in this study. Because the focus of the analysis was winter (i.e., periods when RWIS information was being utilized), WADT was used to provide a more representative value and was calculated on the basis of the number of winter days assumed in the analysis. MVKT was used as a measure of traffic flow or exposure. Another measure used was BPTRT. During winter storms, a winter maintenance schedule requiring staggered work hours may be used to provide the level of service recommended. Each maintenance area, district, and division develops a schedule of effort needed to achieve BPTRT, and , thus BPTRT can be an essential surrogate measure for representing the type of highway and the target level of service.

Collision data consisted of additional information describing the types of individual collisions along with weather conditions at the time of the collisions. These collision data were filtered in such a way that only the preventable collisions derived from RWIS information were retained, which included those that occur during adverse weather and surface conditions such as icy and slushy. Although collisions could occur for reasons other than inadequate maintenance operations in areas with no RWIS station, it was assumed that collisions that occurred during hazardous conditions could be considered preventable if RWIS information were made available to maintenance personnel to help them perform proactive and/or responsive maintenance actions. The total preventable accident numbers (AN) were used to derive the preventable accident rate (AR), which is an indicator of the number of accidents occurring annually on a particular highway section for every MVKT on that section during the same period.

Maintenance Data Processing

Maintenance data included annual winter maintenance costs in three different categories: labor (hours), equipment, and material (sand, salt, brine). Each maintenance record is identified using a unique project identification number. Using the project identification number as a reference, the three data components were fused to calculate the total annual maintenance costs.

Data Merging

Once all of the required data were processed as explained above, highway network data were used to create a base route onto which the preprocessed data were integrated and merged. The primary purpose of this step was to allocate all of the data, which was drawn from different sources and therefore used different spatial resolutions, to equal-sized road segments or grid cells such that each road segment or grid cell could be considered as a candidate RWIS station location. This step required significant effort in terms of geoprocessing the individual sets of data on a GIS platform to obtain the representative values for each parameter considered.

4.4 Alternative Approaches to Finding Optimal Locations

4.4.1 Application of the Surrogate Measures–based Method: Ontario RWIS Network Analysis

This section discusses the application of our first RWIS location optimization approach: using surrogate measures to analyze the Ontario RWIS network planning problem. Two types of surrogate measures, namely, weather- and traffic-related factors, were considered.

4.4.1.1 Surrogate Measures

As mentioned above, RWIS stations should be located in areas that exhibit severe yet less predictable weather events so that the benefits of RWIS can be maximized.

MST and VST: The two commonly used indicators for measuring winter weather severity are MST and VST, defined as the standard deviation of surface temperature. For the areas (or grid cells) that are covered by nearby observation stations (e.g., regular weather or RWIS stations), both measures can be directly estimated using observations. For the areas that are not covered by stations, it is necessary to apply a technique to estimate these variables. In this research, regression models were developed to obtain the relationship between the two temperature measures and several known variables, including latitude (lat), longitude (long), elevation (elev), distance from water (d_w), and relative topography (RT). The justification for choosing such variables is that latitude is expected to affect the spatial variation of surface temperature, whereas longitude may capture the influence of winds. Elevation in meters above mean sea level can be linked to the variability of surface temperature (e.g., the higher the elevation, the lower the temperature), and distance from large bodies of water, i.e., the Euclidean distance in kilometers, represents the degree of continentality (Eriksson and Norrman 2001). Lastly, relative topography was included to describe the exposure and was calculated by taking the difference in elevation between each station location and an average of pixels within the respective radius range (e.g., 1 km, 3 km, and 5 km). Because the monthly variation of surface temperature can vary significantly from one month to another, the two dependent variables, VST and MST, were modeled on a monthly basis.

For the Ontario case study, three-year surface temperature data collected in the month of January from 2006 to 2008 at a total of 45 Ontario RWIS stations were used for modeling. ArcGIS 10.1 was used as a base platform for this study. A digital elevation model with a 1-km spatial resolution as well as water layers, including lakes and seas, were utilized to obtain the aforementioned auxiliary information. Once all the required information were obtained, IBM SPSS software was used to perform the multiple linear regression analysis, with all variables being tested at the 5% significance level. The resulting equations obtained for the two dependent variables were as follows:

$$VST = 0.403(lat) + 0.076(long) + 0.161(dis_w) - 0.011(RT_5) - 5.974,\ R^2 = 72.2\% \tag{7}$$

$$MST = -2.398(lat) - 0.518(long) - 0.016(elev) + 0.296(dis_w) - 0.049(RT_3) + 61.937,\ R^2 = 88.3\% \tag{8}$$

These calibrated equations were used to calculate both the VST and MST values for each cell. Figure 9 shows the resulting VST and MST maps for the Ontario case study.

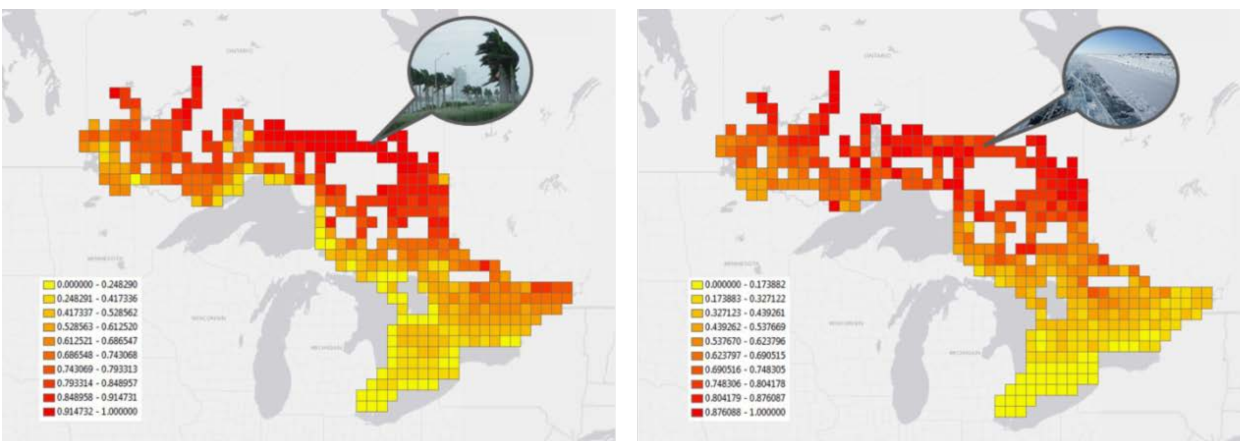


Figure 9. Processed VST (left) and MST (right) maps

From Equations 7 and 8, it can be clearly seen that all regression coefficients make intuitive sense. For instance, latitude, longitude, and distance to water have a positive correlation with VST, implying that as the value of each parameter increases, so does the VST. It is true, particularly during colder months, that surface temperature likely varies to a greater extent in high-latitude regions. Furthermore, VST is likely to be higher for grid cells that are deeper within continents, which are typically more mountainous and therefore experience larger temperature variations. These phenomena are explained graphically in Figure 9 (left): the VST cells in southern regions and/or near lakes tend to exhibit less variation than other cells. As for MST, all regression coefficients except for distance to water were found to be negative. This is observed because the minimum surface temperature drops in the northern regions with higher elevations. Note that MST can vary by a significant amount (~20^{o}C) between the northernmost and southernmost cells in Figure 9 (right).

Precipitation (Snowfall): Distribution of precipitation amounts, particularly snowfall amounts, were thoroughly investigated to determine the regions where heavy snowfalls are likely to occur so that recommendations for RWIS stations could be made accordingly. This was done by analyzing the long-term historical snowfall observations. Daymet is an online weather data archive where daily surface weather and climatological summaries are available for public use (Thornton et al. 2012). SWE describes the amount of water contained within the snowpack, expressed in kg/m^2. Average annual summary maps of SWE covering the entirety of North America were obtained for the period from 2001 to 2005. Because these files came in raster format, a five-year average map was generated by averaging of all available SWE layers using ArcGIS 10.1. Once all the maps were combined and averaged, each cell for the entire grid was assigned the corresponding SWE value (i.e., the sum of all SWE data within each cell). Note that because the SWE data were available at the level of the individual grid cell (1 km^2), there was no need to develop models to infer this variable over the entire region, as was the case with MST and VST. Figure 10 (top left) shows the processed SWE map, where the central regions seem to have the most snowfall and the amounts gradually diminish towards the outer regions. The farthest southern regions appear to have the least amount of snowfall.

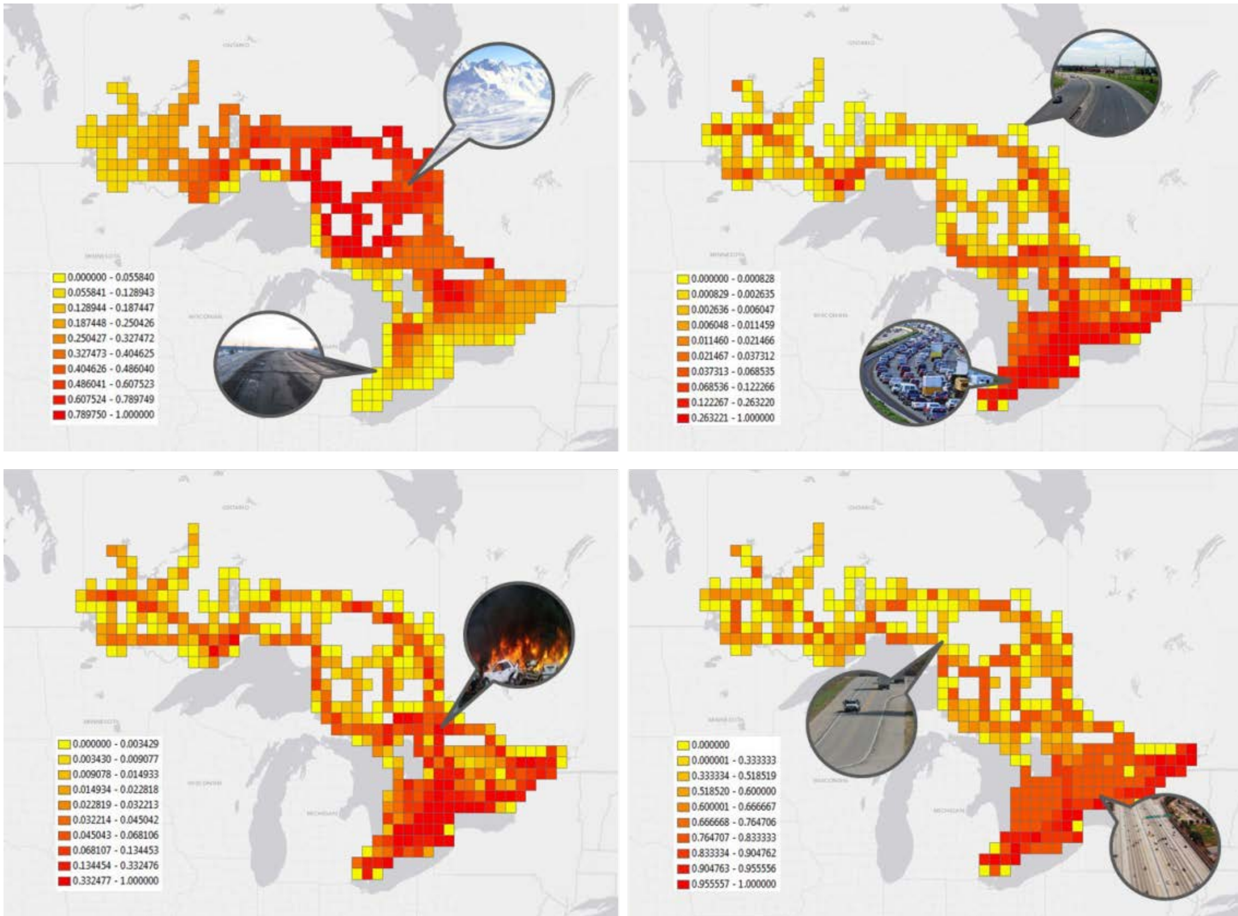


Figure 10. SWE (top left), WADT (top right), WAR (bottom left), and HT (bottom right)

Traffic Volume (WADT), Accident Rate (WAR), and Highway Type (HT): As was emphasized above, RWIS stations should be located in places where traffic volumes and accident rates are high so that the benefits to road users can be maximized. This reasoning can also be applied to highway type, where higher classes of highways should be given a higher priority when installing RWIS stations. For this reason, WADT, winter accident rate (WAR), and highway type (HT) were considered as surrogate measures for locating RWIS stations. The traffic information management center at the Ministry of Transportation of Ontario (MTO) provided data for the period from 2000 to 2010 for provincial highways' winter traffic volumes, accident numbers, and highway classes, all of which were geocoded using a linear highway referencing system. MTO currently has a total of 2588 geocoded locations across the province. With these geocoded locations, WADT data were mapped onto the grid, and the data were averaged and assigned to the corresponding cells. WAR, as used in the analysis, is defined as the number of reportable accidents occurring during winter months on a particular highway section for every MVKT on that section during the period. Representative section lengths for all geocoded points were used to calculate WAR. Four different types of HT that are currently being used by MTO were defined. Following a similar approach to that used for other traffic data, HT data were first geocoded using the linear highway referencing system, and then the averaged values were assigned to each cell.

Figure 10 (top right), (bottom left), and (bottom right) depicts the processed WADT, WAR, and HT maps, respectively. As the figure shows, WAR and WADT data appear to share some common traits, in that there are many "high-risk" cells in the southern region that have relatively heavier traffic loads and higher accident rates. This makes logical sense because an increase in exposure would likely increase the number of accidents. In contrast, the northern regions include many low-valued cells, which indicates that they are less important when traffic is considered as a location criterion. Similar conclusions can be drawn by analyzing the HT map: many high-class highways are situated in the southern region, suggesting a greater need for RWIS stations.

4.4.1.2 Evaluation of Alternatives

Different alternatives were evaluated by relocating Ontario's existing RWIS stations according to each alternative and comparing the results to the stations' current locations. For each alternative, the objective function formulated earlier (see Equation 5) was used to determine the candidate locations based on the values of the given selection criterion. For the analysis, an equal weight of 1 was used for weather and traffic factors, and the maximum number of stations to be installed was set to 140, which is the current number of RWIS stations.

Alternative 1: Weather Factors Combined: For this alternative, weather factors are used to evaluate the current RWIS network in the province of Ontario. The VST values in each cell were added to the corresponding SWE values in each cell. Note that both factors were normalized with a range between 0 and 1 to ensure a fair comparison. Figure 11 shows the results of the combined location selection criteria, and the current Ontario RWIS stations are superimposed on the map. Highlighted cells represent the optimized 140 cells that are recommended as potential RWIS station locations.

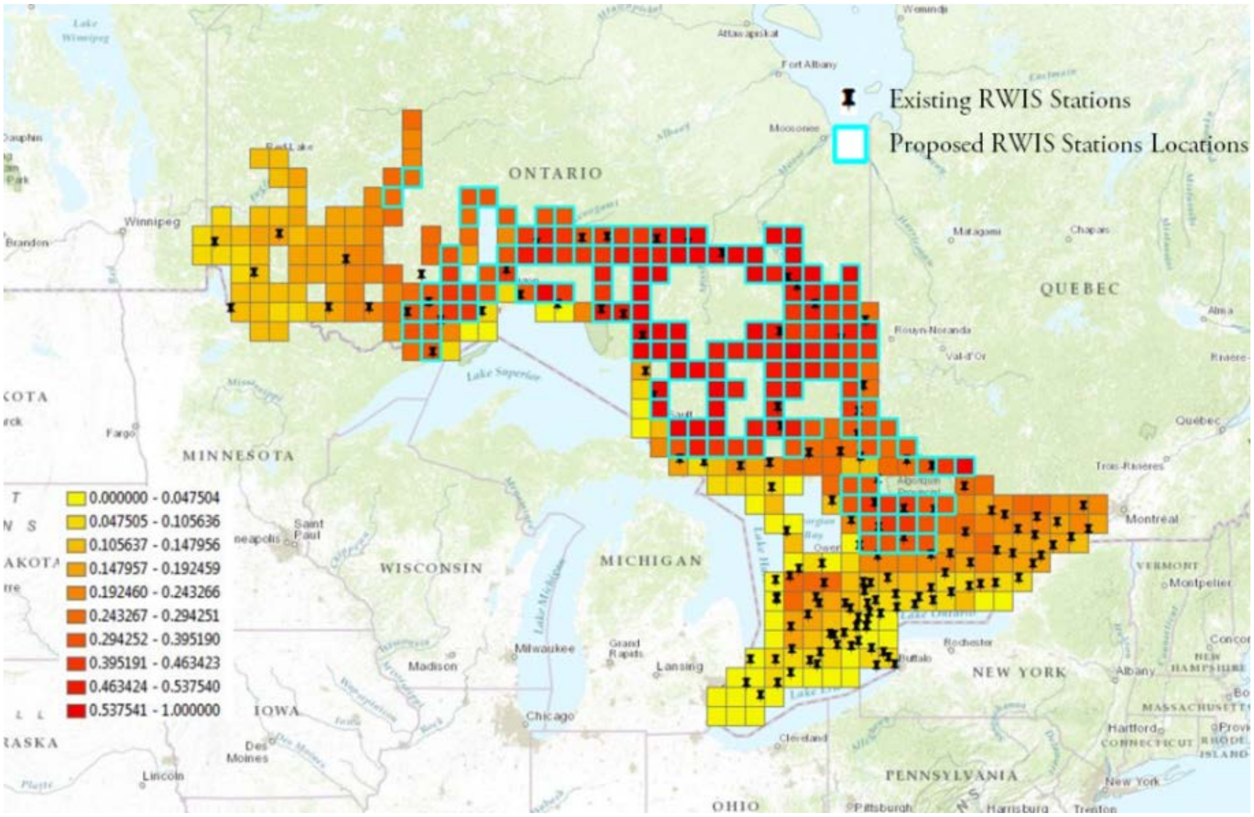


Figure 11. Alternative 1: Weather factors combined

As can be seen in the figure, the map resulting from the combination of two weather factors suggests that potential RWIS sites should be sited in the middle to upper part of the region, where VST and SWE values are significant. The percent of matching (POM) value for this alternative, which describes an evaluation metric for benchmarking the current locations of the RWIS stations, was found to be 30%, with 42 cells matching the existing RWIS station locations. Note that there are many highlighted cells in the central regions where no RWIS stations are currently present to monitor the highly varying weather conditions and historically heavy snowfall events. Based on this analysis, it can be stated that the current RWIS network lacks the ability to capture the variability in weather conditions.

Alternative 2: Traffic Factors Combined: A second alternative examines the two traffic-related factors, namely, WAR and HT. Figure 12 illustrates the proposed 140 locations of RWIS stations when only traffic factors are considered.

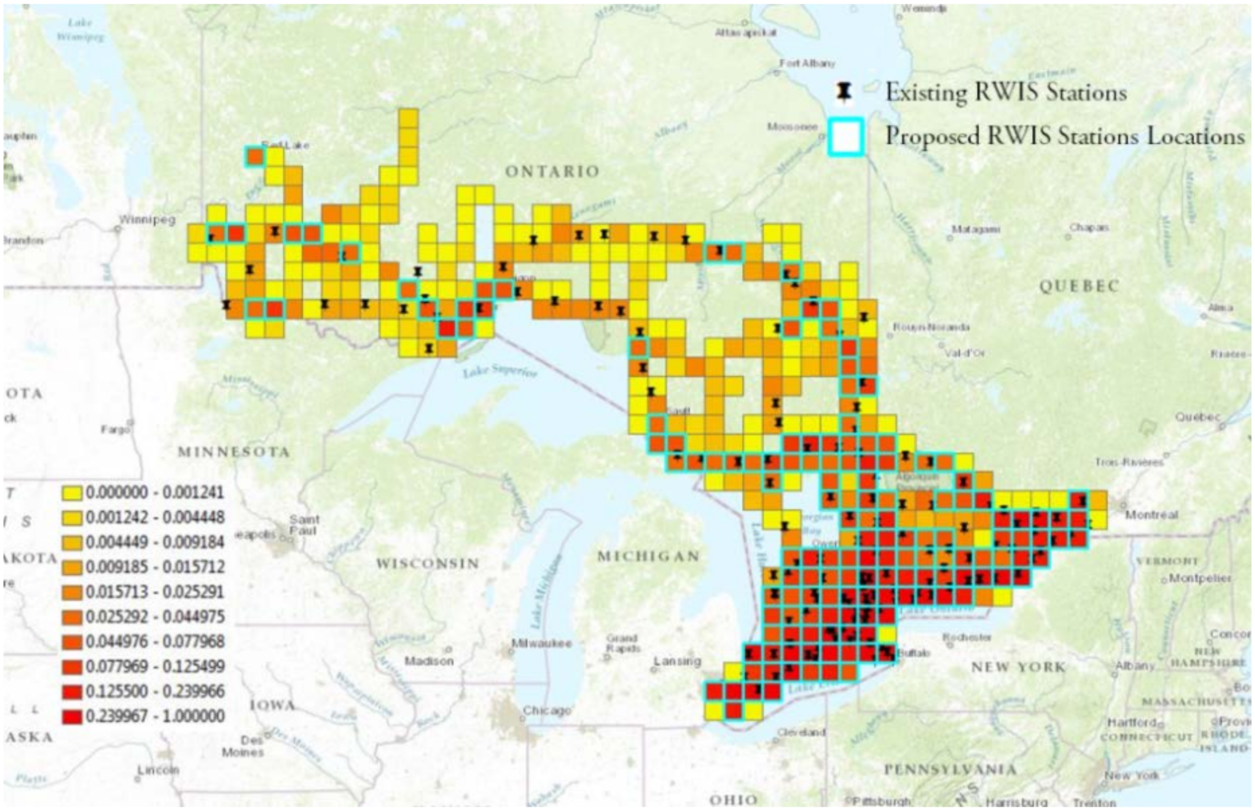


Figure 12. Alternative 2: Traffic factors combined

Note that the map in Figure 12 now focuses more on the areas where high accident rates/highway classes exist. The results of this alternative suggest that almost all of the southern parts of the province should have RWIS stations installed while many parts of the northern region should be left uncovered. Based on this alternative, 110 of the 140 existing RWIS stations (79%) should be located at the same sites. Such a high matching rate should not be viewed as an indication that these location criteria are better than those of Alternative 1; instead, this result should be considered as an indication that these factors are heavily weighted in Ontario's current RWIS location planning practice.

Alternative 3: Weather and Traffic Factors Combined: A third alternative combines both weather and traffic factors to balance the deficiencies and limitations of Alternatives 1 and 2. Figure 13 shows the 140 locations where RWIS stations are recommended to be sited when the combined factors are considered.

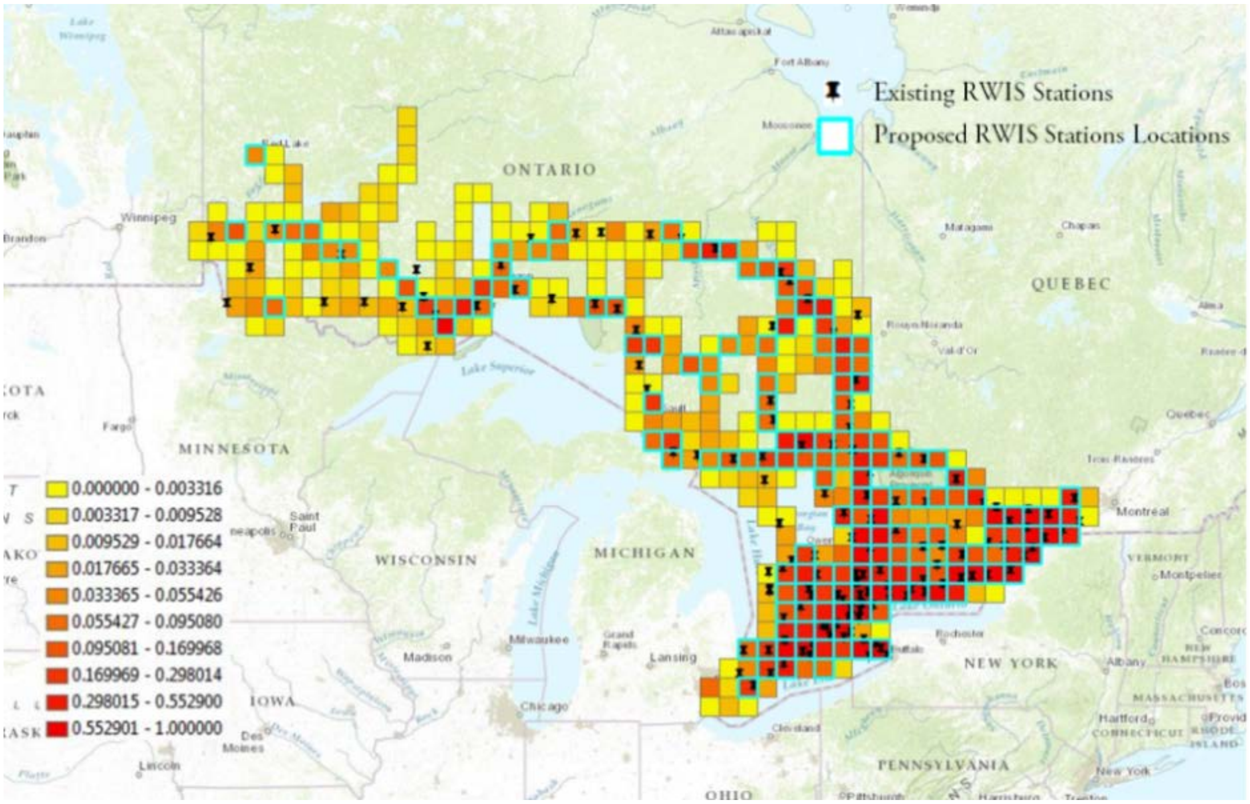


Figure 13. Alternative 3: All factors combined

The POM for Alternative 3 (85%) was found to be the highest of all the alternatives, and a visual inspection of the map in Figure 13 shows that the identified cells are better distributed over the entire province than in Alternatives 1 and 2. It is also noteworthy that the POM is based on the current locations of the Ontario RWIS stations and thus does not provide an absolute measure of the performance of the current network.

4.4.1.3 Summary

In this section, the surrogate measure–based approach for choosing the potential locations of RWIS stations at a regional level was illustrated. Two types of surrogate measures were considered, including three weather-related factors and three traffic-related factors. The weather criteria follow the logic that RWIS stations should be placed where the weather is most severe and varied, while the traffic criteria follow the rationale that serving a higher amount of the travelling public would provide more benefits. A total of three location selection methods were formulated. Alternative 1 accounts for the weather factors, Alternative 2 accounts for the traffic factors, and Alternative 3 is a combination of Alternatives 1 and 2. These alternatives were used to evaluate the current Ontario RWIS network. The findings reveal that Alternative 1 is more focused on the northern region, which experiences highly varying weather conditions, while Alternative 2 is more focused on the southern region, which experiences heavy traffic loads. The high POM rate of Alternative 2 indicates that the current RWIS network has been set up in such a way that it predominantly considers the need for covering the road network. Likewise, the large difference between the results generated by the traffic- and weather-related criteria suggests that the RWIS stations may not have been located optimally. Alternative 3 seems to balance the limitations of the first two alternatives by suggesting that potential RWIS locations be distributed uniformly across the whole province. It is unknown how much weight needs to be put on each of the criteria discussed here, but it is clear that the proposed framework is easy to apply when planning an RWIS network expansion that weights individual criteria based on their importance.

4.4.2 Application of the Cost-Benefit–based Method: Minnesota RWIS Network Analysis

This section demonstrates the application of the cost-benefit–based approach by analyzing the Minnesota RWIS network. Considering the amount of data that needs to be prepared, integrated, and processed, only the northern part of Minnesota was evaluated. This region currently has a total of 46 RWIS stations covering a road network of approximately 11,500 km, as depicted in Figure 14.

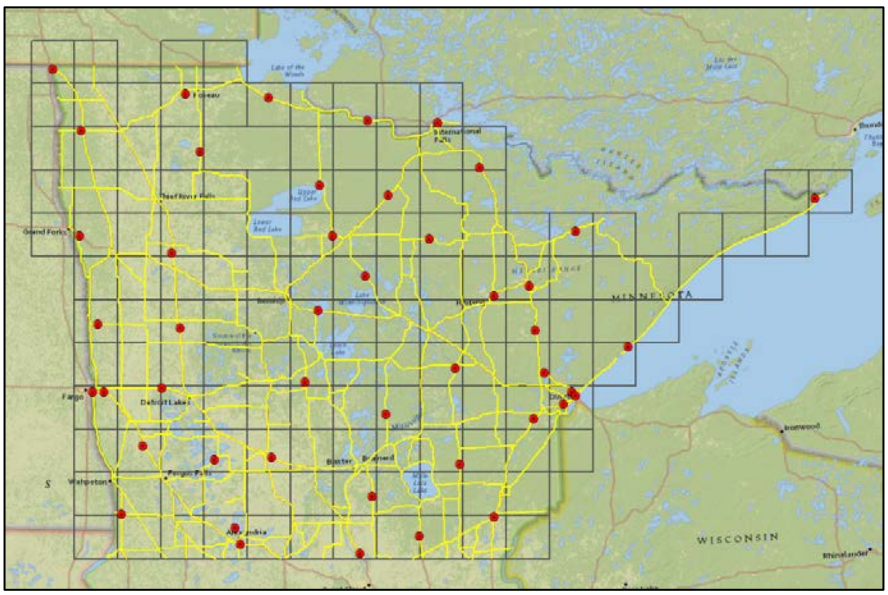


Figure 14. Study area with RWIS stations (red dots) and highway network (yellow lines)

The individual RWIS stations and the Minnesota highway network are shown by red circles and yellow lines, respectively. Figure 14 also shows a grid of cells, each having an area of 30 x 30 km^2. This spatial resolution was determined based on the survey by Kwon and Fu (2012b), which revealed that most states keep a distance of 20 to 50 km between two RWIS stations. The Minnesota Department of Transportation (MnDOT) sets 30 km as the desired spacing between RWIS stations, although this criterion is not a requirement and can be adjusted according to different standards and needs (Rockvam et al. 1998). As mentioned above, only the cells that the highway network lines pass through were extracted because other cells are not considered to be potential RWIS candidate sites, including the cells placed on top of lake areas. It should be noted that the methodology discussed in the following sections can be equally applied to any grid size.

4.4.2.1 Data Processing and Integration

Three sets of data—maintenance, collision, and traffic data—were provided by MnDOT. The data were processed and then integrated into a single data set for use in later analyses. ArcGIS 10.1 and QGIS 1.8 were the primary software used for processing and compiling geocoded data and analyzing mapped information.

Maintenance data were received in an Excel file containing all 1836 winter maintenance event records collected over a total of 16 winter months from 2011 to 2013. Each maintenance record included a unique project identification number along with information on labor, equipment, sand, salt, and brine costs. Using a project identification number as a reference, the data from all available maintenance event records were added and averaged to obtain the annual average cost for each maintenance route. Data on a geocoded base route created for the purpose of mapping the maintenance data were provided by MnDOT. Using the base route data, the processed maintenance data were joined by matching the project identification numbers and were thus geocoded on the map.

Collision data collected over a five-year period (2008 to 2013) contained individual crash records with detailed information. Each record listed day, month, year, data reliability, location, severity, number of vehicles involved, type of collision, and weather and surface condition information. As noted above, it was important to consider only the collisions that could potentially be avoided by proactive and responsive WRM operations using information at least partially obtained from nearby RWIS stations. As such, 18360 records were extracted for collisions that occurred during inclement weather conditions, such as freezing rain and blowing snow, and HRSCs such as wet snow, slush, and ice. Using locational attributes (e.g., latitude and longitude), individual collision records were superimposed onto the base map, and the sum of all available collisions was calculated for each base route, for a total of 369 available routes.

Traffic data consisted of 1369 geocoded AADT counts collected over a 10-year period starting in 2001. Because this study focused on winter seasons, WADT was calculated using a simple conversion factor. The conversion factor used in this study was determined based on empirical evidence confirming that the magnitude of the difference in the average daily traffic between normal days and winter days is stable and consistent. However, it is important to note that the application of a uniform conversion factor for an entire analysis region may not be appropriate or representative because traffic counts may vary depending on the location of analysis. MVKT, used as a measure of traffic flow or exposure, was calculated using the following equation:

$$MVKT = \frac{AADT \times 212 \times SectionLength}{1{,}000{,}000} \quad (9)$$

where Section Length is expressed in kilometers and was determined for all routes using a geometry tool available in ArcGIS. Note that a numerical value of 212 (i.e., the number of winter days in one year) was used instead of 365 to correctly reflect traffic exposure during winter months.

Another important measure used in the analysis was the target BPTRT of a highway route. During winter storms, a winter maintenance schedule requiring staggered work hours may be used to provide the level of service recommended. Each maintenance area, district, and division develops a schedule of effort needed to achieve target BPTRT, and an essential surrogate measure for the type of highway can be extracted from these schedules. This is particularly important for ensuring pair-wise comparisons for constructing RWIS benefit models. By following the bare lane indicator guidelines shown in Table 3, traffic count data were used to determine the BPTRT (e.g., a WADT of 1,000 is given a BPTRT of 9 hours).

Table 3. Bare lane indicator guidelines

Classification	Traffic Volume	BPTRT
Super Commuter	Over 30,000	1 – 3 hours
Urban Commuter	10,000 – 30,000	2 – 5 hours
Rural Commuter	2,000 – 10,000	4 – 9 hours
Primary	800 – 2,000	6 – 12 hours
Secondary	Under 800	9 – 36 hours

Once processed, traffic data together with three new measures—WADT, MVKT, and BPTRT—were integrated and merged onto the base routes to form a new database, with each measure expressed in terms of the base route. These three measures were included in the RWIS benefit-cost modeling phase to investigate their degree of influence on the savings from reduced maintenance costs and collision frequencies.

4.4.2.2. Modeling RWIS Benefits and Costs

As described above, the two dependent variables of interest for this analysis were maintenance cost and number of collisions, expressed in terms of their corresponding base routes, for two distinct scenarios: one with RWIS and the other without RWIS. The rationale for adopting this method is that a highway section covered by a nearby RWIS station is more likely to receive more efficient and cost-effective WRM than a highway section far from an RWIS station. Although RWIS information alone may not provide sufficient information to maintenance personnel in their decision making process, the use of additional information (i.e., RWIS data) can certainly help provide better estimations and lead to better WRM service. This is particularly true when pavement surface condition forecasts are available to maintenance staff to use in deciding whether and how to apply anti-icing chemicals before a snow storm hits to minimize or prevent the formation of bonded snow and ice layers (C-SHRP 2000). Furthermore, because the treatment is done proactively, a smaller amount of chemical is needed to prevent ice bonding than when the road is treated reactively after a snowfall (Epps and Ardila-Coulson 1997).

Figure 15 shows the existing RWIS stations, buffered zones, and roads that are and are not covered by RWIS stations in northern Minnesota. Red dots indicate RWIS stations, yellow circles indicate a 30 km buffer around the RWIS stations, and red and blue lines indicate roads influenced and not influenced by RWIS stations, respectively.

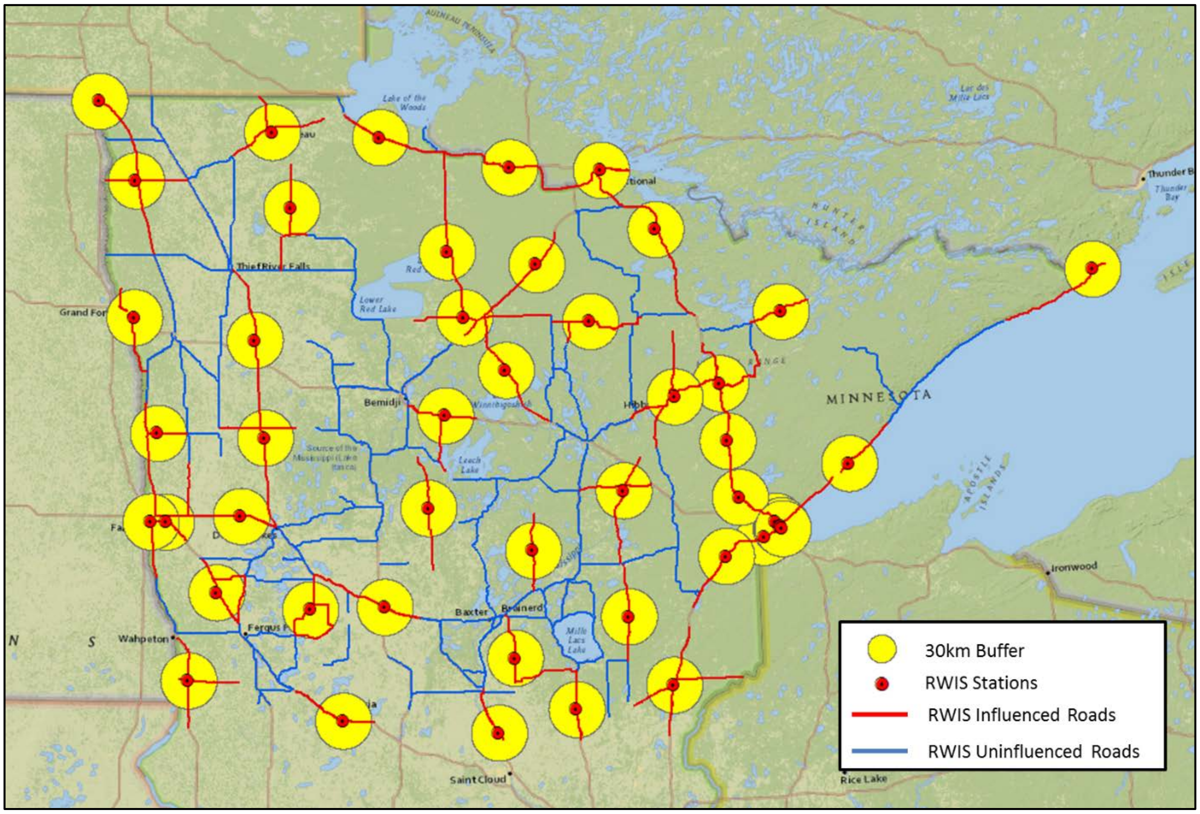


Figure 15. Implementation of the proposed method

As the figure shows, the routes on which RWIS stations are located were categorized as RWIS-influenced routes, while the rest were categorized as routes not influenced by RWIS. Note that for this case study, a buffer zone with a 30-km diameter was chosen because in the current practice an average separation distance of between 20 and 50 km is typically used as a guide for installing another regional RWIS station (Manfredi et al. 2005). This assumption was made to best separate the two categories of routes so that the effect of RWIS could be properly investigated. Such an assumption may not hold true at all times, and the maximum range of RWIS influence may vary by location. However, the underlying methodology for quantifying the RWIS benefits can equally apply under different assumptions, regardless of the grid size selected for analysis.

Once the two groups of routes were identified, the data, including length of the route, maintenance costs, collision frequency, WADT, MVKT, and BPTRT, were extracted for further analysis from the integrated database constructed earlier. The two groups of data were then compared and matched according to highway type and location in order to conduct a fair comparison. Multiple linear regression analyses were conducted to develop models for unit maintenance costs and collision frequency as a function of various variables. All variables were tested at the 5% significance level to determine the statistically significant factors that affect the variations in maintenance costs and collision frequency for the two groups. The resulting equations for the two dependent variables are as follows:

$$UMC_i^{RWIS} = 0.094 \times WADT - 52.593 \times BTRT + 1956.568, R^2 = 53.5\% \quad (10)$$

$$UMC_i^{No\ RWIS} = 0.128 \times WADT - 29.003 \times BTRT + 2196.544, R^2 = 45.7\% \quad (11)$$

$$CF_i^{RWIS} = 20.486 \times MVKT + 1.118, R^2 = 65.8\% \quad (12)$$

$$CF_i^{No\ RWIS} = 64.872 \times MVKT + 1.229, R^2 = 61.7\% \quad (13)$$

where *UMC* and *CF* are unit maintenance costs in $/lane-km and collision frequency, respectively. Given the unit maintenance cost (i.e., UMC_i^{RWIS} and $UMC_i^{No\ RWIS}$), the annual maintenance cost of a given maintenance route (i.e., MC_i^{RWIS} and $MC_i^{No\ RWIS}$) can be expressed as the product of the total route lane kilometers and the unit maintenance cost. Similarly, the annual collision cost of a given maintenance route (i.e., AC_i^{RWIS} and $AC_i^{No\ RWIS}$) can be determined by multiplying the collision frequency (i.e., CF_i^{RWIS} and $CF_i^{No\ RWIS}$) by the unit collision cost.

Based on collision cost data from the FHWA (1988) and historical collision data, the unit collision cost was estimated to be $17,472, which was used in this analysis. Analyses of these equations and their coefficients show that highway routes with RWIS have lower estimated maintenance costs and lower numbers of collisions than routes without RWIS, which clearly indicates the benefits of installing RWIS stations. Note that the resulting equations have moderate R^2 values, which was expected because many other factors than the ones considered in this study are likely to affect the observed variability in collision frequency and maintenance costs. Collisions are rare events and are often caused by a combination of multiple factors related to the driver, the vehicle, and the environment. It should be noted that the benefit and cost models could be further improved by considering other potential contributing factors, such as savings due to reduced patrolling and travel time costs, which can be realized by more effective and efficient winter maintenance operation activities.

4.4.2.3. Analysis of Optimal RWIS Locations

In the next step for determining the optimal RWIS station locations, the estimated benefits for both maintenance and collision were sorted in descending order so that cells with higher benefits could be given priority for consideration over cells with lower benefits. The optimal number of RWIS stations (refer to Section 4.5.1) was used as a threshold to select the top 45 cells as the optimal RWIS station locations in the area being analyzed. The maps in Figure 16 show the top 45 selected (colored) cells recommended as the optimal locations given the three analysis criteria, that is, where the highest benefits can be obtained in terms of maintenance, collision avoidance, and the combined savings.

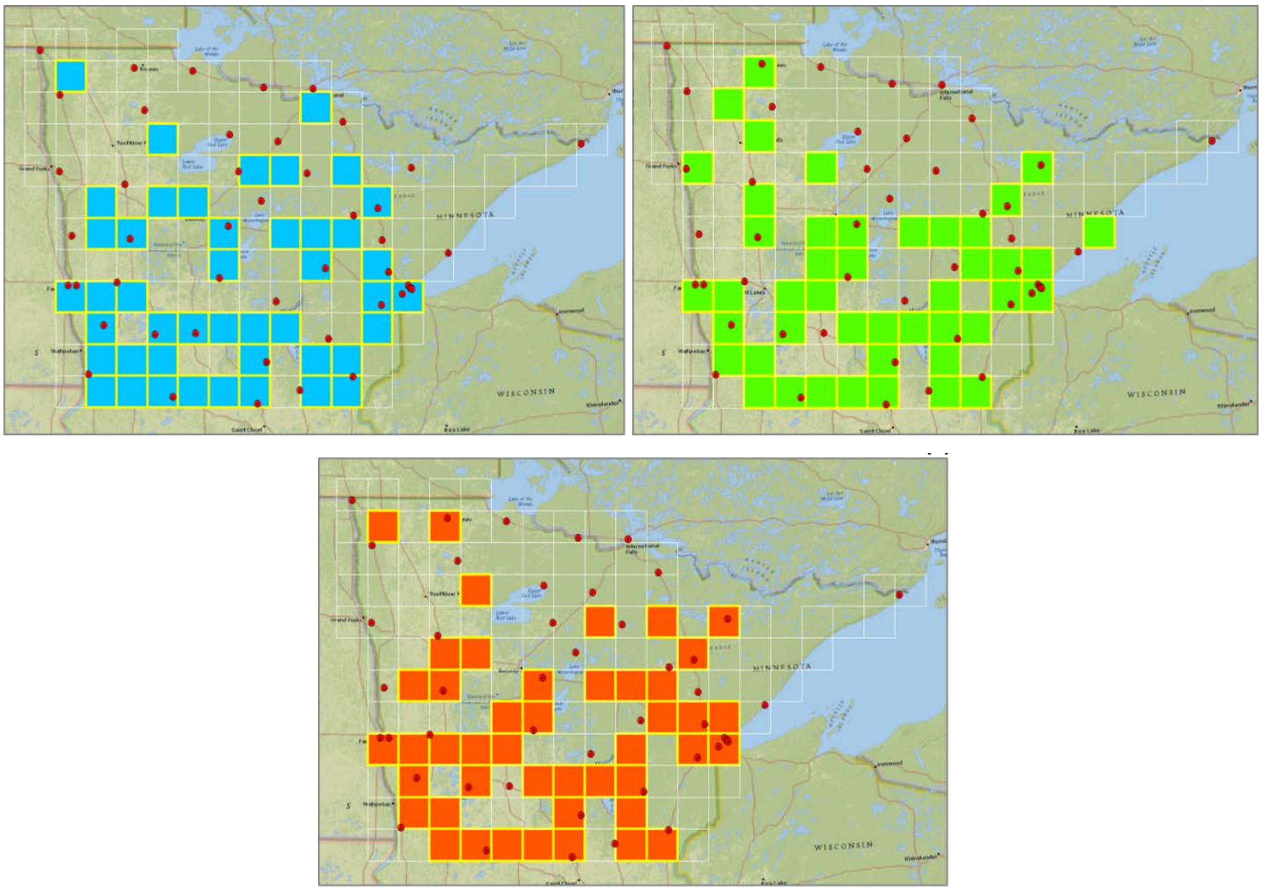


Figure 16. Optimal RWIS station locations in terms of maintenance benefits (top left), collision benefits (top right), and the combined benefits (bottom)

In all cases, it can be seen that the recommended sites are generally well-distributed over almost the entire region, except the northern part of the state, which is relatively less covered by RWIS. This distribution can be attributed to the fact that the models do not account for topographical and meteorological variations. Analysis of such phenomena is essential because inclusion of these factors would likely increase the models' explanatory power and allow the benefits to be better modeled.

It is important to note that the foreseeable monetary benefits presented herein should not be perceived as absolute benefits that are expected to accrue across different regions with different traffic and weather conditions because these benefits could conceivably vary when other evaluation criteria are used. Rather, the proposed method provides a framework with which an existing RWIS network can be evaluated quantitatively. The underlying work should be regarded as an incremental addition to the existing literature, which lacks quantitative evidence that RWIS implementation is truly beneficial. It is anticipated that the proposed method will provide provincial highway agencies with a useful tool for evaluating and optimizing their RWIS networks.

4.4.2.4 Summary

In this section, the cost-benefit–based method described in the previous section was applied to analyze the location and density of the Minnesota RWIS network. The method is the first of its kind to attempt to formalize the ultimate benefits of an RWIS network. A case study based on the current RWIS network in northern Minnesota was used to test the applicability of the proposed method. RWIS benefit models were developed for two groups of highway maintenance routes—those covered by RWIS and those not covered by RWIS—using three types of data, including maintenance costs, collisions, and traffic counts. For data preparation, the study area was divided into 139 equal-size cells, and auxiliary information was extracted from individual cells to estimate the annual costs of both maintenance and collisions. The 25-year life cycle benefits and costs were then determined using the calibrated models and used for identifying the optimal station density and locations. To determine the optimal locations, the benefits based on each criterion were sorted in descending order to prioritize the cells that would enjoy the greatest benefits.

The POM values for all three criteria—maintenance costs, collisions, and the combined benefits—were found to be 80%, 75.6%, and 77.8%, respectively. Similar yet high POMs indicate that the current RWIS siting is able to provide reasonably good coverage in terms of all three criteria. The findings in this study indicate that the proposed method is methodologically sound and is therefore suitable for analyzing the current RWIS siting and recommending where to locate additional RWIS stations, if needed. As mentioned above, it should be cautioned that the data used and the models developed in this study are aggregated on an annual basis such that the factors that influence operational decisions (i.e., when to perform WRM) may be concealed. However, for high-level planning purposes, the proposed method could serve as part of a decision support tool for optimizing RWIS station locations at a regional level.

4.4.3 Application of the Spatial Inference–based Method: Ontario, Minnesota, Iowa, and Utah RWIS Networks

The third alternative, the spatial inference–based method, is formulated to minimize the spatial inference errors (i.e., kriging variance) of RWIS measurements while maximizing the coverage of accident-prone and/or high–travel demand areas. This optimization framework takes explicit account of the value of information from an RWIS network and offers the potential to enhance the overall efficacy of winter maintenance operations and improve the safety of travelers. The features of this method are demonstrated using four real-world case studies from Ontario, Minnesota, Iowa, and Utah.

The four transportation agencies provided their regional RWIS data, which were collected at 10- to 15-minute intervals over three consecutive winters (i.e., October to March) between 2010 and 2013 (2006 to 2008 for Ontario). The data came stratified by individual station, each of which yielded nearly one million rows of measurements, including the variable of interest, surface condition status. The data included a total of 15 surface status codes describing current representative surface conditions expressed in a descriptive format. These status descriptions were listed by order of severity and further classified into four categories, with the most critical category listed first. In this study, the top category, which represents HRSC, was considered. This category includes status codes for snow/ice warning, frost, wet below freezing, and snow/ice watch. Each data entry was checked and counted if it reported anything that belonged to the top category under consideration. A script program was written to efficiently process over 60 million rows of data, returning a yearly (seasonal) average of HRSC frequency for each corresponding RWIS station for all regions.

In addition, the participating agencies provided data on travel demand (AADT and road class) and/or vehicular collision records. To ensure a fair comparison, road class was used as a common traffic criterion. A primary reason for using road class information as the common criterion is that there was a considerable amount of variation in the traffic volume and collision data. Such a large variation may produce biased results when combined with other non- or less-skewed data (e.g., HRSC frequency). Hence, in addition to the first criterion representing HRSC frequency, road class was added as another criterion to obtain a well-balanced optimal RWIS network.

4.4.3.1 Optimal Relocated RWIS Network

This section describes an analysis of the hypothetical problem of relocating the entire set of existing RWIS stations for each of the four regions. The objective of the exercise was to gain valuable information about the current locations and simulate how optimal locations change when different weights are assigned to the two different criteria considered in this study. As discussed above, the greatest benefit of the proposed approach is its ability to simulate and optimize RWIS station locations for any given settings that users define. This ability is advantageous because the costs associated with establishing any monitoring stations are very high (Chang et al. 2007). Additionally, this method provides decision makers with the freedom to choose different weights depending on the needs of the traveling public, winter road maintenance requirements, and agencies' respective priorities in locating RWIS stations.

The RWIS network for each location was optimized under two different scenarios (weather only and weather and traffic combined), as presented in Figure 17.

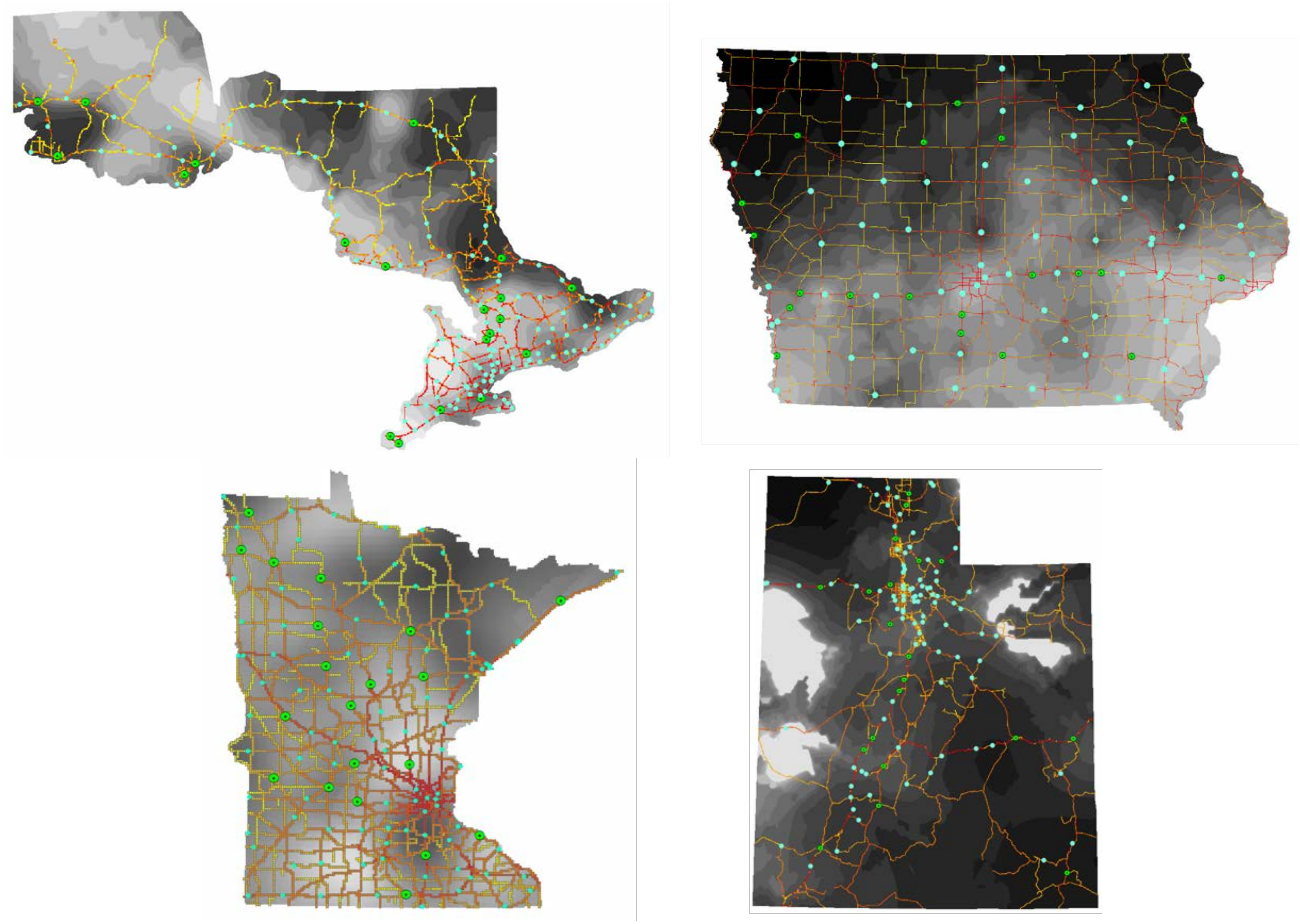
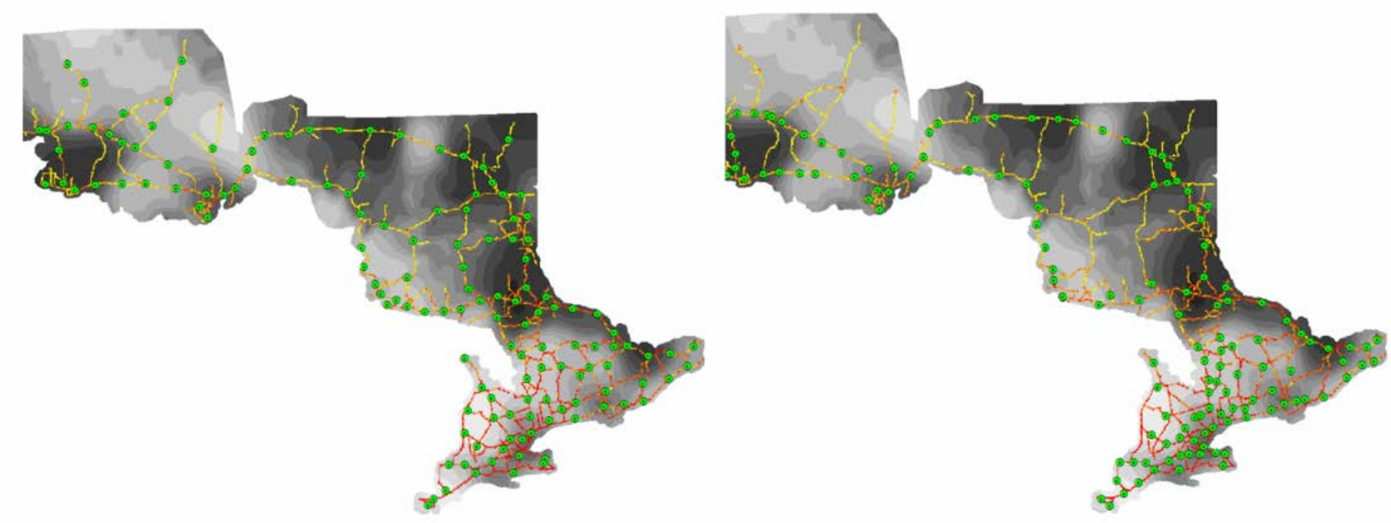


Figure 17. Placement of 20 additional RWIS stations for Ontario (upper left), Iowa (upper right), Minnesota (lower left), and Utah (lower right)

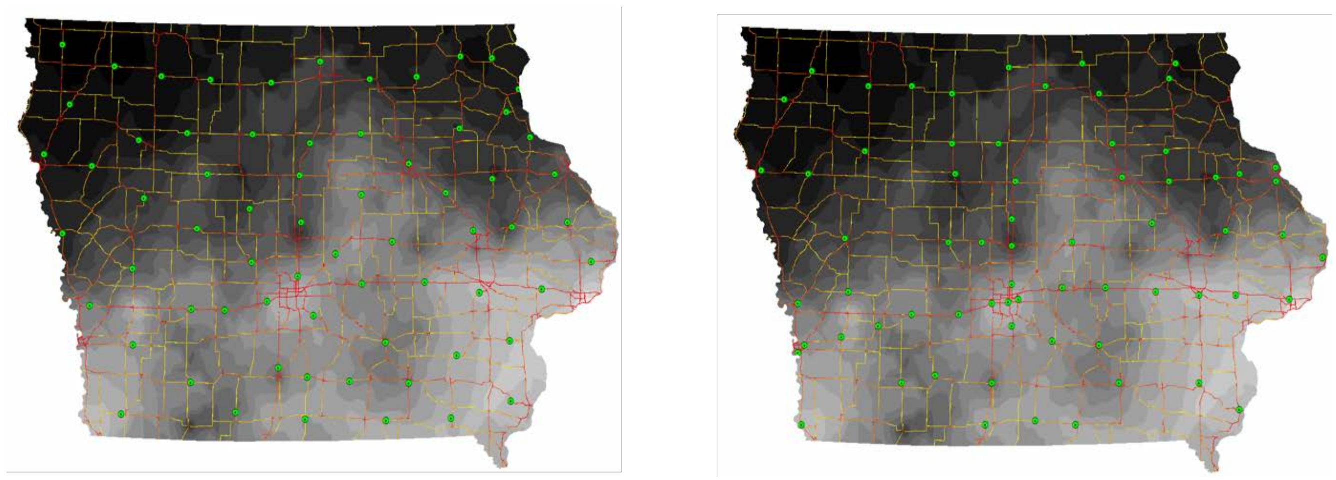
In Figure 17, the optimized RWIS stations are denoted by green circles. The aggregated road classes and interpolated HRSC measurements (with dark shades representing more hazardous areas) are superimposed on the maps to help demonstrate how the assignment of different criteria can contribute to decisions about the optimal locations for individual RWIS stations.

The optimization was run three times for each scheme, and the outputs were visually compared to confirm that the optimization outputs were consistent. The intent of multiple runs was to ensure that the SSA algorithm had reached a (near) optimal solution without becoming trapped in local minima, which is an inherent problem of the SSA algorithm and all other metaheuristic algorithms currently available today.

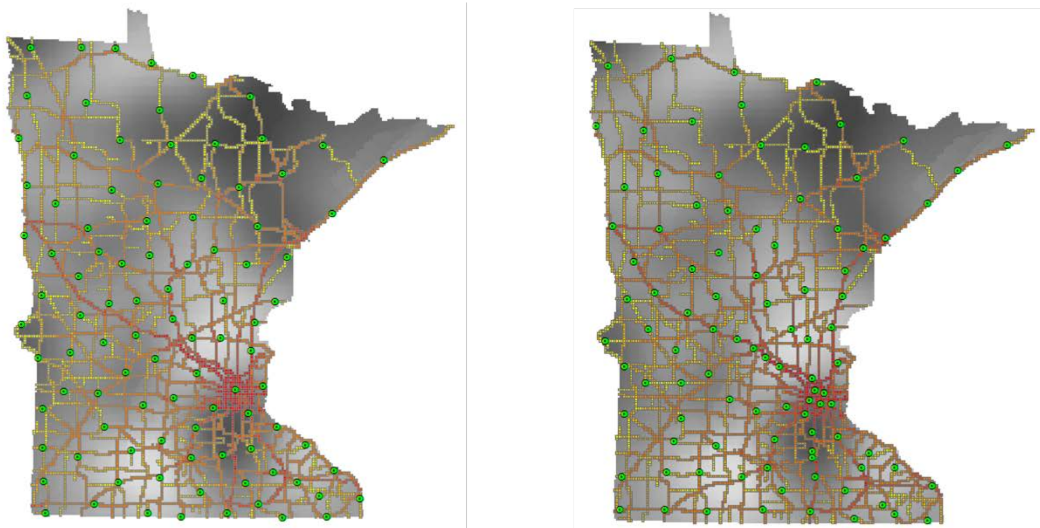
In the maps for Crit1 in Figure 18, kriging variance is only used in the objective function to minimize the spatially averaged kriging variance.



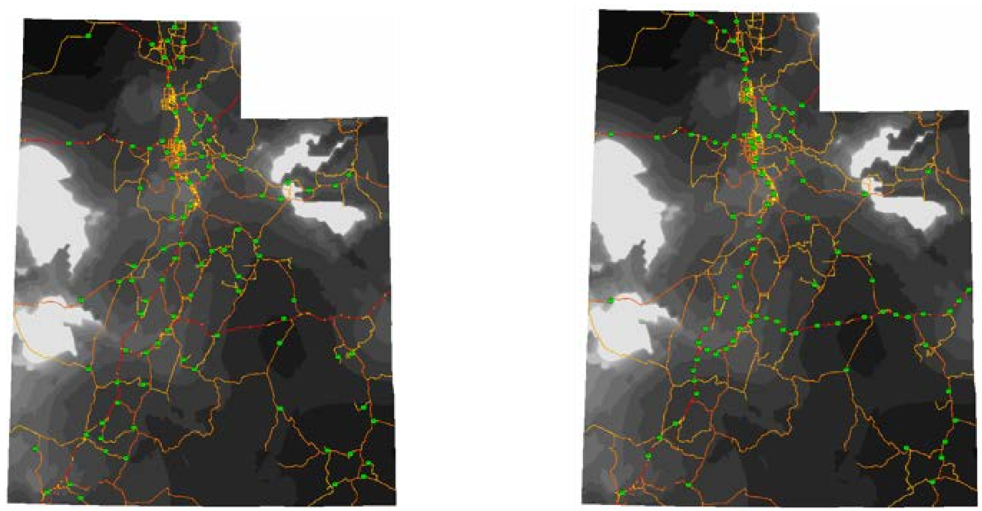
Ontario: Crit1 (left) and Crit1 + Crit2 (right)



Iowa: Crit1 (left) and Crit1 + Crit2 (right)



Minnesota: Crit1 (left) and Crit1 + Crit2 (right)



Utah: Crit1 (left) and Crit1 + Crit2 (right)

Figure 18. Optimized relocated RWIS station locations

In all of the maps in Figure 18, it is evident that RWIS stations are concentrated in locations with a high occurrence of HRSC, particularly in the darker areas representing a higher occurrence of HRSC, without offering much consideration to the traveling public. It is also clear that sites are well distributed over the entirety of each of the study regions, maximizing the coverage on a global scale.

In the right-hand maps in Figure 18, the traffic criterion (i.e., Crit 2), representing road class, has been added to the first criterion and given equal weight. As these maps clearly show, incorporation of the traffic criterion makes it possible to capture high–travel demand areas and thus provide improved balance. The resulting difference in the pattern of RWIS station locations is well manifested; a higher number of RWIS stations have been allocated to areas exposed to high traffic demand.

To evaluate the overall efficacy of each optimized network (shown in Figure 18) with respect to the existing network (shown in Figure 7), the objective function was used to calculate a corresponding numerical value for each optimized network and the current RWIS network. For the optimized networks, this evaluation metric was simply the lowest value obtained at the end of each optimization. For the existing network, a comparable yet equivalent approach was used that included adding the averaged kriging variance and road class given the current RWIS station locations. Table 4 compares the averaged objective function value (for three runs) associated with each optimal solution to that of the current network, along with the percentage of improvement.

Table 4. Comparison of objective function values of the optimized and current networks

Scenarios	Objective Function Optimized / Base Case	% Improvement
Ontario	0.4154 / 0.4771	**12.94%**
Iowa	0.7425 / 0.8748	**15.12%**
Minnesota	0.6854 / 0.8182	**16.23%**
Utah	0.7921 / 0.8942	**11.14%**

As expected, the percentage of improvement, which can be interpreted as the perceived benefits of the relocated RWIS network, was found to vary between 11% and 16%, signifying that the optimized networks are “better” in terms of their ability to monitor various hazardous road surface conditions while considering the needs of the traveling public, as defined in the objective function.

4.4.3.2 Expansion of the Current RWIS network

In the previous section, the proposed method was applied to identify optimal locations for the entire existing set of RWIS stations. This section shows how to apply the proposed method to develop an expansion plan for each of the four regions. The optimization problem was modified to reflect the changes in the base conditions. The objective function was evaluated at each iteration in consideration of the fact that there are fixed RWIS stations throughout the entire optimization process. Identical optimization parameters and weighting schemes (w1 = w2 = 1) were used to locate 20, 40, and 60 additional RWIS stations (green circles) for all four study areas, as depicted in Figure 18. (See Appendix D of this report for more details.)

As can be seen in Figure 18, if the objective of location optimization is to minimize the total estimation errors (and thus maximize the monitoring capability of the RWIS network), new stations should be located in the vicinity of existing stations (cyan circles). Additionally, incorporation of the traffic criterion made it possible to capture high–travel demand areas (shown in red-colored areas) and provide improved balance. A visual inspection of the resulting maps suggests that new stations nicely fill the gaps in the existing RWIS network. Furthermore, an evaluation of the objective function values shows that the current RWIS networks of Ontario, Iowa, Minnesota, and Utah were improved in terms of the defined objective function by 14.7%, 15.9%, 16.3%, 13.6%, respectively, with the placement 20 additional stations.

4.4.3.3 Summary

In this section, an innovative framework was introduced for the purpose of locating RWIS stations over a regional highway network. In the proposed method, the weighted sum of the average kriging variances of HRSC was used to determine the optimal RWIS network design.

This method relies on the sensible assumption that minimizing the total estimation error will, in due course, contribute to improving the overall effectiveness and efficiency of winter road maintenance operations. Road traffic data were incorporated and weighted to provide a balanced network that considers the demands of the traveling public. Case studies of four regions illustrated two distinct scenarios: redesign and expansion of the existing RWIS network. The findings indicate that the optimally redesigned RWIS networks are, on average, 13.58% better than the existing RWIS networks. The results further revealed that the deployment of 20 additional RWIS stations would improve the current network, on average, by 15.13%.

The overall findings of this study show that the new approach is easy and convenient to implement, and therefore appropriate for real-world applications, and integrates key features (road weather and traffic) considered in practice. In addition, this sampling method for determining RWIS station locations provides an alternative to the previous two approaches that offers much improved generalization potential and requires fewer data.

4.5 Alternative Approaches to Finding Optimal RWIS Network Density

4.5.1 The Cost-Benefit–based Method – Optimal Density in Minnesota, US

In addition to explicitly accounting for the potential benefits of an RWIS network, the cost-benefit–based method also provides an opportunity to investigate the optimal RWIS network density for a given region. This section shows how such an analysis can be performed using the same Minnesota network examined above.

The costs associated with an RWIS system can be estimated on the basis of various nominal cost statistics reported in the literature. Based on the literature, RWIS stations normally last for 25 years and, on average, cost about $90,000, which includes the costs of utility installation, traffic control, training sessions, and contract administration (Buchanan and Gwartz 2005). In addition, RPUs and CPUs need to be upgraded every five years, at a projected cost of $10,446. Also, each RWIS station needs to be monitored regularly to ensure that the data being collected are correct and that the station is operating well, a task that typically costs $5,460 per year (McKeever et al. 1998). Therefore, the annualized cost for installing, operating, and maintaining a typical RWIS station is $11,149. It should be noted that the unit cost of an RWIS station can vary significantly over different vendors, and the cost of a station is also dependent on many other factors, including the type and number of sensors used. The cost items used in this case study were based on what is currently available in the literature, and new values can be easily implemented in the analysis to see how they affect the results.

Based on the annual total benefits estimated by taking the sum of the results of Equations 6 and 7, the net present value (NPV) of these benefits can be determined using the following equation:

$$\mathrm{NPV} = \sum_{\mathrm{t}=0}^{\mathrm{n}} \frac{(\mathrm{C})_{\mathrm{t}}}{(1+r)^{t}} \tag{14}$$

where r, t, and n represent the discount rate (i.e., 8.1% as recommended by MnDOT), year of installation, and expected life of an RWIS station (i.e., 25 years), respectively (MnDOT 2013). C is a cash flow value that can be calculated by taking the difference between the RWIS benefits and the RWIS costs.

Figure 19 shows the development of NPV over a 25-year life cycle in terms of RWIS benefits and costs (top) and net benefits (bottom) expressed in terms of number of stations.

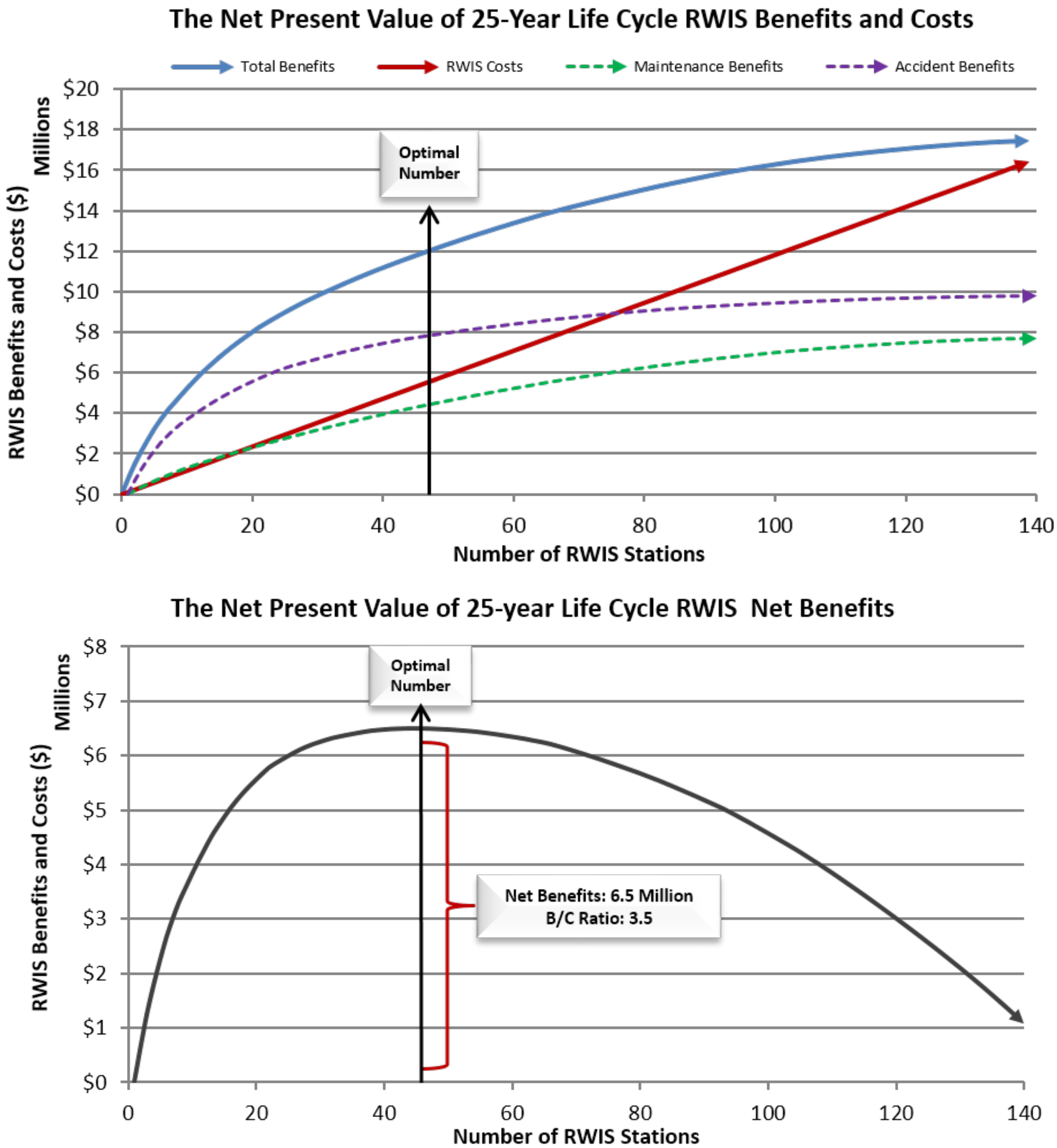


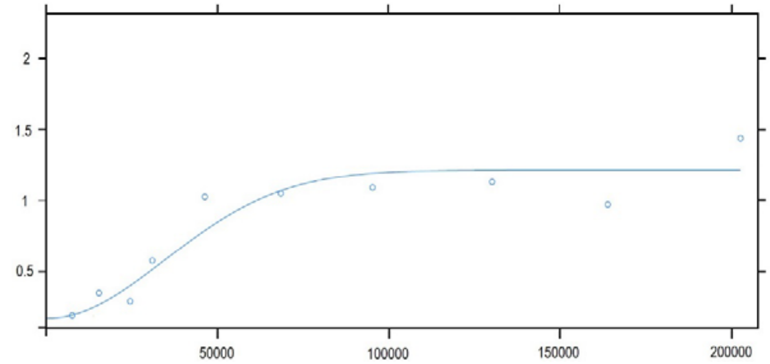
Figure 19. RWIS benefits and costs (top) and projected net benefits (bottom) over a 25-year life cycle

As clearly depicted in the figure, the optimal number of RWIS stations is 45, given the total benefits due to reductions in maintenance and collision costs. The density was found by simply taking the difference between the values of two lines, RWIS benefits and RWIS costs, at their corresponding number of stations; the number of stations where the difference in the two values was greatest was selected as the optimal density. Note that the optimal density number found in this study is very similar to the number of stations in the current RWIS network (42). This finding suggests that the proposed method can be used to test the current RWIS network, determine whether it needs a larger or a smaller number of RWIS stations, and recommend where to locate the next RWIS stations. As illustrated in the bottom chart in Figure 19, using the defined density, the total net benefit over the next 25 years is projected to be approximately $6.5 million. Additionally, using these benefits and costs, the cost-benefit ratio is approximately 3.5. Note that the optimal density found in this study could have been different if the inputs had different values (i.e. if the cost or life expectancy of a single RWIS station was different, as suggested in the referenced literature). However, it is worthwhile to emphasize that the method illustrated herein is dedicated to providing a systematic framework that can easily be applied to regions where the foreseeable monetary benefits need to be estimated to support decision making regarding the number of RWIS stations that should be deployed.

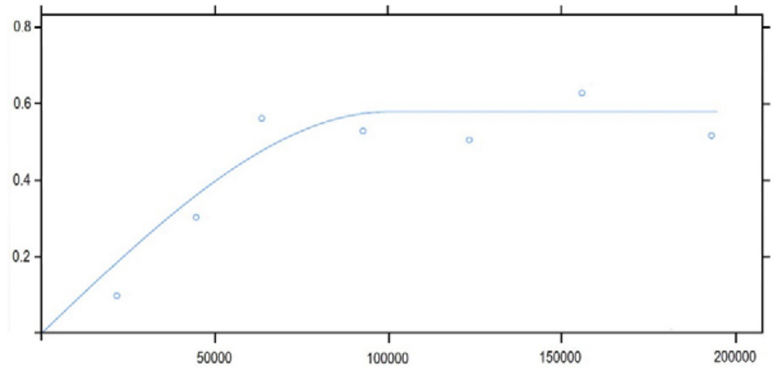
4.5.2 The Spatial Inference–based Method – Optimal Density in Ontario, Minnesota, Iowa, and Utah

While the cost-benefit–based method is more well-defined and intuitive in terms of determining the optimal number of RWIS stations in a given region, the approach is limited in several ways. As mentioned above, the RWIS benefits are estimated using the empirical data in such a way that the findings are likely to be only applicable to that study area. In addition, it is difficult to quantify other intangible benefits, including societal and environmental benefits. Furthermore, the cost-benefit–based method does not consider the use of RWIS information to make inferences about the conditions over an entire network. Intuitively, the more varied road weather and surface conditions a region exhibits, the higher number of RWIS stations that should be installed to maintain the acceptable level of service. Therefore, the aim of the analysis described in this section was to investigate the hypothesis that the optimal RWIS density or spacing for a region is dependent on the spatial variability of the road weather conditions of the region.

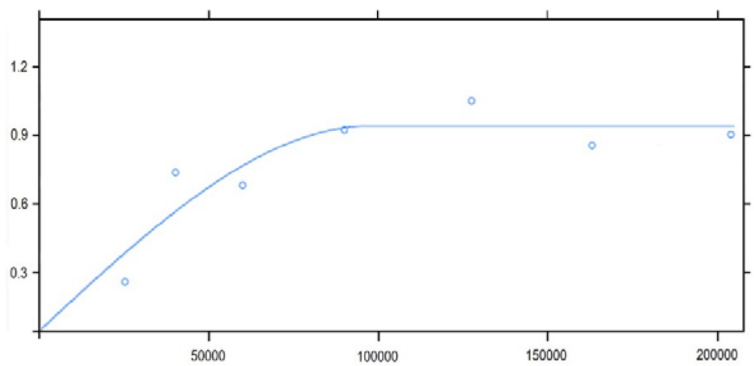
To examine this hypothesis, a geostatistical approach, introduced above, was implemented to characterize the spatial variability of weather conditions over a given region. To fulfill this task, the topological and climate patterns of the four study areas under analysis were first characterized and compared. Without loss of generality, road surface temperature was selected as the variable of interest to represent the overall road weather conditions. For each region, a semivariogram model was constructed to determine the spatial variability of road surface temperature. Figure 20 shows the sample and fitted semivariogram models using the seasonal road surface temperature.



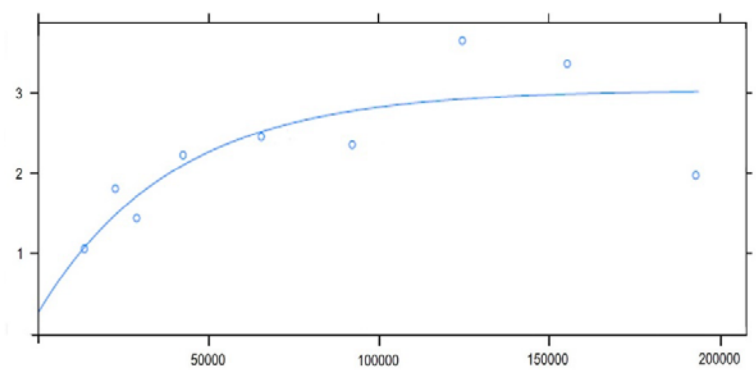
Ontario



Iowa



Minnesota



Utah

Figure 20. Sample and fitted semivariogram models for four regions (x-axis: semivariance, y- axis: lag distance in meters)

As anticipated, and as Figure 20 shows, the spatial correlations of road surface temperatures in Iowa and Minnesota, which have relatively less varied topographies, have longer spatial correlation ranges, suggesting that, on average, the road surface temperature measurements in these two regions vary less (and are thus more predictable) when compared to those in Utah, which features a more varied topography. In addition, Ontario, which has moderate topographic variability, has a spatial correlation range falling between the ranges of the other three regions. Moreover, the spatial structure of road surface temperature in Utah is less stable and tends to fluctuate within a greater range (on the y-axis) as the separation distance increases, whereas the other two regions have less fluctuation in semivariance, which contributes to greater predictive power. The mean ranges in the seasonal data for Ontario, Iowa, Minnesota, and Utah were found to be 72.84 km, 90.48 km, 95.47 km, and 40.47 km, respectively.

With the spatial correlation ranges defined for the four regions, the constrained optimization was run for each region in an iterative fashion by adding one additional RWIS station to the network and recording its corresponding fitness value. The optimization continued until the total number of stations reached 350, an arbitrary number ensuring that the key pattern in the error-density relationship was fully revealed. To ensure a valid and fair comparison, the fitness values were normalized and the number of stations added to the network was converted to two distinct measures: the number of stations per unit area (100 km by 100 km) and the number of stations per unit highway length (100 km). The normalization was necessary because the total area (and length) of each study area was different, and therefore comparing the fitness value directly to the number of stations added would not be considered valid. The two different density measures considered in this study provide transportation agencies with the freedom to choose different units depending upon the type of analysis to be conducted. For instance, if the analysis is intended for a rural area having a smaller size road network, the use of the number of stations per unit highway length would be preferred because the other measure would suggest an overly high number of stations to be installed.

Figures 21 and 22 show a comparison of the RWIS density charts for all four regions, expressed as a function of the two different analysis units.

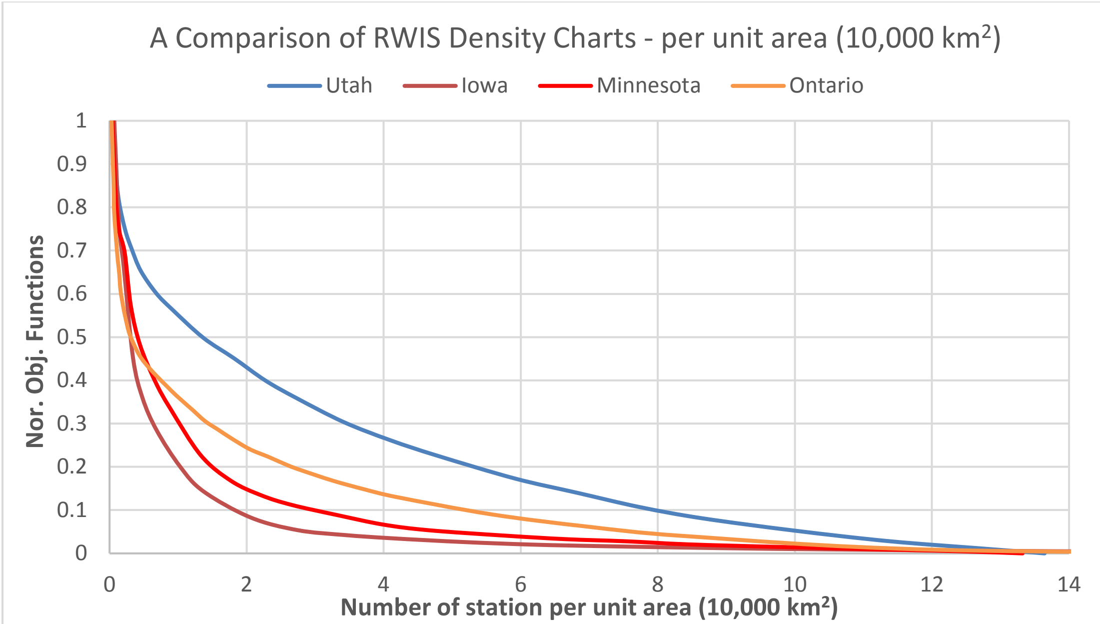


Figure 21. Comparison of RWIS density charts – per unit area (10,000 km^2)

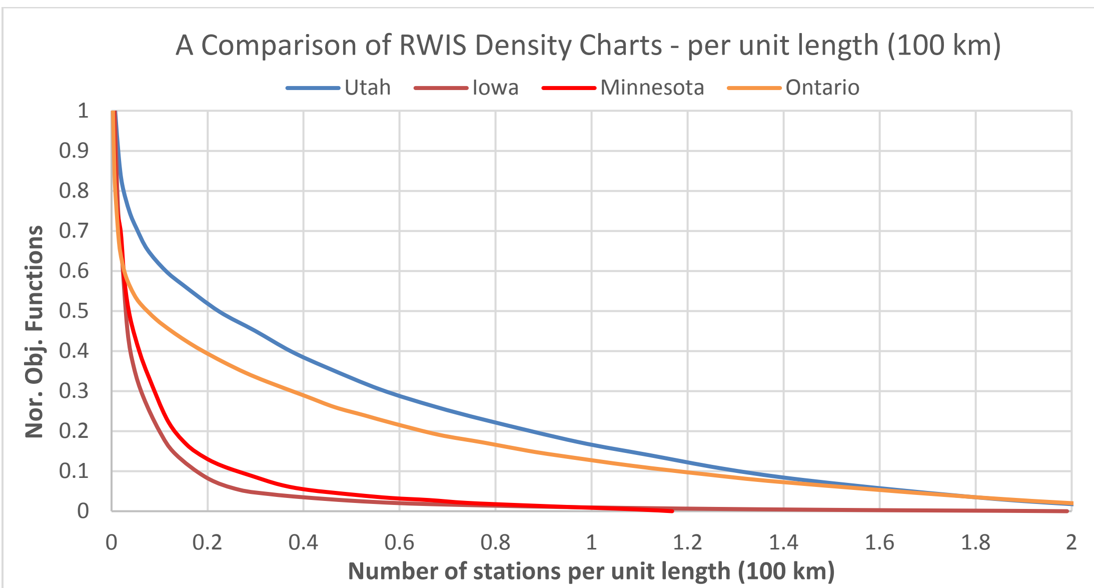


Figure 22. Comparison of RWIS density charts – per unit length (100 km)

A quick visual inspection of the two figures shows that Iowa and Minnesota, having similar topographic characteristics (i.e., less varied topographies), require fewer stations per unit area of 10,000 km^2 (and per unit length of 100 km), while Utah, which has a more varied topography, requires a considerably larger number of stations to achieve the comparable objective function values. Likewise, Ontario, with moderately varied topographic characteristics, requires a larger number of RWIS stations than Iowa and Minnesota but a smaller number than Utah. Another important conclusion that can be drawn is that regions with longer spatial continuities (i.e., Iowa and Minnesota, as defined in the semivariograms) require a smaller number of stations to cover the same area (and the same highway length) than a region with a much shorter spatial continuity (i.e., Utah). This makes intuitive sense because the measurements taken in a less varied topographic region can represent larger areas and highway lengths.

Given the shape of all four curves, it was quite challenging to pinpoint the optimal density. Instead, a rate of change was calculated for every point, and when the change was around 5% (again, an arbitrary number selected for a comparison only), the corresponding density was considered to be optimal. As a result, Iowa, Minnesota, and Ontario would require 2.0, 2.2, and 2.9 stations per every 10,000 km^2, respectively, whereas Utah would need 4.5 stations to cover the same area, indicating that a topographically varied region likely needs about twice as many RWIS stations as less varied regions. When unit length is used to determine optimal density, Iowa, Minnesota, and Ontario would require 0.7, 0.8, and 1.0 stations per every 100 km, respectively, whereas Utah would need 1.6 stations to cover the same length of highway.

To further test the aforementioned hypothesis, the relationship between the optimal number of RWIS stations required per unit area/length and the spatial range was examined, as illustrated in Figures 23 and 24.

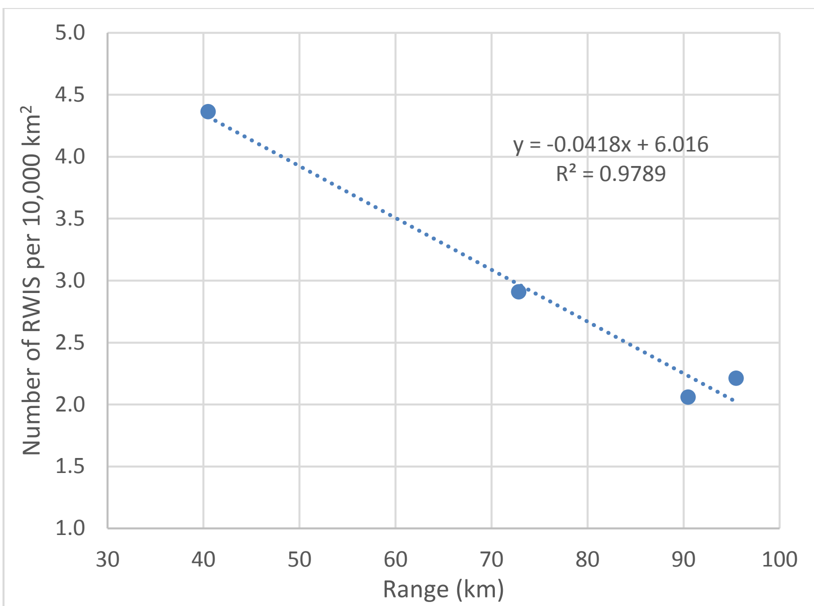


Figure 23. Linear relationship of range versus density (per 10,000 km^2)

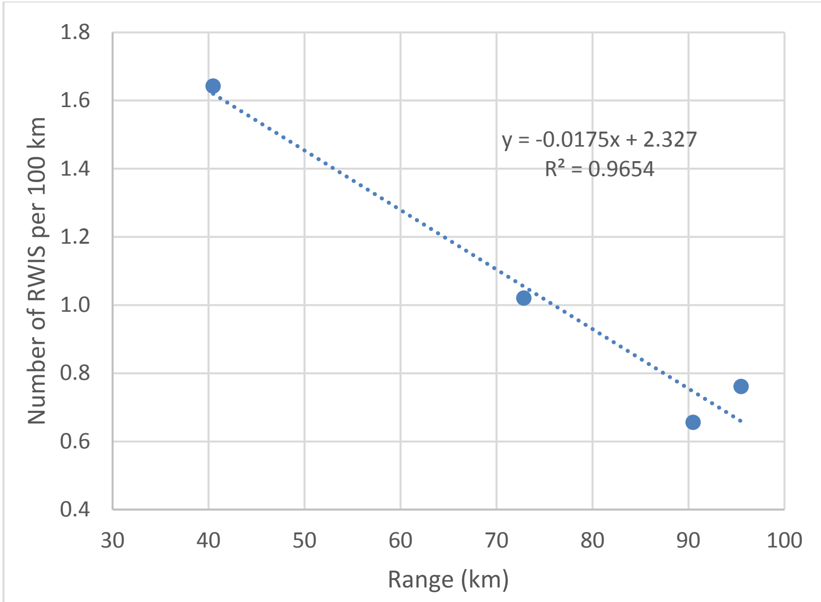


Figure 24. Linear relationship of range versus density (per 100 km)

Although the relationship relies on a small number of case studies, it reveals a clear linkage between the two measures and demonstrates the usability of the correlation range at any given area or length for conveniently determining optimal station density. For instance, if the analysis of interest is the number of stations per unit area, a region with a 60-km range for the given variable of interest would require, on average, 3.5 RWIS stations per every 10,000 km^2 to provide adequate coverage. Similarly, if the analysis of interest is the number of stations per unit length, a region with the same 60-km range would require 1.3 RWIS stations per every 100 km. While there is no doubt that more case studies are required to obtain more promising results, this method certainly provides valuable information, particularly for highway authorities initiating a statewide RWIS implementation plan.

5. CONCLUSIONS AND RECOMMENDATIONS

In this project, we examined various important factors that need to be considered in RWIS network planning and developed and evaluated three alternative approaches for determining the optimal location and density of RWIS stations over a regional highway network. The main findings are summarized as follows:

- A heuristic surrogate measure–based method was developed to formalize various processes utilized in current practice for locating RWIS stations on a road network. Two types of location ranking criteria were considered, including weather- and traffic-related factors, to capture the need to allocate RWIS stations to the areas with the most severe weather conditions and with the highest number of travelers. A total of three location selection alternatives were generated and used to evaluate the current Ontario RWIS network. The findings indicate that the current RWIS network is able to provide reasonably good coverage based on the location criteria considered.

- A cost-benefit–based method was proposed as the second alternative to give an explicit account of the potential benefits of an RWIS network for location and density planning. The approach was developed on the basis of the assumption that a highway section covered by an RWIS station is likely to receive better WRM than a highway section without RWIS coverage. A case study based on the current RWIS network in northern Minnesota shows that the highest projected 25-year net benefits are approximately $6.5 million, with a cost-benefit ratio of 3.5, given the network of 45 RWIS stations.

- The third alternative is a more comprehensive and innovative framework whose objective was to maximize the use of RWIS information (i.e., monitoring capability) to determine winter road weather conditions. Methodologically, the formulation of the RWIS location optimization problem offered several unique features, including explicit consideration of the spatial correlation of winter road weather conditions and high–travel demand coverage. The optimization problem was formulated by taking into account the dual criteria representing the value of RWIS information for spatial inference and travel demand distribution. The SSA algorithm was employed to solve the optimization problem in an efficient manner. A case study based on four study regions, including one Canadian province (Ontario) and three US states (Utah, Minnesota, and Iowa), demonstrated two distinct scenarios: redesign and expansion of the existing RWIS network. The findings indicate that the method developed is very effective in evaluating the existing network and delineating new site locations.

- Additional analyses based on the case study results of the four study areas were conducted to determine the spatial continuity of road weather conditions and the relationship between spatial continuity and desirable RWIS density. Road surface temperature was used as a variable of interest, and its spatial structure for each region was quantified and modelled via semivariograms. The findings suggest that there is a strong dependency between RWIS density and correlation range, that is, the regions with less varied topographies tended to have a longer spatial correlation range (i.e., the measurements are more consistent) than the region with a more varied topography.

- The approaches proposed in this project provide alternative ways of incorporating key road weather, traffic, and maintenance factors into the planning of an RWIS network in a region. The decision regarding which alternative to use depends on the availability of data and resources. Nevertheless, all approaches can be conveniently implemented for real-world applications.

Further research is needed in the following specific areas:

- For the surrogate measure–based approach, temperature measurements can be improved by utilizing a geostatistical interpolation technique such as kriging. Several studies have found that kriging would provide a better estimation than regression, especially when variables are spatially dependent on each other (Hengl et al. 2003, Mesquita and Sousa 2009). In addition, methodological guidelines need to be established for determining the number of RWIS stations to be allocated within a cell. This is particularly important for DOTs that want to install more than one RWIS station within, for instance, a minimum spatial unit of 50 km^2 to enhance and extend their monitoring capability and spatial coverage.

- For the cost-benefit–based approach, first, savings from other sources such as reduced patrols and travel time should be quantified and added to the maintenance and safety benefits to facilitate a more complete analysis. Second, road weather and land-use information should be incorporated into the modeling process to account for the effects of topographical and micrometeorological variations on RWIS benefits and costs. Third, a geospatial analysis is required to spatially examine the extent of an RWIS station's effects and adjust the parameter accordingly. Fourth, because the costs of a single RWIS station can vary depending on many criteria, a range of different values should be tested and validated to see how they affect the findings.

- For the spatial inference–based approach, first, other variants of kriging, such as regression kriging or universal kriging (Bourennane el al. 2000, Hengl et al. 2004, Amorim et al. 2012), can be used to obtain more accurate and detailed results. Second, other heuristic algorithms, including greedy algorithm (Cormen et al. 2001), genetic algorithm (Arifin, 2010), and tabu search (Glover and Laguna 1997), should also be explored and tested. Third, in addition to the global performance measure used in this study (the objective function), it would be worthwhile to use (or develop) another evaluation metric that quantitatively examines the degrees of similarity (e.g., spatial/areal overlap analysis) between the optimized and existing network. This additional metric would provide a more definite measure of the similarity or closeness of one network design to another.

- Additional case studies should be conducted to obtain more conclusive results and to investigate the generality of the model results and their sensitivity to external conditions, including network size, the size of the grid, and input parameters including traffic variables (accident rates/frequencies, AADT), and weather variables (snow intensity, road surface temperature).

- A decision support tool should be developed to automate the solution process of the proposed RWIS network planning models.

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APPENDIX A. SURVEY RESULTS

Q1: Current RWIS deployment: Total number of RWIS stations

Agency	Total Number of RWIS Stations
Utah DOT	94 (This includes 7 portable RWIS trailers)
Minnesota DOT	93
Kansas DOT	43 KDOT plus 10 on turnpike
PA DOT	94
Illinois DOT	57
NDDOT	24
Utah DOT	74 permanent RWIS sites, 7 portable RWIS.
Virginia DOT	82
Ohio DOT	173
PEI	5
MOT B.C.	64
GNWT DOT	1
MTO	140 stations
Alberta Transportation	84 stations are now connected, 17 have been installed and will be connected this year, 17 more will be installed between 2013 and 2016
Alaska DOT	55
Region of Waterloo, Ontario	3 (2 in now, 1 next year)
Illinois DOT	58
UDOT	73
Ohio DOT	172
NDDOT North Dakota	23
Michigan DOT	23
MDOT/Michigan	35
KDOT	43
Wisconsin DOT	60
Iowa DOT	68

Q2: Total number of RWIS stations with webcam

Agency	Number of Stations with Webcam
Utah DOT	59
Minnesota DOT	85
Kansas DOT	8 KDOT sites
PA DOT	82
Illinois DOT	14
NDDOT	10
Utah DOT	44
Virginia DOT	56
Ohio DOT	2
PEI	5
MOT B.C.	31
GNWT DOT	1
MTO	47
Alberta Transportation	All RWIS stations are equipped with the cameras
Alaska DOT	5
Region of Waterloo, Ontario	1 (2 by next year)
Illinois DOT	8
UDOT	73
Ohio DOT	1
NDDOT North Dakota	11
Michigan DOT	23
MDOT/Michigan	35
KDOT	8
Wisconsin DOT	0
Iowa DOT	49

Q3: Total number of RWIS stations with traffic detector

Agency	Number of Stations with Traffic Detector
Utah DOT	5
Minnesota DOT	0
Kansas DOT	5 with Groundhog sensors
PA DOT	0
Illinois DOT	12
NDDOT	0
Utah DOT	2 Portable RWIS Trailers
Virginia DOT	3
Ohio DOT	100
PEI	0
MOT B.C.	0
GNWT DOT	0
MTO	2
Alberta Transportation	None
Alaska DOT	4
Region of Waterloo, Ontario	0
Illinois DOT	8
UDOT	0
Ohio DOT	150
NDDOT North Dakota	0
Michigan DOT	6
MDOT/Michigan	35
KDOT	0
Wisconsin DOT	0
Iowa DOT	47

Q4: Total number of RWIS stations linked to dynamic message sign

Agency	Number of Stations Linked to Dynamic Message Sign
Utah DOT	1
Minnesota DOT	0
Kansas DOT	0
PA DOT	2
Illinois DOT	0
NDDOT	0
Utah DOT	1 is currently being constructed.
Virginia DOT	0
Ohio DOT	1
PEI	0
MOT B.C.	3, 2 more in development
GNWT DOT	0
MTO	0
Alberta Transportation	None but planning to install and integrate RWIS with dynamic message sign at two bridge locations
Alaska DOT	0
Region of Waterloo, Ontario	0
Illinois DOT	0
UDOT	0
Ohio DOT	0
NDDOT North Dakota	0
Michigan DOT	0
MDOT/Michigan	None directly, several in same vicinity
KDOT	0
Wisconsin DOT	0
Iowa DOT	0

Q5: Total number of RWIS stations with non-intrusive pavement condition sensors

Agency	Number of Stations with Non-intrusive Pavement Condition Sensors
Utah DOT	44 (+7 additional road temperature only sensors would make the total 51)
Minnesota DOT	0
Kansas DOT	1 Lufft
PA DOT	0
Illinois DOT	0
NDDOT	0
Utah DOT	11
Virginia DOT	25
Ohio DOT	2
PEI	0
MOT B.C.	1
GNWT DOT	1
MTO	1
Alberta Transportation	None of the stations use non-intrusive sensors
Alaska DOT	1
Region of Waterloo, Ontario	0
Illinois DOT	3
UDOT	45
Ohio DOT	2
NDDOT North Dakota	0
Michigan DOT	0
MDOT/Michigan	2
KDOT	1
Wisconsin DOT	1
Iowa DOT	1

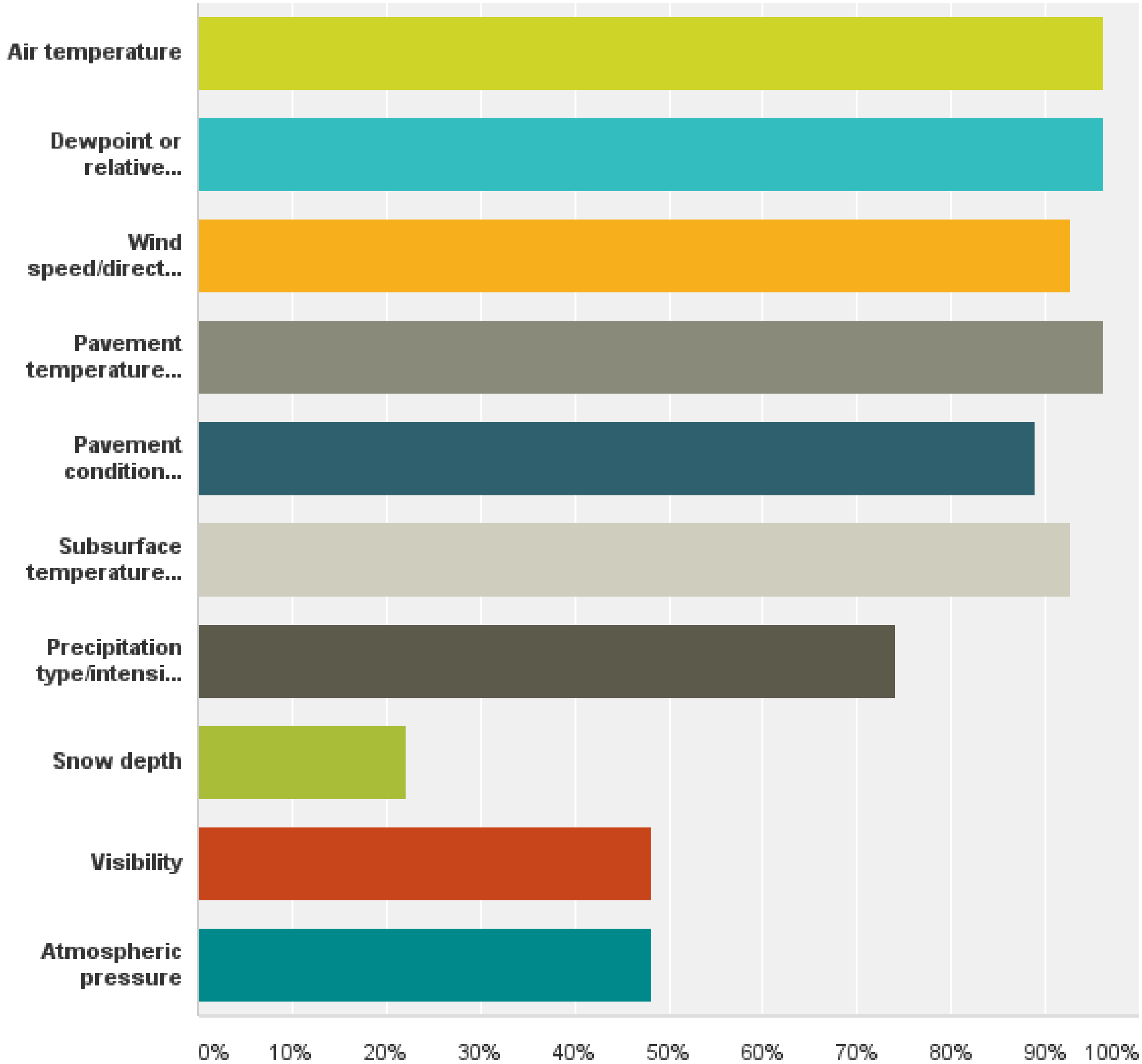
Q6: Total number of RWIS stations linked to fixed automated spray technology (FAST)

Agency	Number of Stations Linked to FAST
Utah DOT	4 (internal system)
Minnesota DOT	1
Kansas DOT	0
PA DOT	16
Illinois DOT	1
NDDOT	2
Utah DOT	Possibly 3 but they the data is strictly internal to spray system.
Virginia DOT	0
Ohio DOT	0
PEI	0
MOT B.C.	0
GNWT DOT	0
MTO	8
Alberta Transportation	Two,-presently there are two fully functioning integrated RWIS-FAST systems at two bridge locations
Alaska DOT	0
Region of Waterloo, Ontario	0 (1 roughed in for future use if needed on new Fairway Bridge)
Illinois DOT	1
UDOT	0
Ohio DOT	0
NDDOT North Dakota	2
Michigan DOT	0
MDOT/Michigan	1
KDOT	0
Wisconsin DOT	0
Iowa DOT	0

Q7: What are the vendors of your RWIS? (e.g., Vaisala)

Agency	RWIS Vendors
Utah DOT	Campbell Scientific, Vaisala, (High Sierra, Lufft - ordered through Campbell)
Minnesota DOT	Vaisala
Kansas DOT	Vaisala and Lufft
PA DOT	Vaisala, SSI, Boschung
Illinois DOT	Vaisala
NDDOT	Vaisala
Utah DOT	Campbell Sci, Vaisala, Lufft, RM Young,
Virginia DOT	Vaisala
Ohio DOT	Vaisala
PEI	Vaisala (Approach Navigations Systems Inc)
MOT B.C.	We build our stations in house with a variety of sensors
GNWT DOT	AMEC Earth & Environmetal
MTO	Vaisala, Campbell Scentific, Lufft, SSI, Boschung
Alberta Transportation	Vaisala (SSI) for older stations and Lufft for all new stations
Alaska DOT	Vaisala
Region of Waterloo, Ontario	Lufft and Vaisala (formerly SSI)
Illinois DOT	Vaisala
UDOT	Campbell Scientific
Ohio DOT	Vaisala
NDDOT North Dakota	SSI Vaisala
Michigan DOT	Vaisala
MDOT/Michigan	Vaisala, Lufft, Campbell,
KDOT	Vaisala
Wisconsin DOT	Vaisala, Lufft
Iowa DOT	Vaisala, Zydax, NovaLynx, Sutron, High Sierra

Q8: What are the typical sensor components of your RWIS?



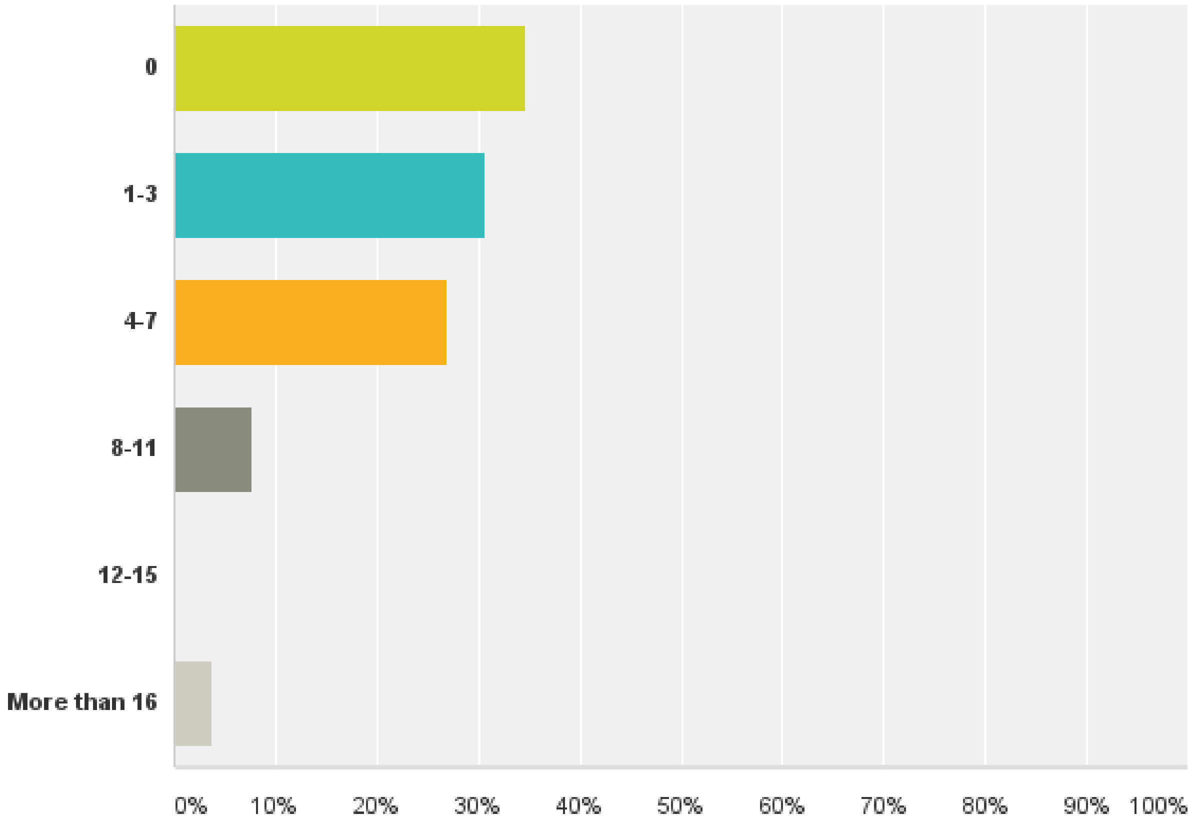
Q9: What is your total annual RWIS maintenance cost?

Agency	Total Annual RWIS Maintenance Cost
Utah DOT	$77,651.16 - FY14, $53,082.00 - FY15, $204,487.52 - Proposed FY16. FY16 budget allows for replacement parts to address an aging system..
Minnesota DOT	$175,000
Kansas DOT	$150,000 for repair and upgrades
PA DOT	$400,000
Illinois DOT	$250,000
NDDOT	$75,000
Utah DOT	$69,556.84 for response maintenance and preventative maintenance. Unknown cost for parts at this time.
Virginia DOT	300,000
Ohio DOT	+/- $630k
PEI	$27,500 for operation and maintenance of 5 units
MOT B.C.	Approx.. $500K
GNWT DOT	$40,000
MTO	approx. $500,000
Alberta Transportation	The RWIS infrastructure is managed under two contracts: first contract - for 80 existing stations with an operations/maintenance summer cost of app. $600 per station per month and winter cost of app. $2,000 per station per month, second contract: for the newly installed and future stations with a monthly cost of $800 per station per month throughout the year plus $250 per station per month for forecasting services only during the winter months Oct. 15–March 31.
Alaska DOT	$350K
Region of Waterloo, Ontario	A field visit to clean and inspect. Very little.
Illinois DOT	$250,000
UDOT	$110,000
Ohio DOT	$620,000
NDDOT North Dakota	We don't have funds set aside, I would guess near the $50,000 but our system is very old and needs many repairs. It is being pieced together to keep running right now.
Michigan DOT	$143,000
MDOT/Michigan	3,800/site/year, plus traffic control and spare parts
KDOT	$50,000
Wisconsin DOT	$130,000
Iowa DOT	$163,200 for maintenance contract plus ~$40,000 unscheduled maintenance

Q10: What is the average installation cost per station?

Agency	Cost per Station
Utah DOT	$40,000
Minnesota DOT	$90,000
Kansas DOT	$30,000
PA DOT	$40,000
Illinois DOT	$80,000
NDDOT	$120,000
Utah DOT	$50,000 with non-invasive road sensors
Virginia DOT	$50,000
Ohio DOT	$2k
PEI	$55,000
MOT B.C.	$55K
GNWT DOT	$200,000
MTO	$75,000
Alberta Transportation	Based on the recent contract: $132,000 per station, RWIS installations at interchanges varied from $135,000 to $180,000 due to long cable connections (to the bridge sensors), power provisions. Integrated RWIS-dynamic message sign at the bridge sites will be in the order of $250,000
Alaska DOT	This is a wide variance due to the geographic extent of Alaska and the type of site being installed. An average cost over the lifetime of the RWIS network would be $125K.
Region of Waterloo, Ontario	$80,000 for new fully loaded site
Illinois DOT	$50,000
UDOT	$30,000
Ohio DOT	$40,000
NDDOT North Dakota	Currently nearly $80,000, new specification hopefully near $30,000 or less
Michigan DOT	$107,000
MDOT/Michigan	$130,000
KDOT	$30,000
Wisconsin DOT	$35,000
Iowa DOT	~$60,000

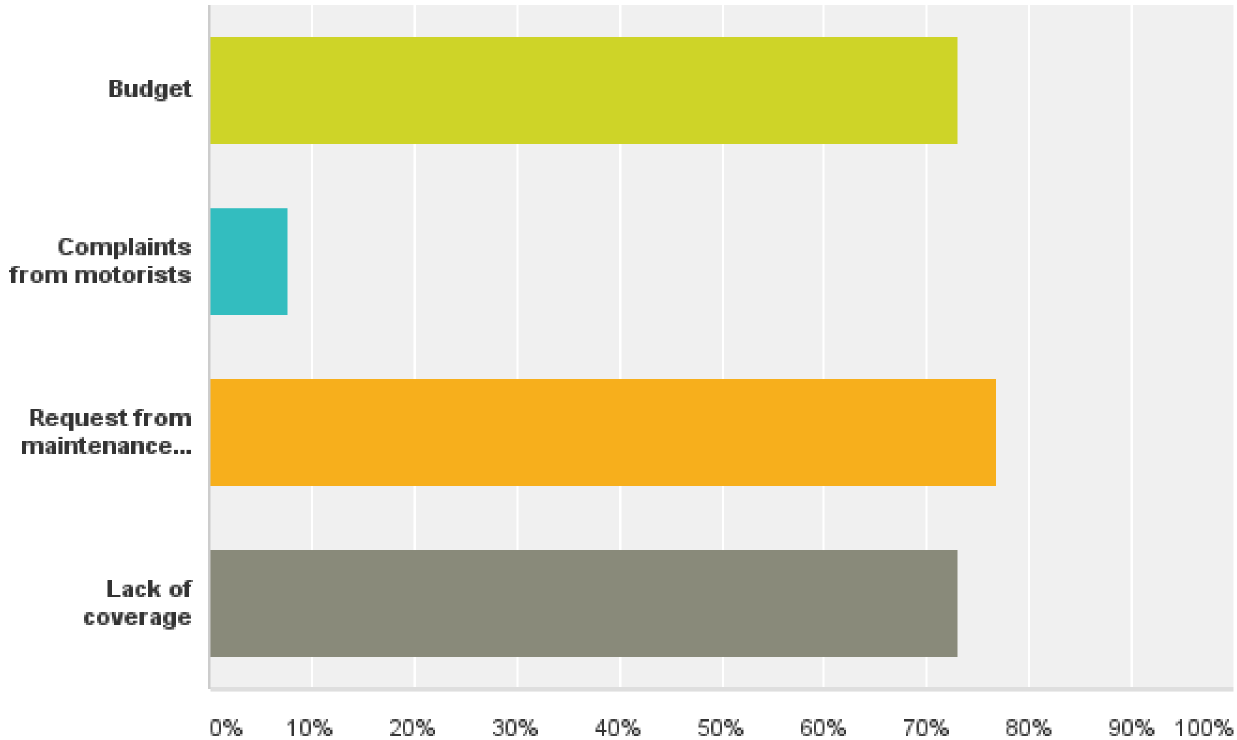
Q11: How many RWIS stations do you plan to deploy next year?



Q12: How many RWIS stations do you plan to deploy in the next five years?

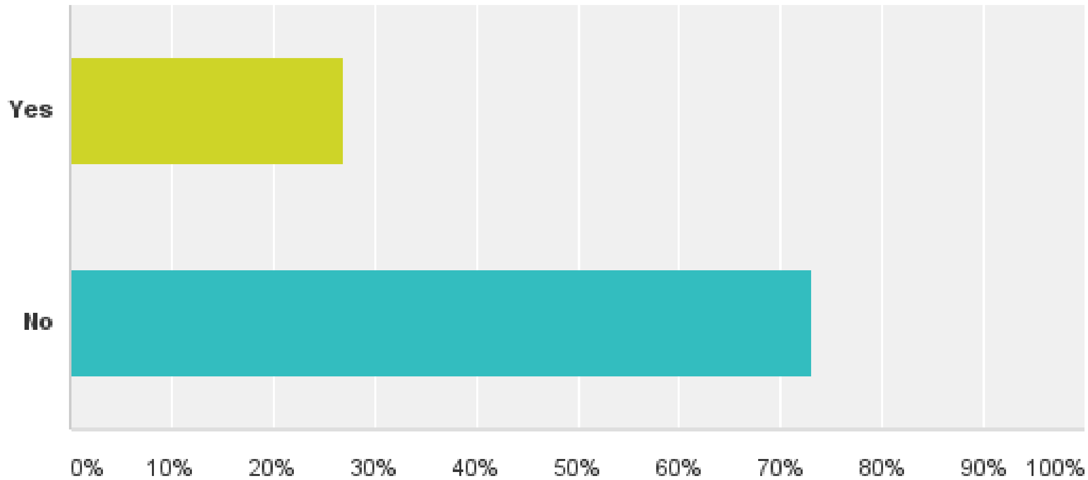
Agency	Number of RWIS Stations Planned for Deployment Next 5 Years
Utah DOT	Around 30 to 40 sites
Kansas DOT	No full sites, possibly some mini sites at existing ITS message boards
Illinois DOT	60
Utah DOT	20
PEI	0
GNWT DOT	4 to 7
MTO	0
Alberta Transportation	8 more stations will be deployed: 1 in 2014 and 7 in 2016
Alaska DOT	10, but there may be some installs of very limited sensor arrays, aka temperature and camera only
Region of Waterloo, Ontario	2
Illinois DOT	15
UDOT	8
NDDOT North Dakota	We are currently updating our specifications and hope to have all our sites updated to a new system in the next 5 to 10 years depending on funding.
Michigan DOT	Unknown.
MDOT/Michigan	Just 16 next year
KDOT	0
Iowa DOT	3

Q13: How do you make decisions on the number of RWIS to be deployed?



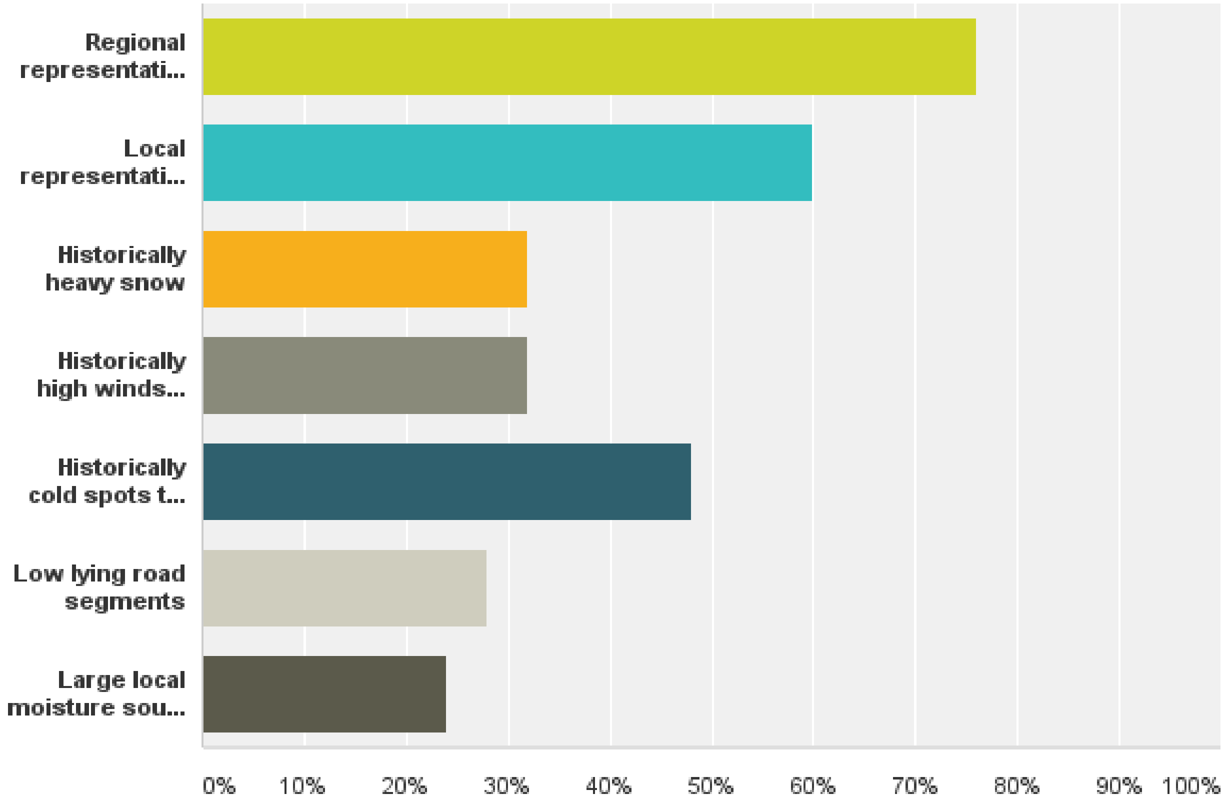
Agency	Decision Making on Number of RWIS Stations to Deploy
Utah DOT	We currently are addressing regional spacing concerns. Construction projects dictate some new sites.
Alberta Transportation	We have taken into consideration climate and meteorological conditions, safety and operational problems. Initial RWIS network plan included NHS and the need to create a Canada wide RWIS network along the major national highways, some key provincial highways were also included in the initial deployment. Budget was another consideration which mainly had an impact on the schedule - after we determined the need for the RWIS stations. New RWIS program which is being implemented now was based on the need to provide coverage for other areas in the province to improve forecasting and provide RWIS observations along the remaining major provincial highways. An expansion study was conducted which also looked at safety and traffic volumes and several stations were also recommended for "hotspots."
Alaska DOT	Meet Department strategic goals
Region of Waterloo, Ontario	Based on weather zone report and field experience
UDOT	New roads or road projects that have need and funding for RWIS
MDOT/Michigan	Jurisdictional changes on a route
Wisconsin DOT	Highway improvement projects

Q14: Do you have a pre-defined spacing requirement? (e.g., RWIS every 50 km)



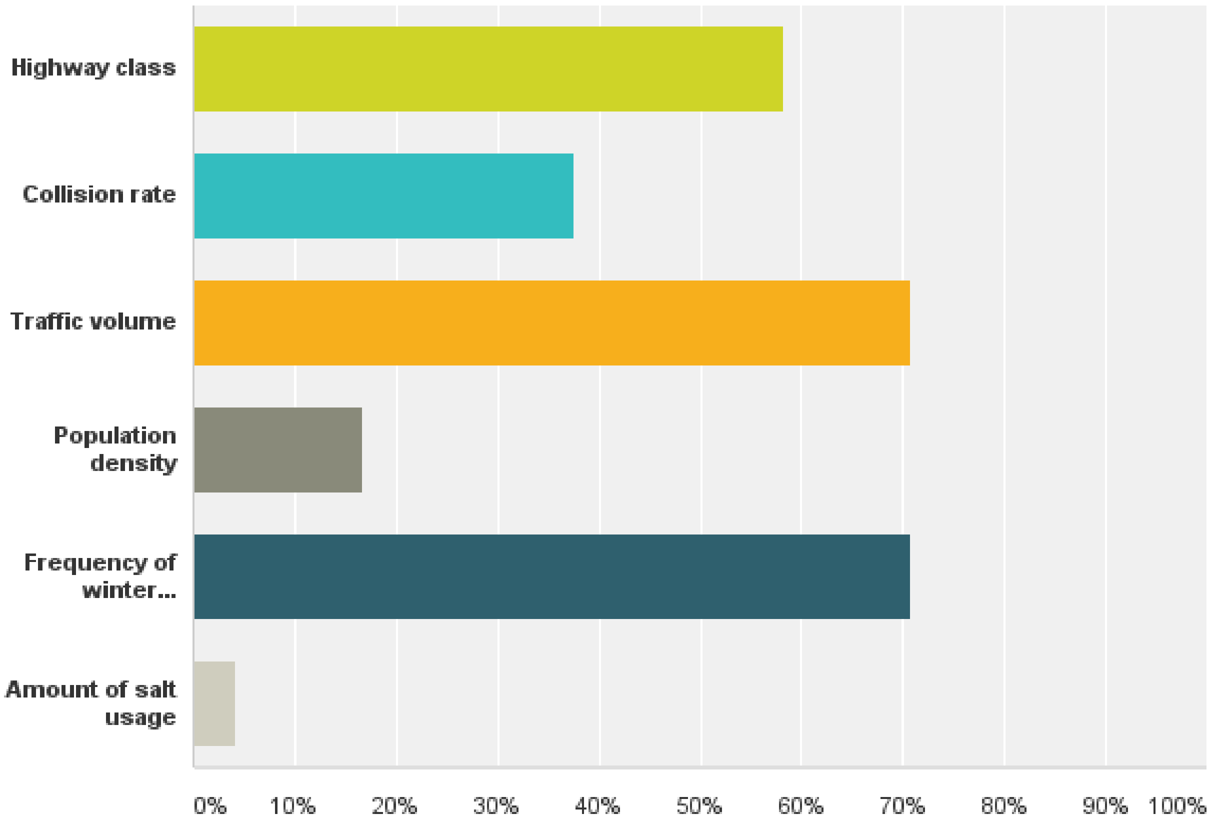
Agency	Pre-defined Spacing Requirement?
Utah DOT	Our current plan is to have an RWIS site every 50 miles on US highways and Interstate routes and within every 10 miles within variable speed limit projects. We hope to fulfill these goals with in the next few years.
NDDOT	We try to use a 30 mile radius for spacing.
Ohio DOT	Every 30 miles
MOT B.C.	Not applicable in mountainous terrain with many micro-climates
Alberta Transportation	In general, the minimum requirement for spacing between the stations is at least 50 km.
Alaska DOT	Based on maintenance station needs. A typical need is to know that is going on at the maintenance station boundaries. A second requirement would be a particular area that has challenging weather conditions.
Region of Waterloo, Ontario	20km range
UDOT	But it is less distance-based, and more phenomenon-based. In complex topography, you have to hit the points that have particular need of observation, or that can be representative of a large area.
Ohio DOT	30 miles
Wisconsin DOT	We do prefer one every 30 miles, but it's not a requirement.

Q15: What are the main factors (or considerations) for deciding the location of RWIS stations at both local and regional scales?



Agency	Main Factors/Considerations for RWIS Station Locations
Utah DOT	Areas of high traffic crashes, research projects, seasonal road closures and traffic management.
Minnesota DOT	When possible, we try to pick areas that are representative of general atmospheric conditions in the surrounding area. MnDOT's RWIS network was carefully selected using input from multiple sources including meteorologists, maintenance supervisors, and through thermal mapping. MnDOT conducted a series of interviews with representatives from all maintenance operations offices within the Department. These in-person meetings allowed the Department to identify those potential locations which are subject to impaired travel conditions such as reduced visibility or hazardous pavement conditions (wet or frozen pavement, frost, blowing snow etc.). In addition, the Regional Weather Information Center (RWIC) of the University of North Dakota, in conjunction with MnDOT, conducted site assessment and evaluation of potential RWIS sites throughout the State of Minnesota. These sites were evaluated as to whether the information from those sites could be used as inputs to mesoscale weather forecasting models or would be used only for detection of localized conditions. Also the sites were evaluated in respect to their location to the nearest National Weather Service Automated Weather Observing System (AWOS) site. Consideration was given to obstructions, both natural and man-made, which may affect atmospheric and road sensing capabilities.
Utah DOT	Heavily weighted to weather forecaster needs and shed maintenance supervisor needs. Like to place them near shed maintenance boundaries.
Virginia DOT	ESS Warrant
MOT B.C.	Locations where winter maintenance is most challenging
MTO	Weather zones
Alberta Transportation	Regional climate and meteorological patterns were analyzed (based on input from meteorologists and regional/local staff) to determine areas which needed more RWIS coverage (more observations to fill in the gaps to improve forecasting capabilities). Also collisions, historical winter road conditions and traffic patterns were analyzed (historical data plus input from local/regional staff) to select the worst road segments which needed accurate RWIS observations from the sensors and cameras - to improve maintenance responses. At the micro scale local staff was very helpful in determining which locations met the FHWA guidelines for selecting the sites (shading, proximity to water and traffic, etc.).
Alaska DOT	Travel corridors, maintenance station boundaries, other agency needs, e.g., railroad, FAA
Region of Waterloo, Ontario	Representative conditions ex. One on a bridge, one in snow belt, west side of region etc.
MDOT/Michigan	Change in maintenance areas
Wisconsin DOT	Improvement project locations

Q16: What other non-weather related factors do you consider when deciding the candidate locations?



Agency	Other Non-weather Related Factors for RWIS Station Locations
Utah DOT	Out of view of private residences, available communication, available solar power (canyons, etc.), favor bridges (first to freeze)
Kansas DOT	None of these are strong factors in our siting considerations.
Utah DOT	The greater the distance away from the maintenance shed, the better.
Ohio DOT	Budget
Iowa DOT	Access to power and communications, distance from maintenance facility

Q17: Do you have any standardized guidelines that help you identify the candidate locations?

Agency	Standardized Guidelines for Candidate Locations
Utah DOT	RWIS siting reports/guidelines are performed on most RWIS sites.
Minnesota DOT	See answer to question 13 above. More documentation may be available as well.
Utah DOT	We do in terms of the vicinity considerations. A full siting reports is done within 5 miles of the desired location with power, communication and obstruction considerations.
Virginia DOT	ESS Warrant
MTO	MTO Guidelines/ TAC guidelines
Alberta Transportation	We use North American guidelines and practices from other jurisdictions.
Alaska DOT	The initial sites were installed based on extensive stakeholder interviews. Since then we have done targeted updates with the maintenance and operations staff. These documents are available if you would like.
Region of Waterloo, Ontario	Yes
UDOT	We decide general location using the aforementioned factors, and have a five-year deployment plan that meets those factors. We also have siting reports that are written up for each siting area that specifies the best exact spot for the site.
Ohio DOT	FHWA
MDOT/ Michigan	FHWA siting guidelines
KDOT	FHWA-HOP-05-026 RWIS ESS Siting Guidelines

Q18: What are the common procedures/practices being undertaken prior to deciding the optimal location of RWIS stations?

Agency	**Common Procedures/Practices for Optimal Station Location Decision Making**
Utah DOT	Identify weather patterns and micro climates. Consider shed boundaries. Street lighting for low light cameras. Traffic/crash data. Local bridges.
Minnesota DOT	MnDOT's RWIS network was carefully selected using input from multiple sources including meteorologists, maintenance supervisors, and through thermal mapping. MnDOT conducted a series of interviews with representatives from all maintenance operations offices within the Department. These in-person meetings allowed the Department to identify those potential locations which are subject to impaired travel conditions such as reduced visibility or hazardous pavement conditions (wet or frozen pavement, frost, blowing snow etc.). In addition, the Regional Weather Information Center (RWIC) of the University of North Dakota, in conjunction with MnDOT, conducted site assessment and evaluation of potential RWIS sites throughout the State of Minnesota. These sites were evaluated as to whether the information from those sites could be used as inputs to mesoscale weather forecasting models or would be used only for detection of localized conditions. Also the sites were evaluated in respect to their location to the nearest National Weather Service Automated Weather Observing System (AWOS) site. Consideration was given to obstructions, both natural and man-made, which may affect atmospheric and road sensing capabilities.
Kansas DOT	Existing sites only.
PA DOT	Under Development
Illinois DOT	Asking experienced field staff in the area.
NDDOT	We will meet with the district and often times have a field review prior to choosing the final location.
Utah DOT	A full siting report is done within 5 miles of a desired location. Shed supervisors and weather forecasters are surveyed.
Virginia DOT	If it warrants one.
Ohio DOT	site surveys
PEI	Discussions with regional staff on locations that would best represent weather patterns for a specific area.
MOT B.C.	Discussion with maintenance personnel, investigation of accident history, thermal mapping
GNWT DOT	No standard procedures are presently in place for determining general location of RWIS stations.
MTO	Reviewing of existing RWIS stations within Weather Zones and spacing between stations
Alberta Transportation	We conducted an RWIS expansion study which looked at various factors and aspects - as described above.
Alaska DOT	DOT needs, Availability of power and comm, Representativeness of the site (aka RWIS Siting Guidelines), Maintenance
Region of Waterloo, Ontario	Availability of Land, Site conditions that are appropriate, priority of location based on traffic, winter conditions, topography, lack of existing site owned by MTO, etc.
Illinois DOT	Work with experienced district staff, they know where their needs are.
UDOT	Required siting is done at each proposed area. Proposed areas are a combination of maintenance, road project needs, public need, weather forecaster need, etc.
Ohio DOT	Traffic volume
NDDOT North Dakota	We work with each district to find out their problem areas as well as looking at the current density and try to obtain a 30 mile radius density.

Agency	Common Procedures/Practices for Optimal Station Location Decision Making
MDOT/Michigan	A concept of operations for that area. Stakeholder meetings,
Wisconsin DOT	Determine need in coordination with local maintenance folks. Include in improvement project plans.
Iowa DOT	Our RWIS Committee collects site requests from area supervisor. The requests are analyzed by the committee and a few are selected, per the budget.

Q19: Do you think a computer software tool for locating new RWIS stations would be necessary and useful?

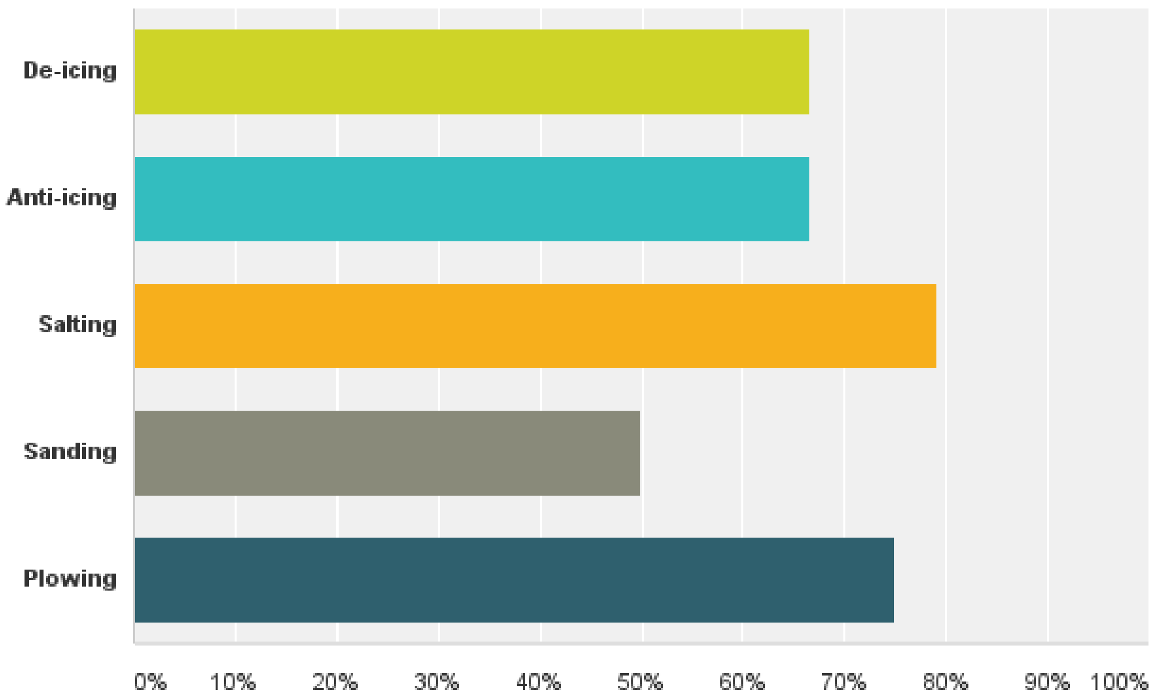
Agency	If yes, please describe
Utah DOT	It would be helpful but it would not dictate where RWIS is located. Often terrain and weather patterns ultimately dictate where RWIS stations are installed.
Minnesota DOT	I believe that a computer software tool could be very useful if it incorporates all the needed factors like how will the site fit in with weather forecasting, etc.
PA DOT	If used in conjunction with local maintenance management input
Ohio DOT	Possibly. depending on the agency need
MTO	Only if it takes into account new technologies (i.e., thermal mapping, Intelldrive, mobile tracking)
Alberta Transportation	It would be beneficial to have Canadian guidelines and perhaps a computer program incorporating every aspects both at the macro and micro levels.
Region of Waterloo, Ontario	If the model took into consideration the types of storms, traffic volumes, other available sites, etc.
MDOT/Michigan	Not sure.... could be just a manual
KDOT	It could provide guidance for installations based on facts not opinions
Wisconsin DOT	It would have to be climate based.
Iowa DOT	Not necessary, but maybe helpful

Q20: In general, what are the greatest challenges that you often encounter when locating RWIS?

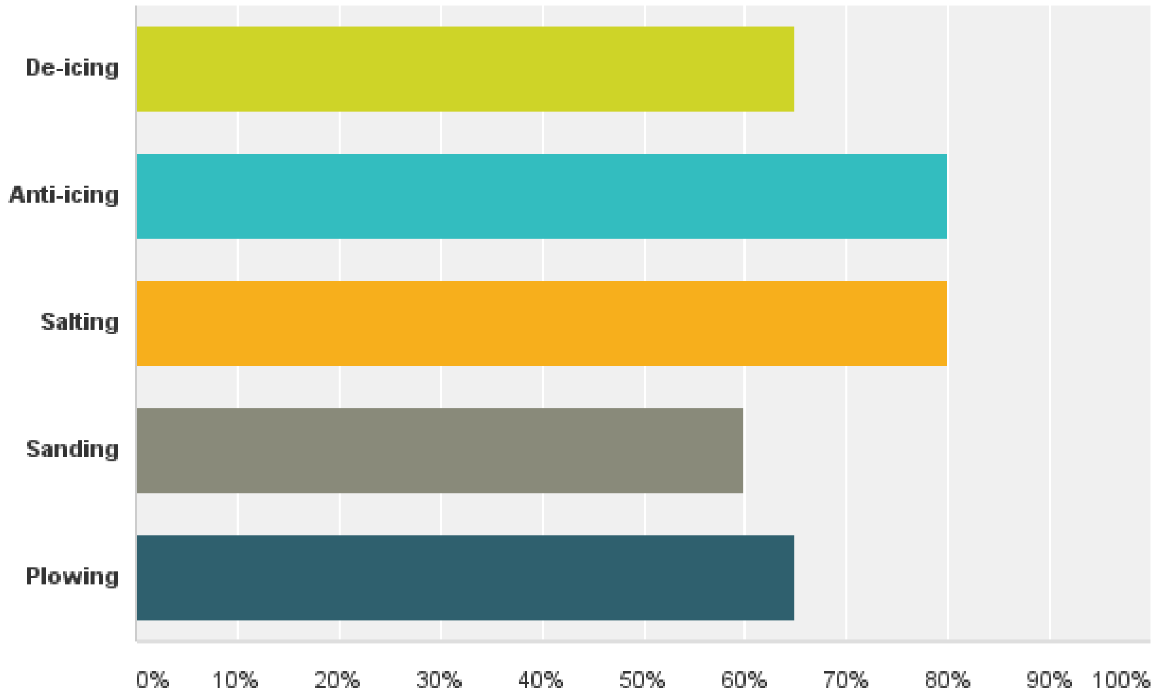
Agency	Greatest Challenges Often Encountered When Locating RWIS Stations
Utah DOT	Power sources and communications. Cell phone coverage is limited in a rural and mountainous state such as Utah. Balancing operational distance of non-invasive road sensors and clear zone requirements. Occasionally right of way is a concern, especially bordering NFS and BLM lands. Soil conditions.
Minnesota DOT	Funding, access to power and good communication for the data stream.
Kansas DOT	Not a current issue for us.
PA DOT	Suitability of desired location, access to power and communication (wired or wireless)
Illinois DOT	Funding has been our greatest challenge.
NDDOT	Trying to balance the density vs. problem areas. If you focus on problem areas your data becomes skewed to a worse degree.
Utah DOT	Communication. Cell phone coverage can be limited in rural areas. Right of way, especially BLM and NFS land.
Virginia DOT	Cost
Ohio DOT	Construction planning
PEI	Finding the balance between regional coverage and ideal locations for capturing all weather patterns.
MOT B.C.	Communications options for data retrieval in remote locations, availability of AC power (reliance on solar power problematic at many locations)
GNWT DOT	Local and regional representation, winter maintenance operations, budget constraints, and availability of power and communication.
MTO	Power, and ROW limitations
Alberta Transportation	At the macro level - it is a time consuming process to gather and analyze the historical data, also the process requires input from many professionals. Consolidating the data and making decisions without clear guidelines. At the micro level - it would be helpful to have a clear procedure with a clearly described process for the field staff.
Alaska DOT	Power and communication Priority maintenance and O&M
Region of Waterloo, Ontario	Since we only have installed weather stations in rural locations, acquiring land was very time consuming. Picking the preferable site was the next toughest along with determining our needs.
Illinois DOT	Lack of budget
UDOT	Lack of communication to the site. Utah has areas of no cell coverage, and many of these are frequently hazardous weather locations.
Ohio DOT	None
NDDOT North Dakota	Most often we would like to deploy in remote areas that lack power and communications. This creates cost issues.
MDOT/Michigan	Budget - installation and maintenance costs
Wisconsin DOT	Cost
Iowa DOT	Weighing all the pros and cons. There never seems to be a perfect site all around.

Q21: What winter maintenance operations do you perform using real-time (e.g., current observation) RWIS data?

Agency	Winter Maintenance Operations Performed Using Real-Time RWIS Data
Minnesota DOT	Maintenance operational planning and deploying crews
Kansas DOT	Camera images
MOT B.C.	Sweeping
Region of Waterloo, Ontario	Occasionally
UDOT	Probably all of these
Ohio DOT	Storm tracking
MDOT/ Michigan	In general, maintenance staff do not access the real time data.



Q22: What winter maintenance operations do you perform using near-future (e.g., forecast) RWIS data?

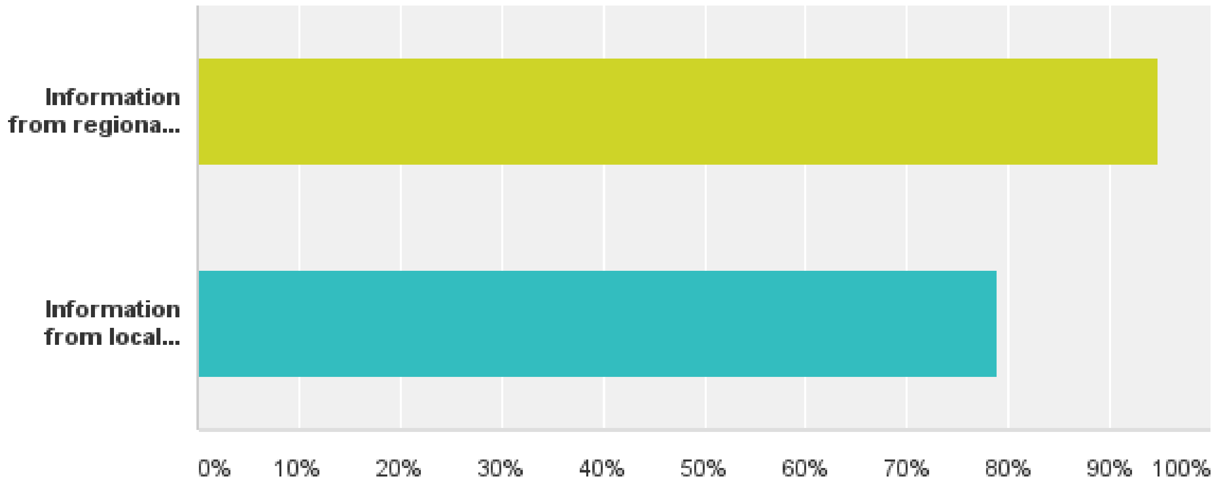


	Winter Maintenance Operations Performed Using Near-Future RWIS Data
Utah DOT	Weather group provides forecast tools for operational decision makers.
Minnesota DOT	Maintenance operational planning and deploying crews.
Utah DOT	We have no site specific RWIS forecasts rather a detailed forecast for the entire route.
Alaska DOT	seasonal weight restrictions primarily
UDOT	Our maintenance activities use forecasts from human forecasters.
Ohio DOT	Storm tracking

Q23: Do you use RWIS (forecast) data for resource planning and preparation (e.g., staff, equipment, and material)?

Agency	**Use of RWIS Data for Resource Planning and Preparation? If yes, please describe what RWIS data (e.g., near-future pavement temperature) you use**
Utah DOT	Weather Group supports in house weather briefings and conference calls to all decision makers within UDOT.
Minnesota DOT	Forecasted wind, pavement temperature, precipitation, air temp, dew point, RH, etc.
Kansas DOT	Standby and crew call out based on pavement forecast data.
NDDOT	The RWIS data is used by Meridian to aid in their forecasting.
Utah DOT	We have no site specific RWIS forecasts rather a detailed forecast for the entire route. The RWIS data helps verify and adjust short term forecasts.
Ohio DOT	Pavement temperature, sub-surface temperature, precip.
PEI	Near future pavement temperature, precipitation type, road conditions, wind speed
MOT B.C.	Hwy Maintenance is privatized - the contractors do this.
GNWT DOT	Snowfall amounts, air temperature, pavement temperature
MTO	Its one of the tools that our AMC contractors use.
Alberta Transportation	I am not directly involved in Maintenance. I can provide contact information for your further inquiries.
Alaska DOT	Pavement and sub-surface temperatures, camera images
Illinois DOT	Pavement temperature forecast
Ohio DOT	Pavement temperature
NDDOT North Dakota	RWIS Data is used by MDSS
MDOT/Michigan	Pavement temps and precipitation (i.e., to prevent an ice bond from forming)
Iowa DOT	pavement temperature, wind, visibility, humidity, precip. probability, precip. type

Q24: What other sources of information (other than from RWIS) do you incorporate for initiating the winter maintenance operations?



Agency	**Other Information Sources Incorporated into Winter Maintenance Operations**
Utah DOT	Weather Group uses all available weather data at their disposal. The Weather Group is under the Traffic Management Division and not under Road Maintenance. Weather Group supports the entire state DOT.
Minnesota DOT	Maintenance Decision Support System (MDSS)
PA DOT	Paid private weather forecast service
Illinois DOT	Forecast from contracted weather service
Utah DOT	We often use NWS locations. We will use local weather data when trusted by the meteorologist in areas of sparse data.
Ohio DOT	Private weather consultants
MOT B.C.	Winter Maintenance Specifications (contract documents)
MTO	Patroller observations
Alberta Transportation	EC, Local weather networks
Alaska DOT	FAA Weather Cameras, other weather cameras, We have a good cooperative relationship with the National Weather Service and the Federal Aviation Administration (FAA has installed two web cameras at RWIS sites and will do another in 2013). We also have cooperative agreements with the National Park Service and River Forecast Center (NWS), and the Depart of Fish and Game. See Alaska Weather Links on our web site.
Region of Waterloo, Ontario	Intellicast and other websites that show large storms (clippers and Colorado lows, etc.) forming days away. Presence of salt residual on road.
UDOT	Not sure the distinction here.
Ohio DOT	Consultants
MDOT/Michigan	Past experience of weather conditions in that area
Wisconsin DOT	MDSS
Iowa DOT	Communications from other maintenance supervisors

Q25: Please feel free to leave any comments or suggestions on the RWIS site selection process.

Agency	Comments/Suggestions on the RWIS Site Selection Process
Minnesota DOT	It is very important to include Meteorologists in the decision to make sure your RWIS system is able to be used to help on a broader scale (weather forecasting models), but also to find out which atmospheric sensors you will actually need since you don't want to double up if there is another weather station close to the area you are considering for an RWIS. You may just need to have pavement information and camera and no or limited atmospherics needed.
Kansas DOT	RWIS and information it provides through our weather service provider are tools used by our Maintenance decision makers.
Illinois DOT	If citing is a concern portable RWIS sites could be used to help with gathering data to make a decision.
Virginia DOT	What you see on the road is a environmental sensor station not an RWIS
Ohio DOT	This would be a good tool for developing users.
MOT B.C.	In complex mountainous terrain there is no optimal spacing of stations. Site selections are based on operational needs for data to support local decision making.
Alaska DOT	I invite you to take a look at the information we provide to travelers and the maintenance engineers (for seasonal weight restrictions) on our RWIS public web site at http://roadweather.alaska.gov. The Alaska Weather Links demonstrates the partnerships that DOT has developed. Also note the cooperative observations we provide (Mentasta Pass, Klondike).
Ohio DOT	Any RWIS activity needs front line user buy-in or it is not worth the effort.

APPENDIX B. MATHEMATICAL FORMULATION OF THE SPATIAL INFERENCE–BASED APPROACH

Consider a region of interest, which is discretized into N grid cells with each cell represented by a single point and labeled by i with i ∈ 1, 2, …, N. There are a total of M monitoring stations (RWIS) labeled by k with k ∈ 1, 2 , … , M, and their locations are known and denoted by a vector X, where X = [x1, …, xM] and xk represents the location (cell label) of RWIS station k. Let z be a variable of interest, which is observable at the M locations. Based on the observations from the M number of RWIS stations, we are interested in estimating the condition at any given location i, denoted by $\hat{z}(i|X)$, which is an estimate of the true value z(i) given observations at X. Our variable of interest, kriging variance is then expressed by $\sigma^2[\hat{z}(i|X)]$, which reflects the needs for installing RWIS stations

To formulate the problem as an integer programming problem, we introduce a decision variable yki (i ∈ 1, . . . , N, and k ∈ 1, . . . , M) with yki = 1 if an RWIS station k is assigned to cell i, 0 otherwise. Following the previous notation, yki is related to xk in X as follows:

$$x_k = \sum_i (y_{ki} \cdot i), \ \forall i \in N, \forall k \in M \tag{B-1}$$

The fitness function (objective function) combining the two location criteria is expressed in the following discrete formula:

$$\underset{X \subset \Omega}{Min} \quad \phi(X) = \left[\frac{1}{N} \cdot \sum_i \left(\sqrt{\sigma^2 [\hat{z}(i) \mid X)]} \right) \cdot \omega_1 + \frac{1}{M} \cdot \sum_i \left(\mu_i^{-1} \cdot \sum_k y_{k,i} \right) \cdot \omega_2 \right], \quad \forall i \in N, \ \forall k \in M \tag{B-2}$$

Subject to:

$$\sum_i \sum_k c_{k,i} \cdot y_{k,i} \le B, \ \forall i \in N, k \in M \tag{B-3}$$

$$\sum_i \sum_k y_{k,i} = M, \ \forall i \in N, k \in M \tag{B-4}$$

$$y_{k,i} \in \{0,1\} \ \forall i \in N, k \in M \tag{B-5}$$

where,

Ω	an index set that defines all of the candidate RWIS station locations in the study area
X	a subset of Ω and a solution set, X = [x_1, …, x_m]
N	a total number of all highway grid cells
M	a total number of RWIS stations to be deployed
c_{ki}	a total cost of an RWIS station *k* at site *i*
B	a total available budget
$\sqrt{\sigma^2\left[\hat{z}(i) \mid X\right]}$	the square root of the kriging error variance at *i* given *X*
μ_i^{-1}	the inverse of mean collision frequency at *i*,
ω_1, ω_2	the weights for criteria 1 and 2

The objective function represents the sum of average kriging variance of estimating, for instance, the HRSC frequency and average collision frequency, given *X*. The kriging variance term is root-squared, as appeared in the first part of the objective function so that estimation errors can be expressed in the same unit as the observations themselves. The weighting factors can be viewed as a way to combine the two measures into a common unit. The second term of the objective function represents the sum of average collision frequency. The binary decision variable y_{ki} is there to take account for those measured only when an RWIS station location, *k* is allocated to site *i*. Average collision frequency is calculated using the minimum gridded cell, within each of which, all collision events are aggregated. The constraint provided in Equation B-3 represents the cost limit of installing RWIS stations in the study region. During installation, the stations may be equipped with different sensors based on various requirements. Furthermore, the annual maintenance costs for individual sites may also vary depending on the proximity to maintenance facilities. Hence, c_{ki} is added to take account for all supplementary costs in addition to the cost of installing a single RWIS station *k* at site *i*. Another constraint that appears in Equation B-4 ensures that a fixed number of RWIS stations are deployed. The weighting terms, ω_1, ω_2 are added so that an RWIS planning department can adjust and/or apply different weights according to their importance. For simplicity and convenience herein, a fixed number (and a uniform cost) of RWIS stations are deployed.

It is worthwhile noting that some sites may not have access to power and/or communication utilities; another important factor that must be considered to ensure that the data can be obtained and processed in real time (Manfredi et al. 2008). The optimization framework introduced in this paper, however, can be easily extended to take additional factors into account by introducing another binary decision variable (i.e., 1 if a potential RWIS site has power/communication network in its vicinity, and 0 otherwise). Alternatively, the cells that do not satisfy the local requirements can be filtered out first such that only candidate locations are considered.

APPENDIX C. OPTIMIZED RELOCATED RWIS NETWORK

Table C-1. Locations of relocated RWIS stations – single criterion [Crit1]

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
1	-86.3865	49.7799	-92.8933	41.6849	-95.9947	44.9342	-109.9216	37.5770
2	-90.7094	49.1064	-94.7151	41.4973	-93.3589	43.5595	-112.4866	39.3270
3	-80.0849	46.4065	-92.5682	41.9822	-92.8736	46.8873	-111.9280	38.9630
4	-75.3554	45.3365	-91.6400	41.6165	-94.7169	44.8007	-109.4496	37.3001
5	-81.3134	42.8179	-91.7007	42.0540	-96.2557	47.0980	-110.7942	39.5857
6	-82.7557	42.1192	-90.8135	42.4382	-95.0897	43.8946	-111.0817	39.8563
7	-77.6607	45.4891	-94.7920	42.7345	-96.2903	46.5202	-111.9325	41.0619
8	-80.6535	46.0856	-93.7786	41.0955	-93.5996	47.8420	-112.0302	41.3388
9	-79.7180	48.1016	-92.8093	43.1284	-95.3317	48.9255	-112.3640	38.9800
10	-84.7890	47.4734	-95.8136	42.4827	-94.8597	45.6119	-109.3883	37.4405
11	-77.0709	45.7635	-93.1796	41.8980	-96.9293	47.8391	-110.3374	39.1308
12	-83.2122	47.6226	-96.3389	42.5494	-90.7380	47.6359	-111.6709	40.7396
13	-81.6357	45.2332	-95.0869	43.1291	-94.6176	43.5503	-111.4630	40.9959
14	-85.4710	49.7723	-94.5680	42.4494	-92.1244	44.3479	-109.7615	38.5435
15	-86.9273	48.7970	-94.5512	43.1132	-94.5471	45.3360	-112.0511	41.7962
16	-81.8160	45.7408	-90.9784	41.6327	-92.9870	44.3105	-112.4346	37.8063
17	-93.7766	51.0094	-93.4970	40.7334	-93.4359	44.2334	-112.4657	39.4716
18	-84.0061	46.3315	-95.2435	42.2677	-95.3823	45.5169	-109.5880	40.4121
19	-89.0074	48.5199	-91.4733	43.2659	-96.7249	45.6914	-113.1445	41.8306
20	-89.3289	49.4153	-91.3279	40.8510	-94.7014	48.7706	-112.3035	39.1161
21	-82.5902	42.2385	-92.2266	41.6950	-95.0143	45.1753	-112.5523	38.6025
22	-92.9976	49.8164	-94.0832	42.7333	-93.0640	46.4447	-111.2816	40.6155
23	-91.3951	48.7380	-91.0714	42.7001	-93.1958	47.3401	-113.0410	38.4038
24	-79.3929	46.1875	-92.6445	40.7249	-92.4594	47.4924	-112.0018	38.8225
25	-77.3825	44.2314	-96.1103	41.9981	-92.7881	45.0321	-111.8314	41.7915
26	-80.8085	43.0615	-95.4318	40.7438	-93.8768	44.5447	-112.2744	40.6859
27	-93.2804	50.6667	-96.1783	43.3253	-95.9837	47.6699	-111.9608	40.3818
28	-80.1552	47.6456	-93.4125	41.4646	-94.5484	48.2243	-111.8257	41.2077
29	-79.0468	43.9327	-91.9903	42.3215	-92.9322	45.7743	-112.2618	41.7595
30	-89.5390	48.5282	-93.4729	41.0302	-92.8736	43.6648	-111.5716	40.6105
31	-78.6669	44.1702	-91.4838	42.4147	-92.2645	43.9161	-111.8596	40.6298
32	-92.1077	48.7357	-92.9032	42.3149	-95.8262	46.2679	-113.0503	37.7252
33	-80.2963	49.5886	-90.6825	42.0964	-93.8199	47.4409	-111.7859	38.5125
34	-82.2778	46.2064	-91.3244	41.2756	-94.6609	46.5385	-112.6596	38.2728
35	-82.1288	42.9905	-93.5699	42.4506	-94.0875	43.5117	-111.9282	40.4981
36	-89.4902	48.0848	-94.3551	41.4912	-91.6709	44.0462	-111.9512	41.9394
37	-84.8212	48.1634	-95.3472	41.7700	-96.2125	43.5101	-111.6504	38.4176

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
38	-79.1793	43.1137	-90.4385	41.8160	-96.2693	43.8786	-112.3134	38.2530
39	-81.2628	43.3827	-93.3491	43.2501	-94.4284	43.9588	-111.5647	39.5014
40	-94.4098	49.7501	-92.6423	41.2719	-94.2714	45.8081	-109.7630	40.3079
41	-79.9074	45.3070	-94.0766	41.8340	-93.0041	48.3923	-112.5244	37.4925
42	-78.6880	45.0717	-91.8339	42.7725	-95.2117	47.8690	-113.5315	37.1245
43	-92.0710	50.0857	-91.8915	41.1778	-95.9113	45.3883	-111.7170	40.1002
44	-82.4610	48.2117	-92.4010	40.9877	-94.3567	46.1524	-111.3952	41.9327
45	-84.5174	49.7640	-91.3218	42.8829	-96.7464	47.2990	-112.5109	40.7067
46	-78.3405	46.2610	-91.8129	43.2816	-91.7722	47.8136	-111.9185	39.5577
47	-81.5744	48.2380	-92.2960	43.1404	-96.3236	44.7160	-110.4057	40.3388
48	-94.6322	49.7740	-95.3257	41.2323	-95.4479	44.9174	-111.4725	40.5043
49	-84.7169	47.0935	-93.4581	42.6769	-93.0364	44.7212	-111.5434	40.3927
50	-82.2193	42.4313	-91.1816	43.0416	-93.2421	44.9850	-111.5920	40.9227
51	-82.1263	45.8440	-92.3868	42.5297	-95.4617	43.6413	-112.0920	41.6271
52	-80.4660	48.5319	-94.7055	40.9800	-94.4159	44.3929	-111.0306	40.4778
53	-80.4561	43.3274	-91.2856	42.0744	-96.7573	46.7219	-112.6460	38.0609
54	-79.7670	47.2544	-93.8865	43.0980	-94.5511	47.3759	-111.8384	39.7066
55	-92.4980	49.6895	-95.6005	43.1860	-95.7783	45.8161	-113.1029	37.0704
56	-79.7876	45.9292	-93.0299	41.0009	-92.4955	43.5055	-113.3759	40.7240
57	-76.1742	44.7130	-93.5804	41.7388	-95.3082	45.9638	-113.1485	39.1096
58	-81.6642	47.0930	-93.9065	41.5583	-93.0717	43.9012	-112.8538	37.6895
59	-79.6887	47.6458	-94.6685	42.0628	-94.7286	46.9399	-111.7414	40.3395
60	-81.8544	47.5446	-94.1069	42.2085	-94.0390	46.4438	-110.5301	38.6902
61	-91.7050	49.4344	-93.5516	42.1204	-91.2711	43.7091	-111.7031	39.1787
62	-77.5798	46.1497	-91.9571	40.7374	-91.7953	43.5128	-109.8226	37.2260
63	-93.7868	49.8397	-94.2251	40.7774	-94.8952	44.2714	-111.9574	39.9848
64	-83.3941	46.2950	-96.0777	42.9085	-93.9418	45.5911	-113.7046	37.5711
65	-78.2444	44.3048	-95.3160	42.6763	-91.6324	47.0292	-111.0711	39.2260
66	-79.7397	44.8067	-95.7925	41.4997	-93.9851	48.6279	-111.0733	39.3779
67	-74.6379	45.4843	-92.9031	42.7451	-95.5095	46.5664	-111.6070	41.3385
68	-92.1073	49.5313			-93.7846	43.8011	-111.7377	41.0945
69	-77.3299	44.5486			-96.4178	46.0364	-111.4670	40.7749
70	-83.7251	46.4289			-93.5922	44.7803	-112.2839	38.5813
71	-78.1020	44.8791			-92.5969	46.0136	-109.5835	38.5700
72	-79.5907	43.6676			-94.8636	46.0028	-110.8367	39.7412
73	-83.3955	46.8828			-93.9454	44.1913	-111.3513	38.7682
74	-82.3834	49.4005			-93.5937	46.6075	-110.5265	38.0142
75	-87.0297	49.6862			-92.5735	44.5621	-109.4357	38.0136
76	-80.1386	48.0545			-95.7452	44.1770	-112.7904	37.5648
77	-80.8003	48.7594			-92.7921	47.9082	-111.9017	40.7717
78	-79.2887	45.0461			-96.4344	45.3098	-110.5060	40.1756

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
79	-79.7085	44.3823			-92.3934	46.5228	-113.2428	37.2106
80	-79.7508	46.6820			-93.4368	46.0185	-109.6180	37.5412
81	-81.6770	49.2764			-92.9838	45.4399	-112.0839	39.3337
82	-84.3620	46.7519			-93.9565	46.9864	-110.7552	40.2089
83	-84.7937	48.9182			-95.3184	47.2860	-112.1081	40.7698
84	-77.2707	45.0860			-96.8050	48.8924	-112.1287	38.6847
85	-81.6257	42.9942			-96.8177	48.3407	-110.1259	40.2595
86	-76.0220	45.2947			-95.3330	44.5391	-112.0420	40.6481
87	-80.6251	46.5166			-96.3036	44.2636	-111.4254	39.6359
88	-90.6970	50.3161			-95.7053	46.8357	-112.3958	40.2795
89	-93.5584	48.6179			-92.6395	44.0327	-111.8095	39.9810
90	-75.3938	44.8170			-93.8709	45.1759	-112.8454	37.8504
91	-80.8182	44.4063			-93.4845	45.5888	-112.0136	41.5222
92	-77.8310	45.0435			-94.3554	47.8292	-109.3088	37.8734
93	-85.8231	48.7112			-91.9161	43.7488	-110.4726	38.9420
94	-90.4558	48.6461			-95.1130	46.4313	-112.0709	39.6575
95	-81.7476	46.2408			-94.2323	44.8925	-111.8684	41.6262
96	-81.1764	46.4177			-95.8146	48.2825	-112.6506	39.3121
97	-89.7452	48.2882			-95.9190	48.9221	-111.2599	39.6455
98	-79.1269	44.3698						
99	-81.0687	49.0601						
100	-79.6347	44.0213						
101	-78.2638	43.9737						
102	-78.8903	46.2847						
103	-76.1721	44.3457						
104	-76.7721	44.2802						
105	-78.2588	45.5095						
106	-79.2235	43.0147						
107	-88.2949	49.0209						
108	-85.2055	48.5498						
109	-80.9055	47.6460						
110	-88.1297	49.3617						
111	-94.0455	49.3946						
112	-81.2918	48.5318						
113	-94.4565	48.7214						
114	-80.7360	43.9841						
115	-84.1951	46.5530						
116	-79.9651	43.1873						
117	-77.0702	45.4811						
118	-79.1565	46.5011						
119	-80.2587	44.0659						

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
120	-93.9179	48.7547						
121	-82.8535	46.1879						
122	-79.9178	48.5210						
123	-83.6155	49.6816						
124	-91.1841	49.8462						
125	-81.5261	46.6632						
126	-87.7395	49.6685						
127	-80.2152	45.5026						
128	-74.8351	45.0675						
129	-79.2649	45.4712						
130	-81.6267	43.6739						
131	-92.9250	48.7180						
132	-88.6522	48.6678						
133	-81.1168	44.6270						
134	-80.1474	42.8217						
135	-84.1063	47.9275						
136	-81.5312	44.1426						
137	-90.2810	51.0711						
138	-80.2435	43.5425						
139	-76.6643	45.4907						
140	-79.8613	43.5431						

Table C-2. Locations of relocated RWIS stations – dual criteria [Crit1+ Crit2]

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
1	-79.1696	43.1603	-95.8287	41.0908	-94.5250	45.6150	-110.3500	39.2990
2	-82.2211	42.3332	-93.7992	40.9659	-93.7030	43.6550	-110.2134	38.9847
3	-74.6003	45.5018	-91.2071	43.0259	-92.6664	47.7956	-111.8595	40.7189
4	-76.0756	45.3178	-93.5687	42.5570	-95.0457	45.0774	-112.1474	39.2278
5	-80.9250	48.5453	-93.4815	41.6602	-93.5331	44.7731	-110.8048	39.5840
6	-82.0626	45.9445	-96.0497	41.7966	-92.1365	44.1876	-112.3288	41.8055
7	-79.7915	47.3496	-90.4294	41.5963	-96.3035	43.6196	-113.0790	37.6956
8	-79.9161	47.8557	-95.4291	43.1850	-95.1157	44.1668	-112.5228	41.8961
9	-94.8048	49.7137	-94.7276	41.4949	-91.7456	46.9880	-112.4241	40.6830
10	-86.0894	49.7849	-93.5729	42.4048	-93.8052	44.9018	-111.8393	39.7463
11	-80.3644	43.6964	-92.4380	41.3328	-95.0036	45.3660	-111.5165	41.0370
12	-75.6209	45.0558	-92.9897	41.0136	-93.2165	46.6267	-109.3815	38.1655
13	-91.9715	48.7256	-95.6943	41.3563	-93.2433	44.0255	-111.9508	40.6931
14	-79.7639	43.6026	-91.6756	42.0266	-91.5234	43.9081	-111.6601	41.0405
15	-80.6232	48.5916	-92.5327	42.8082	-95.4734	46.4014	-111.6452	40.1758
16	-82.6337	42.0680	-94.4210	41.0097	-95.7605	43.9926	-112.6149	38.1469
17	-84.3280	46.6666	-92.1891	42.4362	-96.2669	43.6337	-111.4042	40.9877
18	-81.0655	49.0599	-90.8588	41.6302	-96.8246	48.3429	-111.7088	40.7542
19	-84.2000	49.7437	-93.5681	41.9397	-94.3733	44.6521	-109.5981	40.3884
20	-74.6900	45.0653	-92.9026	42.3225	-94.3442	45.9700	-112.2014	41.7111
21	-92.9553	49.8151	-91.9833	42.3153	-93.8672	46.3839	-112.0143	41.2243
22	-91.5023	48.7121	-93.7604	41.6525	-94.4157	45.1000	-111.8016	40.3691
23	-80.1618	48.0751	-91.9346	40.9854	-94.5130	46.3375	-112.5151	38.8013
24	-93.0823	48.7169	-92.2772	41.6973	-96.2974	46.5228	-109.4841	37.5001
25	-94.2699	49.7302	-91.3884	41.2800	-95.2862	43.8110	-113.2015	40.7225
26	-77.3022	45.8820	-90.6788	42.1488	-95.9030	43.6359	-110.8061	38.8658
27	-78.9587	45.3543	-96.1203	42.0150	-92.6616	44.0298	-111.6134	40.7553
28	-79.9308	43.1536	-93.9749	41.5439	-94.8727	46.0816	-112.6201	38.4877
29	-80.5248	43.4942	-92.9788	41.6836	-96.4700	46.0486	-112.7807	41.9732
30	-79.2357	42.9142	-92.2999	43.2848	-96.9663	48.8083	-111.7283	38.9150
31	-79.3249	44.9605	-93.3401	43.0748	-93.9520	44.1759	-111.1039	39.2567
32	-81.3021	42.8273	-95.8372	41.4961	-95.9273	46.1474	-112.4905	38.5908
33	-86.8901	48.7756	-96.3885	42.4839	-92.9910	45.4603	-112.7002	37.2211
34	-79.7941	45.0686	-91.8734	41.6863	-93.1728	43.6556	-109.2998	37.8717
35	-85.1516	48.5185	-91.6485	41.7946	-94.0946	43.6379	-111.5066	40.7297
36	-76.8740	45.6248	-95.0956	40.9913	-94.2260	47.9219	-112.8828	37.8370
37	-78.3460	44.2657	-94.5660	41.4946	-93.3105	44.3126	-112.2523	39.1190
38	-80.0748	43.9195	-91.7992	42.1860	-95.6171	44.4558	-109.9358	37.6012
39	-80.8631	43.0211	-95.2956	41.5004	-95.3001	46.9119	-112.0380	40.7694

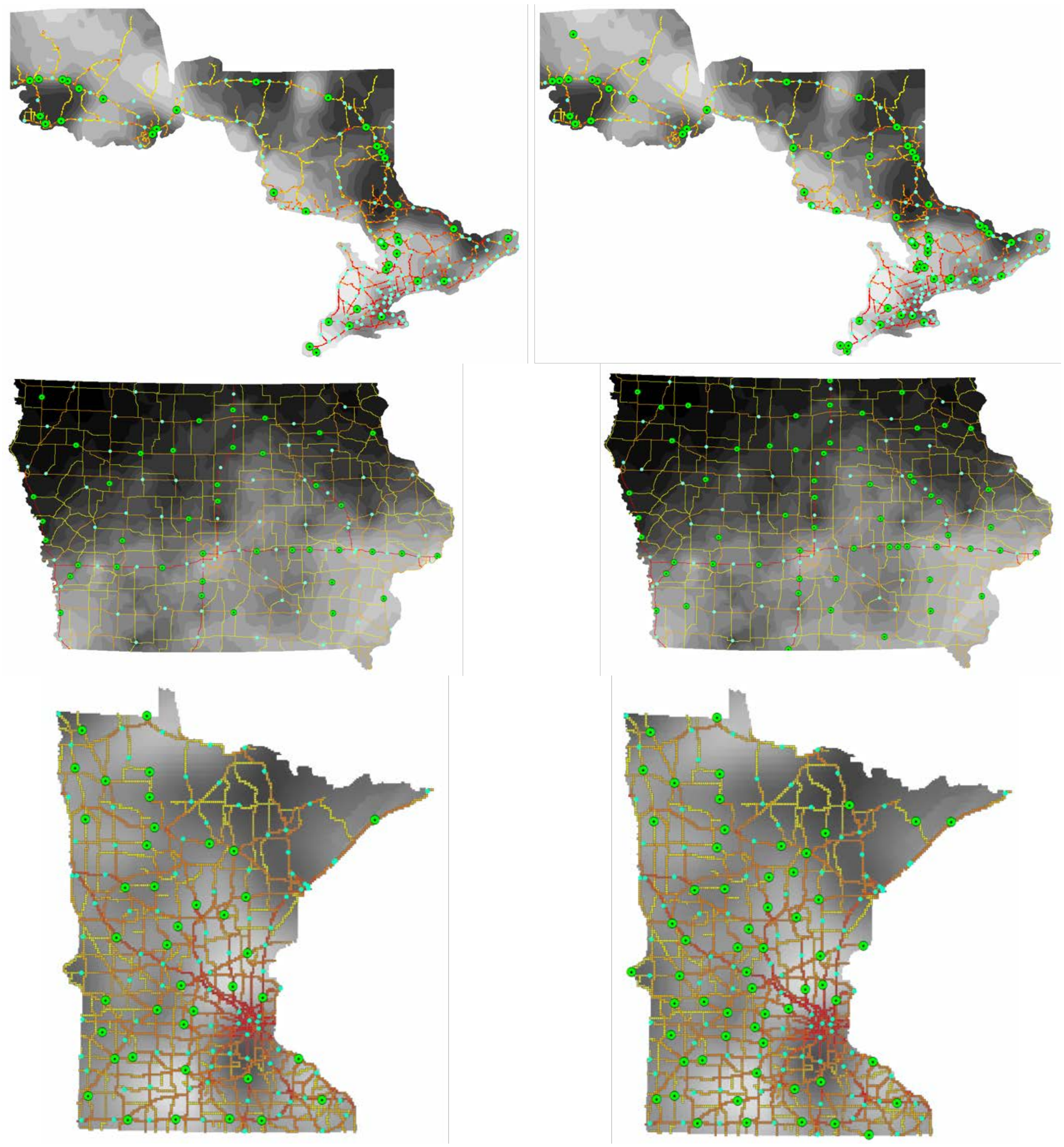
Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
40	-79.8055	43.3141	-93.7790	41.4798	-96.1548	45.5738	-111.7780	41.1327
41	-92.5182	49.6896	-96.1793	43.2364	-94.2219	45.5205	-112.0205	41.1251
42	-93.9156	49.0972	-94.6937	42.4503	-92.8255	46.2491	-112.3751	38.5467
43	-88.6413	48.6780	-93.3619	42.7964	-95.4003	43.6337	-112.3523	38.9495
44	-81.3063	48.5055	-93.1787	41.6929	-95.5300	45.2840	-112.0625	41.5369
45	-84.3571	46.8847	-91.3987	40.6242	-94.9960	44.6326	-109.6077	37.2540
46	-83.6429	49.6864	-96.2888	42.2919	-95.5599	45.6170	-112.7488	40.7569
47	-79.3293	45.5402	-92.7283	41.6979	-93.6531	47.7571	-112.6601	38.3761
48	-82.3371	42.9918	-95.7122	43.4352	-92.6877	43.7062	-111.5130	38.7980
49	-90.7125	49.1160	-90.6696	41.6049	-93.6160	46.8185	-109.6900	38.9514
50	-89.1186	48.8310	-94.8028	43.1283	-93.6644	46.0516	-111.3478	38.7676
51	-78.5391	43.9211	-95.8046	40.7995	-93.4894	48.5306	-111.8294	39.8918
52	-80.9529	43.9501	-95.5681	42.4762	-96.3423	43.9529	-111.2751	41.0681
53	-78.1836	45.4987	-94.1172	43.0808	-90.2374	47.7797	-112.5955	38.6603
54	-79.6482	44.6908	-94.9677	41.4964	-96.7445	46.9586	-111.9092	39.6138
55	-79.6367	44.1218	-92.5188	40.7364	-96.7274	47.7023	-109.0933	39.1904
56	-85.9824	48.6907	-93.1837	41.3246	-92.8943	44.4532	-113.7460	39.0618
57	-84.8049	48.0906	-96.1180	42.8082	-93.1662	45.0662	-109.3432	38.9789
58	-89.8955	48.8025	-95.1766	42.0709	-91.5892	43.5732	-111.9315	38.8792
59	-76.7716	44.2807	-91.2436	41.6615	-92.4823	47.2926	-110.0455	38.9495
60	-90.3334	48.6655	-95.4045	41.4993	-96.4321	45.2905	-111.9916	39.4741
61	-79.5364	43.7142	-94.2654	41.4913	-95.9536	44.7904	-111.9386	41.0156
62	-79.4569	43.1879	-93.5724	42.1546	-93.4960	47.2284	-112.3002	40.6674
63	-94.1851	48.7063	-93.3492	43.3612	-95.8592	46.8276	-109.4397	37.6580
64	-94.0573	49.4282	-92.3179	42.4538	-94.6733	43.6697	-111.7186	40.2786
65	-76.6133	45.4610	-91.3429	42.4679	-95.8677	45.1129	-111.7303	40.0631
66	-79.4215	44.6426	-95.8982	41.3483	-96.2058	47.1833	-109.2258	39.0794
67	-79.9102	43.9602	-91.7136	43.1210	-94.4675	44.3189	-111.9194	40.6385
68	-93.8598	49.8464			-92.8558	44.7516	-112.2412	38.6018
69	-80.1099	43.4452			-96.2559	44.2702	-112.5779	40.7250
70	-87.8214	49.6568			-93.6865	45.2500	-111.0670	38.8452
71	-79.4068	46.1877			-96.2778	44.6978	-111.2578	40.3033
72	-84.5848	47.3109			-93.9031	44.5042	-112.0879	41.6221
73	-94.5394	49.7898			-95.4856	44.8540	-112.1513	38.6854
74	-80.3308	46.4441			-92.6454	44.5613	-109.8899	38.9263
75	-77.7623	44.4603			-93.0248	45.2577	-112.0327	41.3279
76	-81.5602	42.9682			-93.2942	44.5286	-111.6001	38.8821
77	-84.0516	46.3396			-93.9862	45.3725	-112.1787	40.7475
78	-75.5115	44.7302			-95.3873	45.8468	-111.9073	40.4426
79	-86.7070	49.7443			-96.1206	48.0880	-110.4578	38.9305
80	-75.0423	44.9926			-93.6571	45.8062	-112.0840	39.3353

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
81	-78.7970	44.8006			-92.1299	43.8049	-111.4092	40.8035
82	-94.5870	48.7206			-95.0192	47.5933	-112.1693	41.9104
83	-78.5709	44.1059			-95.2706	48.8719	-109.6659	38.6359
84	-78.9333	44.1024			-91.7815	47.9247	-112.0644	38.8051
85	-79.0889	43.8322			-94.3135	47.3605	-112.1837	39.9339
86	-84.9946	49.7560			-94.5540	48.5383	-112.0475	41.4221
87	-77.1907	44.8664			-95.3450	48.2827	-110.6934	38.3928
88	-81.2088	44.5302			-92.5338	46.6313	-111.1984	39.9308
89	-81.7630	42.5515			-92.9898	45.7888	-111.9069	40.8553
90	-80.8800	48.8850			-92.9075	47.4621	-113.2108	37.5074
91	-92.5999	48.7565			-96.8416	45.5960	-111.8558	38.9371
92	-78.0320	44.9479			-95.4467	47.7001	-111.4053	40.4960
93	-77.3928	44.1937			-92.7989	44.9525	-110.4374	40.1661
94	-79.9814	45.3415			-94.4889	46.7691	-112.6521	38.2716
95	-77.0121	44.2519			-92.9289	48.2441	-113.8214	40.7429
96	-76.2028	44.3386			-96.0041	48.7894	-111.8852	40.5268
97	-82.4340	42.6061			-93.2640	44.8905	-113.5330	37.1250
98	-75.4147	45.3472						
99	-77.7716	44.0733						
100	-79.1250	44.4309						
101	-84.0686	46.3517						
102	-88.2495	49.0388						
103	-82.9040	42.2115						
104	-81.9249	42.9921						
105	-89.3030	48.3752						
106	-89.9002	48.2404						
107	-74.9042	45.3419						
108	-82.1449	49.3403						
109	-80.2492	43.1636						
110	-82.8566	49.5263						
111	-79.8107	46.7437						
112	-81.3828	43.5489						
113	-79.2780	45.2811						
114	-78.0679	46.2235						
115	-80.5678	46.0013						
116	-93.9160	48.8285						
117	-81.7585	46.2840						
118	-81.3875	49.1305						
119	-92.8154	49.7865						
120	-91.8480	49.4557						
121	-80.2984	48.3974						

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
122	-91.3118	49.2991						
123	-82.9726	46.1941						
124	-81.3147	45.0249						
125	-93.3271	49.8413						
126	-79.2857	43.9947						
127	-80.5075	43.1365						
128	-79.0926	46.2726						
129	-82.6218	46.3765						
130	-79.6576	44.4335						
131	-93.6397	48.6191						
132	-79.6895	48.1193						
133	-79.1551	46.5360						
134	-88.0839	49.4895						
135	-84.8268	47.7556						
136	-89.5638	48.0389						
137	-81.3911	46.6082						
138	-80.5487	42.8299						
139	-89.6360	48.4194						
140	-80.9318	43.3705						

APPENDIX D. LOCATION PLANS FOR ADDING NEW RWIS STATIONS

40 Additional Stations | **60 Additional Stations**



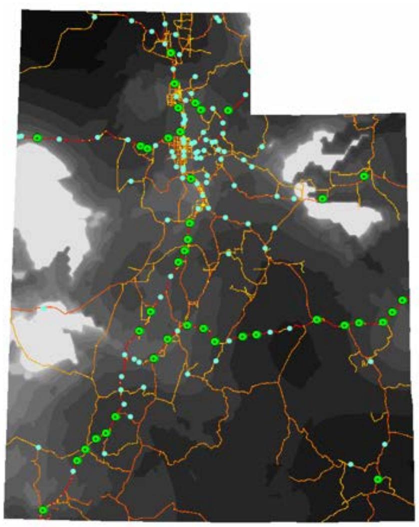
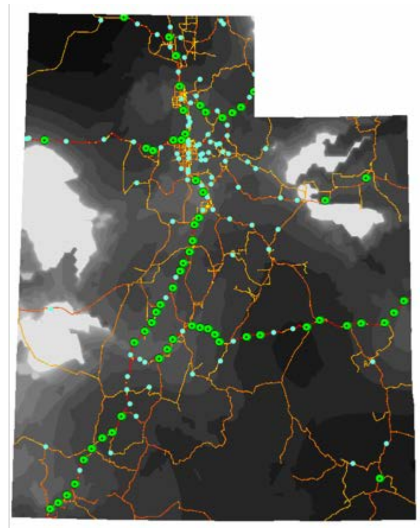
 

Table D-1. Locations of 20 additional RWIS stations

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
1	-79.9208	43.1376	-96.2381	42.2266	-90.7397	47.6298	-112.2882	39.0622
2	-82.8731	42.2395	-93.3527	42.8084	-96.7960	48.2711	-111.4833	38.7768
3	-82.6046	42.0682	-90.9113	41.6352	-93.3193	46.6236	-111.8018	40.3696
4	-79.7479	44.5313	-91.9164	41.0027	-95.8441	46.0485	-110.1243	40.1748
5	-81.2538	42.8775	-95.7975	40.9770	-95.3034	47.2865	-112.0795	41.6011
6	-79.6436	44.6787	-94.3597	41.4926	-92.3065	44.4737	-112.4483	40.6817
7	-92.7913	49.7859	-95.6731	41.3749	-94.6463	46.2206	-111.6787	41.0460
8	-89.2200	48.4651	-93.7781	41.3491	-94.4948	44.9291	-111.3293	41.0399
9	-79.2621	46.3839	-96.0991	41.9656	-94.5666	45.4390	-110.2113	38.9856
10	-82.1269	49.3431	-93.3286	41.0151	-94.2937	46.5161	-112.2450	38.6045
11	-89.2984	48.3940	-92.9986	41.6809	-93.5684	47.2371	-112.4339	38.8724
12	-83.0225	46.2066	-93.8496	43.0997	-95.0119	45.1088	-112.9434	37.8067
13	-93.7089	48.6347	-95.5659	41.5008	-93.5713	45.4332	-109.8648	38.9309
14	-79.2827	45.4881	-95.0074	41.4943	-93.6085	43.6832	-112.0989	40.7697
15	-76.9863	45.7154	-94.2241	42.7728	-93.2696	44.2143	-109.5951	40.3876
16	-94.3425	49.7911	-92.4862	41.6930	-95.1243	46.7479	-113.7783	40.7381
17	-78.4518	44.1990	-93.7886	41.1930	-95.2724	47.9287	-113.0761	37.6974
18	-84.3493	46.7330	-92.2371	41.6949	-96.1683	48.1238	-112.0267	41.3041
19	-79.8252	45.2301	-91.2941	42.9517	-96.6982	48.7785	-109.3835	38.9554
20	-79.2981	45.0072	-95.6516	42.8019	-96.0043	45.2163	-111.8120	39.9347

Table D-2. Locations of 40 additional RWIS stations

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
1	-79.9208	43.1376	-96.2381	42.2266	-90.7397	47.6298	-112.2882	39.0622
2	-82.8731	42.2395	-93.3527	42.8084	-96.7960	48.2711	-111.4833	38.7768
3	-82.6046	42.0682	-90.9113	41.6352	-93.3193	46.6236	-111.8018	40.3696
4	-79.7479	44.5313	-91.9164	41.0027	-95.8441	46.0485	-110.1243	40.1748
5	-81.2538	42.8775	-95.7975	40.9770	-95.3034	47.2865	-112.0795	41.6011
6	-79.6436	44.6787	-94.3597	41.4926	-92.3065	44.4737	-112.4483	40.6817
7	-92.7913	49.7859	-95.6731	41.3749	-94.6463	46.2206	-111.6787	41.0460
8	-89.2200	48.4651	-93.7781	41.3491	-94.4948	44.9291	-111.3293	41.0399
9	-79.2621	46.3839	-96.0991	41.9656	-94.5666	45.4390	-110.2113	38.9856
10	-82.1269	49.3431	-93.3286	41.0151	-94.2937	46.5161	-112.2450	38.6045
11	-89.2984	48.3940	-92.9986	41.6809	-93.5684	47.2371	-112.4339	38.8724
12	-83.0225	46.2066	-93.8496	43.0997	-95.0119	45.1088	-112.9434	37.8067
13	-93.7089	48.6347	-95.5659	41.5008	-93.5713	45.4332	-109.8648	38.9309
14	-79.2827	45.4881	-95.0074	41.4943	-93.6085	43.6832	-112.0989	40.7697
15	-76.9863	45.7154	-94.2241	42.7728	-93.2696	44.2143	-109.5951	40.3876
16	-94.3425	49.7911	-92.4862	41.6930	-95.1243	46.7479	-113.7783	40.7381
17	-78.4518	44.1990	-93.7886	41.1930	-95.2724	47.9287	-113.0761	37.6974
18	-84.3493	46.7330	-92.2371	41.6949	-96.1683	48.1238	-112.0267	41.3041
19	-79.8252	45.2301	-91.2941	42.9517	-96.6982	48.7785	-109.3835	38.9554
20	-79.2981	45.0072	-95.6516	42.8019	-96.0043	45.2163	-111.8120	39.9347
21	-79.9654	45.3326	-92.9147	42.7468	-94.3180	45.1070	-111.8367	38.9315
22	-79.9218	47.8628	-91.3373	41.6628	-95.4485	44.4753	-109.1337	39.1652
23	-79.2334	45.3396	-93.3501	43.2195	-95.5102	43.6407	-110.9689	38.8453
24	-85.0717	49.7570	-91.1887	41.1508	-91.8802	43.9281	-111.9495	39.5520
25	-93.0022	49.8158	-91.7760	42.1711	-93.7509	46.3903	-112.0738	38.7937
26	-93.9810	49.8260	-93.9825	42.0313	-92.9942	45.2924	-112.8190	37.8663
27	-92.3321	49.5833	-92.8796	43.1279	-93.2842	45.8778	-109.4826	37.4157
28	-93.0675	48.7193	-96.1794	43.3146	-95.1561	47.5259	-112.7114	38.0269
29	-80.9321	43.3698	-96.0427	41.7611	-94.0556	47.3299	-111.6322	38.9018
30	-80.1121	48.0324	-92.0791	42.9664	-95.3724	49.0007	-112.3631	40.6627
31	-89.1507	48.4917	-94.9348	41.7782	-95.2848	48.2579	-109.2625	39.0536
32	-80.5697	48.5494	-94.7000	42.7346	-94.8556	45.9788	-113.5724	37.0946
33	-74.7446	45.4359	-93.5693	42.2271	-95.7903	44.4458	-111.7572	41.1140
34	-91.3306	49.3057	-91.9222	41.3389	-96.5416	47.6028	-111.8395	39.7737
35	-88.3234	49.0101	-95.1448	42.3974	-93.0138	43.6626	-113.1731	37.5866
36	-79.7908	47.6970	-93.7734	41.6518	-96.0466	44.7918	-109.6885	38.9501
37	-77.3701	44.2001	-92.1364	42.3936	-96.2716	43.9405	-111.9716	41.0642
38	-93.9172	48.8362	-90.4000	41.5989	-95.7043	46.7213	-111.1427	38.8255
39	-89.3178	48.3502	-91.8135	41.6856	-94.4549	44.3233	-111.9486	40.8282

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
40	-82.0945	42.9909	-93.5742	42.4008	-94.6189	43.6615	-111.8766	39.6641

Table D-3. Locations of 60 additional RWIS stations

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	y	x	y	x	y	x	y
1	-79.9208	43.1376	-96.2381	42.2266	-90.7397	47.6298	-112.2882	39.0622
2	-82.8731	42.2395	-93.3527	42.8084	-96.7960	48.2711	-111.4833	38.7768
3	-82.6046	42.0682	-90.9113	41.6352	-93.3193	46.6236	-111.8018	40.3696
4	-79.7479	44.5313	-91.9164	41.0027	-95.8441	46.0485	-110.1243	40.1748
5	-81.2538	42.8775	-95.7975	40.9770	-95.3034	47.2865	-112.0795	41.6011
6	-79.6436	44.6787	-94.3597	41.4926	-92.3065	44.4737	-112.4483	40.6817
7	-92.7913	49.7859	-95.6731	41.3749	-94.6463	46.2206	-111.6787	41.0460
8	-89.2200	48.4651	-93.7781	41.3491	-94.4948	44.9291	-111.3293	41.0399
9	-79.2621	46.3839	-96.0991	41.9656	-94.5666	45.4390	-110.2113	38.9856
10	-82.1269	49.3431	-93.3286	41.0151	-94.2937	46.5161	-112.2450	38.6045
11	-89.2984	48.3940	-92.9986	41.6809	-93.5684	47.2371	-112.4339	38.8724
12	-83.0225	46.2066	-93.8496	43.0997	-95.0119	45.1088	-112.9434	37.8067
13	-93.7089	48.6347	-95.5659	41.5008	-93.5713	45.4332	-109.8648	38.9309
14	-79.2827	45.4881	-95.0074	41.4943	-93.6085	43.6832	-112.0989	40.7697
15	-76.9863	45.7154	-94.2241	42.7728	-93.2696	44.2143	-109.5951	40.3876
16	-94.3425	49.7911	-92.4862	41.6930	-95.1243	46.7479	-113.7783	40.7381
17	-78.4518	44.1990	-93.7886	41.1930	-95.2724	47.9287	-113.0761	37.6974
18	-84.3493	46.7330	-92.2371	41.6949	-96.1683	48.1238	-112.0267	41.3041
19	-79.8252	45.2301	-91.2941	42.9517	-96.6982	48.7785	-109.3835	38.9554
20	-79.2981	45.0072	-95.6516	42.8019	-96.0043	45.2163	-111.8120	39.9347
21	-79.9654	45.3326	-92.9147	42.7468	-94.3180	45.1070	-111.8367	38.9315
22	-79.9218	47.8628	-91.3373	41.6628	-95.4485	44.4753	-109.1337	39.1652
23	-79.2334	45.3396	-93.3501	43.2195	-95.5102	43.6407	-110.9689	38.8453
24	-85.0717	49.7570	-91.1887	41.1508	-91.8802	43.9281	-111.9495	39.5520
25	-93.0022	49.8158	-91.7760	42.1711	-93.7509	46.3903	-112.0738	38.7937
26	-93.9810	49.8260	-93.9825	42.0313	-92.9942	45.2924	-112.8190	37.8663
27	-92.3321	49.5833	-92.8796	43.1279	-93.2842	45.8778	-109.4826	37.4157
28	-93.0675	48.7193	-96.1794	43.3146	-95.1561	47.5259	-112.7114	38.0269
29	-80.9321	43.3698	-96.0427	41.7611	-94.0556	47.3299	-111.6322	38.9018
30	-80.1121	48.0324	-92.0791	42.9664	-95.3724	49.0007	-112.3631	40.6627
31	-89.1507	48.4917	-94.9348	41.7782	-95.2848	48.2579	-109.2625	39.0536
32	-80.5697	48.5494	-94.7000	42.7346	-94.8556	45.9788	-113.5724	37.0946
33	-74.7446	45.4359	-93.5693	42.2271	-95.7903	44.4458	-111.7572	41.1140
34	-91.3306	49.3057	-91.9222	41.3389	-96.5416	47.6028	-111.8395	39.7737

Station Number	Ontario		Iowa		Minnesota		Utah	
	x	**y**	**x**	**y**	**x**	**y**	**x**	**y**
35	-88.3234	49.0101	-95.1448	42.3974	-93.0138	43.6626	-113.1731	37.5866
36	-79.7908	47.6970	-93.7734	41.6518	-96.0466	44.7918	-109.6885	38.9501
37	-77.3701	44.2001	-92.1364	42.3936	-96.2716	43.9405	-111.9716	41.0642
38	-93.9172	48.8362	-90.4000	41.5989	-95.7043	46.7213	-111.1427	38.8255
39	-89.3178	48.3502	-91.8135	41.6856	-94.4549	44.3233	-111.9486	40.8282
40	-82.0945	42.9909	-93.5742	42.4008	-94.6189	43.6615	-111.8766	39.6641
41	-77.1631	45.7916	-95.8221	43.1617	-94.3644	45.9740	-113.2731	37.3479
42	-79.3094	45.1377	-91.6763	42.9921	-95.9403	43.9914	-111.4618	40.9930
43	-79.0521	44.2356	-93.5690	41.9011	-92.7255	47.8681	-112.0850	39.3065
44	-76.3068	44.3267	-92.3727	41.6936	-94.6752	45.6525	-111.5412	38.8500
45	-76.8112	45.5711	-93.8439	42.7323	-95.0325	44.7982	-112.1713	41.7886
46	-83.3751	47.7660	-91.0353	41.8875	-93.2406	45.4995	-111.7045	40.2566
47	-90.9487	50.3065	-92.6184	41.9946	-93.8754	45.1748	-111.7603	40.0007
48	-78.3517	44.2585	-92.5674	40.7268	-93.7454	44.1190	-111.9926	39.4710
49	-81.6814	47.7375	-95.3755	41.0314	-95.4521	45.2477	-111.7303	38.9144
50	-82.5553	42.2429	-93.3521	43.4804	-96.8382	45.6018	-112.1459	38.6941
51	-84.0673	46.3523	-95.4262	43.1864	-96.1053	46.2667	-111.2209	41.0969
52	-79.4417	44.5725	-93.4366	42.6979	-91.4266	47.6482	-113.4732	37.1577
53	-84.7915	47.9804	-91.6485	41.8139	-94.3401	44.7247	-111.9935	40.7661
54	-81.3711	46.3722	-93.2577	41.3515	-93.8047	46.9863	-112.3476	38.9599
55	-94.6320	49.7765	-92.7658	42.3647	-94.2825	46.9098	-112.2416	39.1406
56	-80.3906	43.1582	-92.2961	43.3515	-93.2005	47.5020	-112.7797	41.9740
57	-93.7808	51.0061	-91.8846	42.2387	-92.3939	43.5097	-113.3705	37.2322
58	-79.4710	42.9432	-91.0601	42.2947	-94.7929	43.9500	-112.5590	38.7596
59	-80.5915	46.0298	-92.1852	42.4517	-95.9337	45.5797	-111.0470	41.2504
60	-75.8990	45.3123	-93.9236	40.5903	-92.4725	46.0140	-110.3804	38.9214

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