EVALUATION OF THE EFFECTIVENESS OF DIRECT LIQUID APPLICATION FOR REDUCING CHLORIDE INPUTS TO RYERSON CAMPUS AND URBAN AREAS IN TORONTO

By

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A MRP

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ABSTRACT

In the winter of 2018/19, Ryerson University began a pilot project which saw the implementation of Direct Liquid Application (DLA) of road salts in select areas within its campus. This study evaluated the reductions in chloride applications that occurred due to the pilot, as well as estimated the chloride reductions that could occur if the project was expanded at Ryerson and if other organizations in Toronto were to adopt DLA. This was done through an analysis of recorded road salt application rates on Ryerson campus. The analysis revealed that the incorporation of DLA into Ryerson's maintenance program reduced chloride inputs to Ryerson Campus. The analysis also illustrated that similar 'savings' could be expected if DLA were expanded to the rest of campus, Green P parking lots, GO train stations, and TTC streetcar waiting areas. Recommendations for future DLA implementation are given.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

Chloride based road salts used for ice and snow control are an integral aspect of winter safety maintenance practices (City of Toronto, 2016). However due to the adverse impacts of chloride pollution, primarily to aquatic ecosystems (Beggel & Geist, 2015; CEQG, 2011; Corsi, Graczyk, Geis, Booth, & Richards, 2010; Fay & Shi, 2012; Hintz & Relyea, 2017; Sanzo & Hecnar, 2006), many organizations and municipalities are attempting to reduce their road salt use by adopting more efficient salt application techniques (Transportation Association of Canada, 2013). Direct Liquid Application (DLA), which involves the application of liquid salt brine to target surfaces, is one such technique (Crewe & Gowda, 2018; Fonnesbech, 2007; S. M. K. Hossain, 2014). Although many municipalities have adopted DLA for select roadway salting practices (Transportation Association of Canada, 2013), DLA is not widely used by organizations for common non- roadway salting. Ryerson's Road Salt Reduction Pilot project, which has seen the implementation of DLA on Ryerson's Campus, was designed to illustrate that the implementation of DLA for non- roadway surface salting is a cost-effective approach to reduce the chloride requirements associated with winter maintenance practices. This Major Research Project presents the results of the 2018/19 Ryerson Road Salt Reduction Pilot Project and uses the associated data to explore the benefits of expanding the use of DLA to other organizations in the City of Toronto.

2. Literature Review

2.1 Utility of Road Salts and De-icing Chemical for Winter Maintenance

In northern regions, winter roadway conditions pose serious threats to pedestrian and driver safety. In Canada, 12% of all traffic related fatalities and injuries are associated with these adverse conditions (Kelsall & Redelmeier, 2016). To increase winter transportation safety, winter maintenance managers rely heavily upon chemicals to remove snow and ice from roads and walkways. These chemicals typically lower the freezing point of water, melting snow and ice in below zero conditions. Many chemicals are used for this purpose, however due to its effectiveness, low price and abundance, the majority of organisations, institutions and governments use Sodium Chloride ($NaCl$)(Baltrėnas & Kazlauskienė, 2009; Kelly et al., 2010; Laffray et al., 2018). Approximately 4.9 billion tonnes of $NaCl$ are used on Canadian roads each year (Environment Canada, 2001), and the City of Toronto alone applied 812,534 tonnes of road salt to its sidewalks and roadways between 2010 and 2016 (City of Toronto, 2016; Environment Canada, 2001).

2.2 Environmental Impacts of Chloride-Based Road Salts

Despite their utility for snow and ice control, chloride-based road salts have serious negative environmental impacts. In 1999, a Canadian federal environmental assessment found NaCl based road salts to be toxic as defined by Section 64 of CEPA 1999 due to the tangible threat of serious or irreversible environmental damage as a result of NaCl road salt use (Environment Canada, 2001). However, the Ministers' Expert Advisory Panel was forced to consider the safety benefits of road salts, as any substance control measures developed through federal toxic substance assessments must not compromise human safety. Due to the utility of road salts in winter maintenance, it was determined NaCl would not be regulated by law (Environment Canada, 2001).

2.3 Negative Impacts to Water

In water, NaCl readily dissociates into Na^+ and Cl^- (Kotalik, Clements, & Cadmus, 2017). The Cl^- ion is not absorbed, metabolized or broken down by any natural process and therefore the dispersion of the Cl^- will be identical to the water which carries it (Siegel, 2007). The majority of Cl^- particles will travel quickly over impermeable surfaces and through storm sewers into regional lakes, rivers and streams (Meriano, Eyles, & Howard, 2009; Ramakrishna & Viraraghavan, 2005). Melt events following winter storms often results in stream Cl^- concentrations spikes over 640 mg/L (Perera, Gharabaghi, & Noehammer, 2009), which create conditions that are acutely toxic to fish, macroinvertebrates, insects, amphibians and aquatic plant species (Beggel & Geist, 2015; CEQG, 2011; Corsi et al., 2010; Fay & Shi, 2012; Hintz & Relyea, 2017; Sanzo & Hecnar, 2006). Where dissolved road salt interacts with permeable surfaces, such as ditches and lawns, chloride can percolate through the soil and into the groundwater table. Slow flowing subsurface pathways gradually transport this Cl^- into surface waters, resulting in the consistent input of Cl^- into surface waters well into the spring and summer seasons. This process often elevates surface water Cl^- content above long term (chronic) protection guidelines (120mgCl^-/L) which can impact the survival, growth and reproduction of aquatic organisms during the spring and summer growing season (CEQG, 2011; Oswald, Giberson, Nicholls, Wellen, & Oni, 2019; Wallace & Biastoch, 2016). Upon dissolution, the transport of the Na^+ ion is reduced due to cation exchange reactions occurring in the soils near the application location. However, after several years of NaCl application, the soil's Na^+ exchange capacity can become exhausted (Labadia & Buttle, 1996) and the Na^+ will then proceed to infiltrate into groundwater. This can compromise aquifer-based drinking water sources as increased Na+ consumption elevates the risk of hypertension (Daley, Potter, & Mcdowell, 2009; Robinson, Hasenmueller, & Chambers, 2017). The contamination of groundwater due to NaCl has been well documented in Toronto (Howard & Maier, 2007; Labadia & Buttle, 1996; Pilon & Howard, 1987) as several aquifers near the cities urban centers have been found to possess elevated Na^+ and Cl^- contents. The continued use of road salts throughout the future expansion of Toronto is also expected to jeopardize aquifers currently used for drinking water (Howard & Maier, 2007).

2.4 Soils and Plants

Soils exposed to NaCl can experience altered acidity, displacement of nutrient cations, reductions in soil permeability, and increases in the mobilization of heavy metals (Cunningham, Snyder, Yonkin, Ross, & Elsen, 2008; Fay & Shi, 2012; Laffray et al., 2018; Ramakrishna & Viraraghavan, 2005). These processes often cause urban soils to become toxic due to their high exposure to chloride-based road salts (Cunningham et al., 2008). NaCl exposure also significantly affects plant health. Depending on the plant species, vegetation exposed to NaCl can experience a reduction in biomass, injury, disease and death. A study in Toronto found that high exposure to NaCl road salt was associated with roadside tree mortality and declining tree foliage patterns (Ordóñez-Barona, Sabetski, Millward, & Steenberg, 2018).

2.5 Infrastructure

Sodium chloride is a very corrosive chemical and causes extensive damage to urban infrastructure. NaCl exposure can critically weaken the concrete and embedded rebar components of reinforced concrete structures. This process is considered the most damaging mechanism to urban bridges and buildings worldwide (Hájková, Šmilauer, Jendele, & Červenka, 2018; Stewart & Vu, 2000). Sodium chloride has also been shown to corrode metal vehicle components (Li et al., 2013). It is estimated that the cost of corrosion damage and protection practices for the highway and automobile industry in the United States costs between 16-19 billion dollars per year (Kelly et al., 2010).

2.6 Importance of Reducing Road Salt Use

The negative environmental impacts of NaCl have led to the development of a variety of alternative de-icing and anti-icing chemicals, including potassium formate (KCHOO), beet-sugar and salt brine de-icers (Fu, Omer, & Jiang, 2012; Rasa, Peltovuori, & Hartikainen, 2006). Although many of these chemicals have shown to be effective snow and ice control substances, the majority have their own set of associated negative environmental impacts and are often more costly to produce (Kelly et al., 2010). As a result, it is likely that sodium chloride will continue to be widely used due to its low cost, performance and the nature of existing infrastructure (Baltrėnas & Kazlauskienė, 2009).

However, many organizations have begun prioritizing the reduction of road salt use through the incorporation of novel techniques and industry-defined best practices. In Canada, the Canadian Code of Practice for the Environmental Management of Road Salts outlines several of these best practices

(Environment and Climate Change Canada, 2016), such as the use of electronic salt spreaders, the prewetting of roads salts prior to application, and the use of road weather information systems (Environment Canada, 2012)The implementation of these strategies has been successful in reducing the amount of road salt needed to ensure safe winter conditions in several municipalities (Transportation Association of Canada, 2013). For example, in the Toronto area, the mean normalized road salt application rate decreased by 26% in the period after the code of conduct best practices were implemented (Kilgour, Gharabaghi, & Perera, 2013). These reductions in Cl^- use have reduced the environmental harm caused by winter road maintenance in Toronto. It is estimated that the 26% reduction in road salt application rates has benefitted up to 14% of freshwater taxa due to the associated reductions in acute and chronic chloride levels (Kilgour et al., 2013). Despite these successes, road salt pollution remains a massive environmental issue in the City of Toronto, with many local waterways experiencing Cl^- levels between 125 - 775 mg Cl^-/L (WWF, 2019).

2.7 Anti Icing and Direct Liquid Application

A technique that is often included in industry best practices is the use of Direct Liquid Application (DLA) of road salts during the anti-icing of roads and walkways. Anti-icing refers to the pre-treatment of target surfaces with road salt prior to winter precipitation events. The interaction between the road salt and the precipitation creates a liquid layer of brine in-between the pavement and the accumulating snow or ice. This prevents the ice from bonding to the pavement, increasing the ease of ice and snow removal and reducing the need of additional salts applications to remove bonded ice (Perera et al., 2009).

2.8 Direct Liquid Application

DLA involves the use of a liquid chloride-based brine for anti-icing. Various chemical concentrations are utilized, however the most common is a 23.3% NaCl brine solution. This method has been shown to reduce the quantity of chloride needed during anti-icing (Crewe & Gowda, 2018; Fonnesbech, 2007; S. M. K. Hossain, 2014) in part due to the increased retention of the chemicals on the target surface (Fonnesbech, 2007).

Following brine application, the water in the solution evaporates leaving behind a layer of sodium chloride particles on the target surface. This method more evenly distributes the NaCl over the target surface, offering better ice and snow protection than conventional road salts (Alger, Adam, & Beckwith, 1994). Additionally, the particles left behind by the brine are less likely to be thrown off the target surface during application and due to vehicle and pedestrian traffic. A study by Fonnesbach (2007) found that after 2 hours of low vehicle traffic, surfaces applied with brine retained 21% more NaCl than those applied with conventional rock salt. The study also found that following 2 hours of heavy vehicle traffic, brined surfaces retained 30% more NaCl.

However, it is agreed upon that brine is not effective during winter storm events with high accumulation values or liquid precipitation (Schlup, 1993). These types of winter storms can cause dilution of the NaCl, causing the Cl^- to be removed from the target surface (Cuelho, Harwood, Akin, & Adams, 2010; S. M. K. Hossain, 2014).

2.9 Use of DLA in Canada and Toronto

In 2009, 35% of municipal road organizations had incorporated the use of DLA into their winter ice and snow control strategies (Environment Canada, 2012). The City of Toronto began utilizing salt brine and DLA in the winter of 2003-04 (City of Toronto, 2016). Currently, the City of Toronto utilizes approximately 2,000,000 liters of salt brine per year and estimates that salt trucks outfitted with the capacity for DLA experience a 10% reduction in salt use (Transportation Association of Canada, 2013). However, the City of Toronto currently does not have the capacity to utilize DLA on the entirety of Toronto's road networks, only utilizing this technique for salt applications to priority areas such as steep hills and bridges (City of Toronto, 2016).

3. Ryerson Road Salt Reduction Project and Research Questions

In an effort to reduce its annual chloride use, over the winter of 2018/19 Ryerson University experimented with the DLA of a 23.3% NaCl brine for anti-icing within its downtown campus (Figure 1). Throughout the winter season, in response to select forecasted precipitation events, brine was applied to four pilot areas in the place of conventional rock salt. Additionally, the total amounts of brine and rock salt applied within the test areas were recorded, along with the air and surface temperatures, and expected precipitation event characteristics for 10 winter precipitation events.

The facilities maintenance team has stated that salt use was dramatically reduced due to the use of brine, possibly by as much as 4000 kg (D. Batko, pers. comm.). However, it is important to empirically quantify these values so that the groups involved in the planning of this project, such as the Ryerson Sustainability Office and Ryerson Urban Water, can accurately disseminate the results and justify the continuation of the project at Ryerson. Therefore, the primary goal of this research is to provide Ryerson facilities, the Ryerson Sustainability office, Ryerson Urban Water, and other interested external organizations, with an understanding of the impacts of the incorporation of DLA during the winter of 2018/19 in terms of NaCl, Cl^- and financial savings.

The expansion of DLA at Ryerson is also of interest to Ryerson facilities, the Ryerson Sustainability office, and Ryerson Urban Water as these groups are interested in furthering the sustainability of Ryerson Campus. With the aim of providing justification for this expansion, this study will also estimate the material and financial savings that would occur if DLA was used on all areas of Ryerson Campus.

Additionally, alternatives to road salt and road salt reduction strategies have become a common topic of discussion in Toronto and Canada over the past several years. Many organizations are investigating strategies to reduce their NaCl use due to the large environmental impact of these chemicals. Advocacy groups, particularly the World Wildlife Fund, are actively seeking examples and or case studies of brine pilot projects to promote the adoption of DLA to external organizations. Therefore, an additional goal of this project is to illustrate the utility of DLA to reduce NaCl use. Not only will the savings experienced by Ryerson act as an example of the utility of DLA, but the data collected from the Ryerson Road Salt Reduction project will be used with GIS data and data analysis techniques to estimate the material and financial savings that could occur from the adoption of DLA by specific organizations within the City of Toronto. These are referred to as the DLA expansion case study scenarios.

Lastly, a series of recommendations will be developed regarding the use of brine, and the development and improvement of non- roadway DLA pilot projects such as the Ryerson Road Salt Reduction Project.

This study will therefore address the following research questions:

1. ***Was the use of the DLA an effective approach for reducing chloride inputs to the Ryerson University campus over the 2018/19 winter season?***
2. ***What is the estimated reduction in (i) chloride inputs and (ii) material cost if DLA use was expanded to all areas on Ryerson University campus, select Go Stations, TTC streetcar stops, and Green P parking lots in the City of Toronto?***
3. ***What is the estimated reduction in Cl^- and material cost from the use of DLA in a variety of winter scenarios?***

4. Methodology

4.1 Pilot Salt Reduction Zones and Application of Brine

Ryerson University is a mid-sized urban university within the dense area of downtown Toronto, Canada (Figure 1). The Ryerson campus is quite compact, contained within two square city blocks (Gerrard St east to Dundas St east between Yonge and Jarvis St). The Ryerson maintenance team is responsible for maintaining safe winter conditions on all walkways, sidewalks, and stairs on Ryerson property, as well as the public sidewalks adjacent to Ryerson campus buildings. This includes snow removal and regular surface salting during the winter season. The maintenance team is not responsible for the maintenance of the public roads within the campus area, however they are responsible for the two private walking streets on campus.

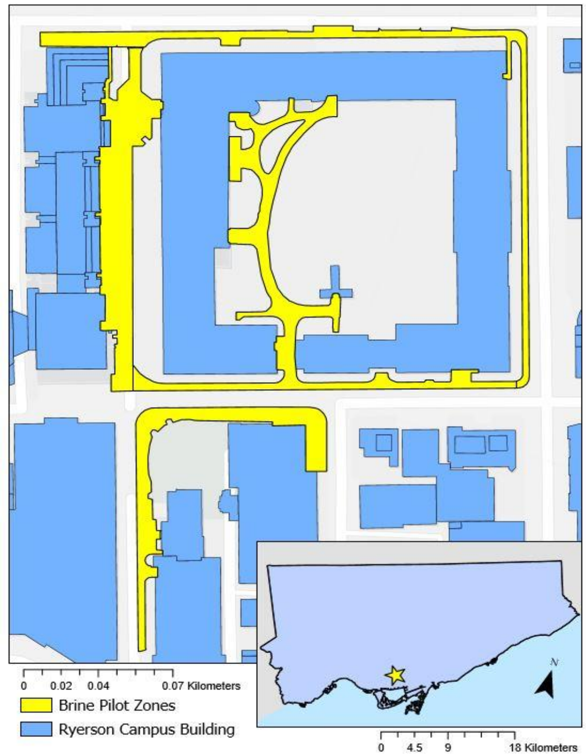

Figure 1. Figure 1. Ryerson Road Salt Reduction Pilot Zones and location of Ryerson University in the City of Toronto (inset)

The four brine pilot zones utilized in this study were located on the western area of campus, between Yonge and Church and Gerrard St. and Dundas St. (Figure 1). These zones were selected by the maintenance staff based on their knowledge of campus salting and foot traffic requirements, and due to their proximity to the Ryerson maintenance garage where the brine equipment is stored.

Over the 2018/19 winter season, the Ryerson maintenance staff utilized a 23.3% NaCl brine solution for anti-icing during select winter storm events. In accordance to standard best practices and academic research (City of Toronto, 2016; Environment and Climate Change Canada, 2016; Environment Canada, 2012), brine was primarily utilized for anti-icing during winter storms characterized by low to moderate levels of snow fall without the presence of liquid precipitation. Specifically, maintenance staff aimed to utilize brine for any winter precipitation events in which forecasts predicted up to 3 cm of snow accumulation and less than 1 mm of rainfall. Conventional rock salt was used for anti-icing for any winter precipitation event with greater than 3 cm of forecasted accumulation and greater than 1 mm of freezing rain. Additionally, anti-icing with brine or rock salt was only performed by Ryerson staff when temperatures were forecasted between 0 and -12 degrees Celsius. This is in response to the decreased effectiveness of NaCl at low temperatures (Crewe & Gowda, 2018; Cuelho et al., 2010; Fay & Shi, 2012; S. M. K. Hossain, 2014).

The applications of the NaCl brine were carried out using an automated liquid sprayer mounted on a campus sidewalk plow. Manual hose sprayers were also used to apply brine to areas inaccessible to the campus vehicle. Conventional rock salt applications were done using a standard salt spreader mounted on a similar vehicle and done manually by hand. Of the 10 recorded salting events, only brine was utilized for 5, and only rock salt was used for the remainder. Each precipitation event had at least one application of either salt or brine in each test zone, and several have two documented applications. Two applications occurred during relatively long duration storm events. The amount of snow accumulation and the presence of freezing rain was also recorded; however, the amount or intensity of rain was not recorded. To provide an estimate of the amount of rain during salting events, daily total rainfall data was acquired from the Canadian Historic Climate Database Pearson International Airport Weather station (Government of Canada, 2019). This is the most proximate weather station to Ryerson that reports rain accumulation daily. The utilization of the historic weather data introduced a small degree of error into all sections of this analysis that utilized this data. This is due to the minor variations in weather patterns observed between the Pearson International airport and Ryerson's campus.

On dates which had two salting events, and freezing rain was indicated for both salting events, the daily total rainfall was split evenly between the two salting events. The salting events, the event type and their associated mean Cl^- application rates can be seen in Table 1.

4.2 Statistical Comparison of Chloride Application Rates

Prior to the estimation of material and financial savings, it was necessary to confirm that DLA required less Cl^- than conventional rock salt. Various other road salt related studies that have utilized statistical t-testing to confirm an observed difference between two salt application methods. For example, t-testing has been used to compare the performance of liquid de-icing agents, and to compare the melting speed of NaCl road salts on various surface types (Fu et al., 2012; S. M. K. Hossain, 2014).

Rather than utilizing t-testing to evaluate the performance of the chemicals themselves, t-testing was used to assess the performance of the application method in terms of the amount of Cl^- applied to surfaces. Specifically, independent sample t testing was used to assess whether the difference in mean brine event and rock salt event Cl^- application rates were statistically significant. Independent sample t-testing is used to assess the difference between observed values with different grouping variable. In this case, the grouping variable used was the method of NaCl application. The mean Cl^- application rate per event was computed for every salt application event via excel. SPSS statistical software was then used to assess the distribution of the data and run the independent sample t test.

Table 1. Brine and rock salt application event dates, event characteristics and mean Cl^- application rate across all 4 pilot zones.

Brine Event Date	Event Characteristics	Application Method	Mean Cl^- Kg/m^2
2019-01-20	Snowfall (3cm)	Brine	0.0077
2019-02-05	Freezing Rain (<1 mm daily total)	Brine	0.0175
2019-02-06	Snowfall (2cm) + Freezing Rain (7.4 mm)	Brine	0.0196
2019-02-11	Snowfall (3cm)	Brine	0.0105
2019-03-02	Snowfall (3cm)	Brine	0.0154
2019-01-23	Snowfall (2cm) + Freezing Rain (3.6 mm)	Rock Salt	0.0361
2019-01-23	Snowfall (<1cm) + Freezing Rain (3.6 mm)	Rock Salt	0.0328
2019-02-06	Freezing Rain (7.4 mm)	Rock Salt	0.0320
2019-02-07	Freezing Rain (0.6 mm)	Rock Salt	0.0189
2019-03-02	Snowfall (2cm)	Rock Salt	0.0268

Additionally, the variability of Cl^- application rates observed between zones was assessed by creating a series of box plots and visually assessing the distribution of the Cl^- application rates observed in each zone. If significant variability were to be found between zones it would not be reasonable to utilize the mean Cl^- applications rate from all pilot zones in the estimation of Cl^- savings.

4.3 Estimation of Chloride Reduction during Recorded Salting Events

4.31 General Approach

Studies assessing the performance of salt application techniques often utilize and record each type of salt application technique side by side, within the same general environment and weather conditions (Fu et al., 2012; S. M. K. Hossain, 2014; S. M. K. Hossain et al., 2016). This allows for the comparison of performance in a way that controls for the effect of weather conditions. As these side by side comparison were not performed in the Ryerson Road Salt Reduction Pilot, a different method will be employed to estimate Cl^- reductions. The hypothetical amount of Cl^- that would have been applied to the test zones if only rock salt had been used over the 10 recorded events will be estimated. This hypothetical value will be referred to as the "*business as usua*l" 2018/19 Cl^- mass (BAU). The BAU will then be compared to the actual amount of Cl^- applied during those events, referred to as the "*actual*" 2018/19 Cl^- mass (ACT). Computing the difference between the BAU and the ACT mass values will produce an estimation of Cl^- reductions experienced in 2018/19. Although this method is less ideal, this is the most feasible method of Cl^- reduction estimations available given the nature of the data. Additionally, the estimations are based on observed salt application events, which increase the validity of the estimates.

To calculate the BAU mass value, the 5 recorded Cl^- masses applied via brine were replaced with masses of Cl^- derived from observed 2018/19 rock salt application rates and the areas of the brine pilot zones. These values are referred to as the "replacement" Cl^- mass values.

A possible method of replacement mass estimation that was investigated was the use of a regression analysis. Multiple regression could have been used to relate environmental characteristics, such as accumulation of snow and rain, and temperature to rock salt application rates observed during rock salt application events. If successful, this relationship could have been used in conjunction with the observed weather characteristic of the brine application events to statistically predict each replacement mass. However, the pilot project dataset contained too few data points to perform a valid multiple regression as only 20 data points were present in the dataset (Bonett & Wright, 2011).

Instead, a BAU scenario was developed using the total average rock salt Cl^- application rate across all recorded rock salt application events. The masses of Cl^- applied during the 5 brine application events were replaced by replacement masses derived from this total average Cl^- application rate and the total area of the pilot zones. These replacement values are referred to as the "non-weather specific" replacement values and Cl^- estimations.

However, as several of the observed rock salt application events took place during conditions which required a larger amount of maintenance (i.e., heavy snow and rain), this estimation may overestimate the replacement masses and therefore the savings experienced in 2018/19. To account for this issue, "weather specific" replacement masses and Cl^- estimations were also generated. In these estimation, each brine event Cl^- mass was replaced using a rock salt Cl^- application rate derived from rock salt application events observed in similar environmental conditions as the brine event being replaced. This was expected to increase the accuracy of the replacement mass estimation by accounting for environmental conditions. However, this may have reduced the robustness of the estimate as fewer data points were utilized to generate each replacement Cl^- mass.

4.32 Weather specific replacement mass the calculation

To generate the weather specific BAU estimation, a weather event classification system was developed to classify the environmental conditions observed during each brine and rock salt application event. This was done using existing weather classification systems developed for public policy and academic research (Matthews & Andrey, 2017; Zhou, Mcmahon, Walton, & Lewis, 2000). Snow accumulation was classified into three groups, Light Snow (0.2 - 1.9 cm accumulation), Moderate Snow (1.91 - 4.9 cm accumulation), and Heavy Snow (> 4.9 cm). These classifications were based on the weather classification system used in the Ontario Ministry of Transportation's Weather Severity Index (Matthews & Andrey, 2017). This classification system was developed using an optimization algorithm which directly related daily weather conditions with associated maintenance demand. For example, the algorithm determined that snow accumulation above 1.9 cm requires medium maintenance, while accumulation under that threshold typically require low maintenance activities. This is an optimal weather classification system for use in this analysis as separating the application rates based on maintenance requirements is the primary concern.

Liquid precipitation values were classified into six categories, No rain (0 mm), Light rain (0.1 - 0.9 mm), Showers (1 - 2.9 mm), Rain (3.0 -9.9 mm), Heavy Rain (10.0 - 24.9 cm) and Very Heavy Rain (>24.9 cm). This classification system was adopted from a study by Zhou et al, 2000 who developed a classification system to assess daily rainfall values in Australia (Zhou et al., 2000). This classification system generally agrees with many daily total rainfall classification systems used in Canada (Zhang, Hogg, & Mekis, 2001; Prairie Climate Center, 2019), however it has a larger number of criteria and therefore will increase the accuracy of the weather classifications used in this analysis. Mixed snow and rain precipitation events were classified using a combination of the two previous systems. For example, "Light snow, Light rain".

Each salt application event was classified into the above categories. Due to the limited number of recorded salting events, not all the categories were filled. However, each brine event did have a corresponding rock application event classified into the same category, allowing for the estimation of the BAU Cl^- mass value.

The weather specific replacement masses were then calculated using the average Cl^- application rate of all rock salt application events grouped into the same weather category as the brine event being replaced, and the total area of the pilot zones. The weather specific BAU masses were then computed, and the difference between these BAU and ACT Cl^- masses were calculated (Figure 2).

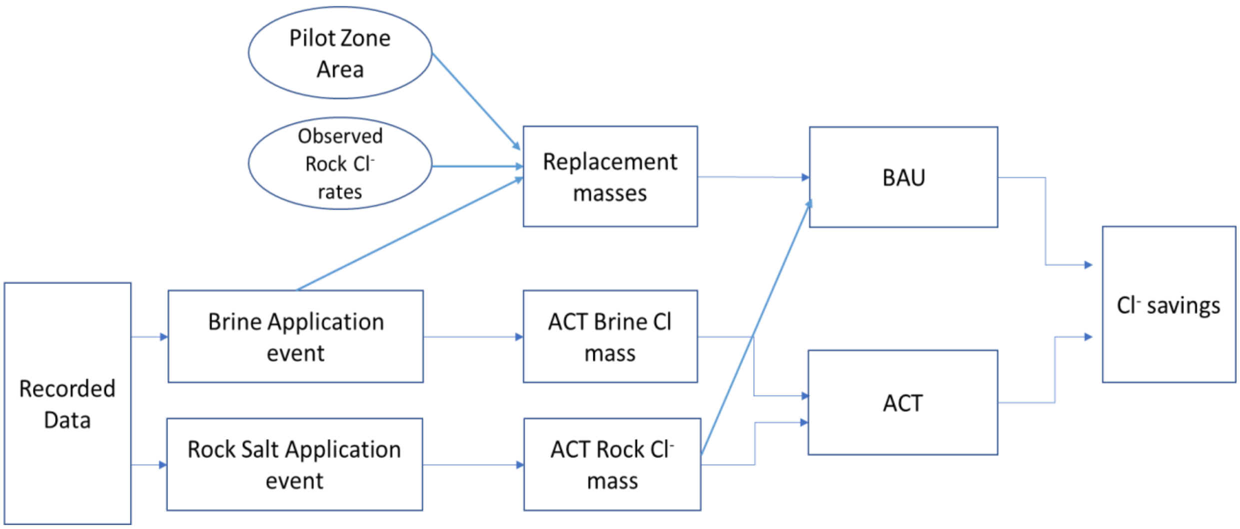

Figure 2. Workflow for the estimation of Cl^- savings over observed salting events.

Rock salt application rates from all test areas were used in the creation of the replacement masses, rather than using rock salt application rates observed within the same test area as the brine event being replaced. This was due to the limited amount of data available, as some weather categories did not contain enough records to provide a robust representation of rock salt application rates. In future years when more data is available, replacement masses should be generated from rates observed within the same brine zone as those being replaced. However, as there was very little change in Cl^- application rates between zones, this is not expected to cause significant error in the material savings estimations.

4.4 Scaling Chloride Reductions to Whole 2018/19 Salting Season at Ryerson

To estimate the Cl^- savings that occurred over the entire 2018/19 winter season, an ACT Cl^- mass value and a BAU Cl^- mass were estimated for the entire 2018/19 winter season. This was done by identifying likely brine and rock salt application events that occurred outside of the recording period, and subsequently assigning and a Cl^- application rate to each event based on the events weather characteristics. This enabled the creation of the 2018/19 winter season ACT and BAU Cl^- masses, and the estimation of 2018/19 winter season Cl^- savings. This was done with both the weather specific and non-weather specific replacement masses to generate the weather specific and non-weather specific Cl^- reduction estimations.

Canadian Historic Climate Database records from the Pearson International Airport Weather Station (Government of Canada, 2019) were queried to identify probable brine and rock salt application events that occurred during the 2018/19 winter season. The probable brine application events were defined based on Ryerson Maintenance staff operating procedure discussed in 4.1. Therefore, brine events were defined as any event with no rainfall and between 0.2 and 3 cm of snow accumulation. Rock salt application events were defined as any event with above 3 cm snow accumulation, any event with above 0.1 mm of rainfall, or any event with snow accumulation above 0.2 cm and rain above 0.1 mm.

The classification of weather records based on the maintenance staff operating procedures was utilized even though two observed brine application events in 2018/19 occurred during conditions which fell outside of this procedure. These discrepancies are likely because maintenance activities are planned using forecasted weather data. As forecasted and observed weather conditions will inherently not be identical, there will be cases when the team used brine during conditions that would normally call for rock salt, and vise versa. Therefore, by ignoring these discrepancies, the estimates produced by this analysis should be referred to as the Cl^- savings that could occur under ideal or optimal brine usage.

To generate the brine portion of the ACT Cl^- mass values, each identified brine event was matched with the average brine application rate of the three brine application events observed during environmental conditions adhering to Ryerson's Maintenance team's brine operating procedures. These values were then multiplied by the total area of the pilot zones to generate the brine ACT Cl^- masses.

$$\text{Brine ACT } Cl^- \text{ mass (Kg)} = \text{(Number Brine Events) (Average Brine Application Rate (Kg } Cl^-/m^2\text{)) (Pilot Zone Area (}m^2\text{))} \quad \text{Eq.(1)}$$

To generate the Rock Salt portion of the ACT mass value, the identified rock events were classified into the weather categories described in 4.32. However, as several classification groups did not possess a rock salt application event observed during the pilot project, these categories needed to be amalgamated. For example, there were no “Light Snow” events observed during the pilot project. Therefore, an observed rock application rate could not be matched to a “Light Snow” event identified from the historic data. To be able to match a rock salt application rate to an identified “Light Snow” event, the light snow and moderate snow categories were amalgamated. The amalgamated classification system can be seen in Table 2. The identified rock salt events were then assigned the average rock salt Cl^- application rate from the observed rock salt application events in 2018/19 which fell into the same weather classification category. These application rates were then multiplied by the total area of the pilot zones.

Rock ACT Cl^- mass (Kg) = ∑ (Rock Salt Event) (Corresponding Rock Salt Application Rate (Kg Cl^-/m^2)) (Pilot Zone Area (m^2)) Eq. (2)

The sum of these values were added to the brine Cl^- ACT mass to produce the 2018/19 winter season ACT Cl^- mass value.

ACT Cl^- mass (Kg) = Brine ACT Cl^- mass (Kg) + Rock ACT Cl^- mass (Kg) Eq. (3)

Table 2. Amalgamated weather classification system and number of events observed during the 2018/19 pilot study.

Classification	**Observed Rock Event**	**Criteria**
Snow	1	>3 cm snow accumulation
Light rain	1	0.1-0.9 mm rain
Rain	1	>0.9 mm of rain
Light Snow Rain	1	≤ 1.9 cm snow, > 0.1 mm rain
Moderate to very heavy snow rain	1	> 1.9 cm snow, >0.1 mm rain

The 2018/19 non- weather specific winter replacement masses were then calculated by multiplying the total number of identified brine events by the total average rock Cl^- application rate, and the total area of the pilot zones. This was also done utilizing the average rock Cl^- application rate derived from the rock salt event which occurred during typical brining conditions (i.e., snowfall (<3 cm)) to generate the weather specific replacement mass.

Non-Weather Specific Cl^- Replacement Mass (Kg) = (Number Brine Events) (Total Average Rock Salt Application Rate (Kg Cl^-/m^2)) (Pilot Zone Area (m^2)) Eq. (4)

Weather Specific Cl^- Replacement Mass (Kg) = (Number Brine Events) (Weather Specific Average Rock Salt Application Rate (Kg Cl^-/m^2)) (Pilot Zone Area (m^2)) Eq. (5)

These values were then used to generate the Non- Weather Specific BAU and Weather Specific BAU. The ACT value was subtracted from the BAU values to produce the weather specific and non- weather specific 2018/19 winter season Ryerson Cl^- reductions estimations (Figure 3).

Weather Specific BAU Cl^- mass (Kg) = Weather Specific Cl^- Replacement Mass + Rock ACT Cl^- mass (Kg) Eq. (6)

Non- Weather Specific BAU Cl^- mass (Kg) = Non- Weather Specific Cl^- Replacement Mass (Kg) + Rock ACT Cl^- mass (Kg) Eq. (7)

Weather Specific Cl^- reduction estimation = Weather Specific BAU Cl^- mass (Kg) - ACT Cl^- mass (Kg) Eq. (8)

Non- Weather Specific Cl^- reduction estimation = Non- Weather Specific BAU Cl^- mass (Kg) - ACT Cl^- mass (Kg) Eq. (9)

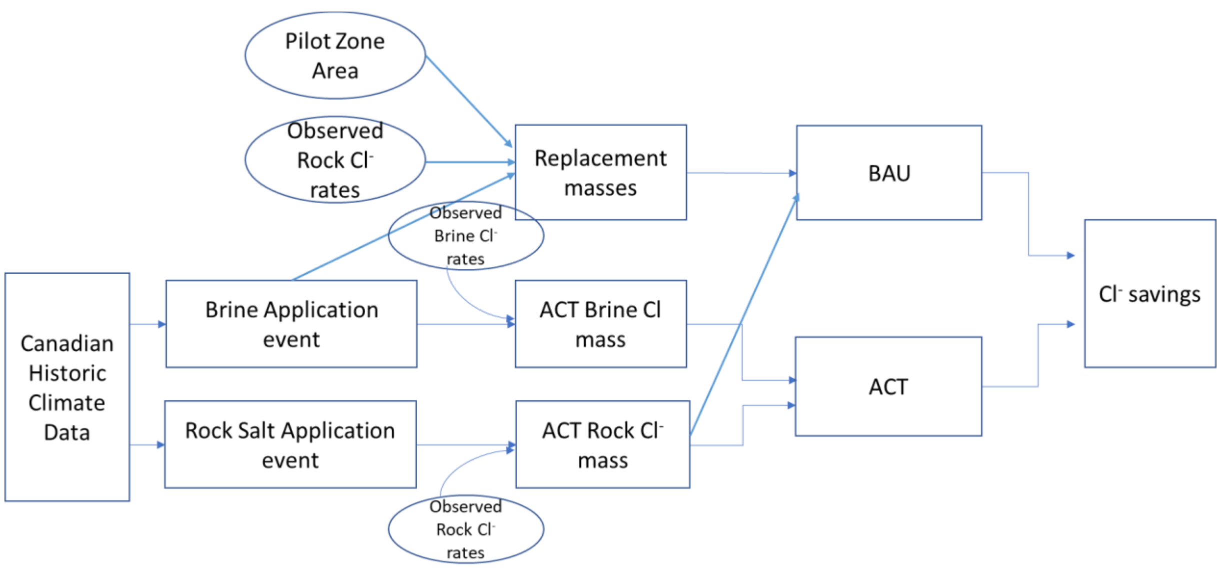

Figure 3. Workflow for the Cl^- savings estimation for entire 2018/19 winter season.

Additionally, it was previously mentioned that several winter storm events observed during the pilot project required two salting applications. However, the justifications for the multiple applications were not given, and therefore it was difficult to predict which historic winter storm events would have required multiple salt application. We therefore assumed that each identified winter storm event only required a single salting.

4.5 Estimation of Reduction in Chloride Inputs and Material Cost if DLA Use was Expanded to Ryerson, Metrolinx Go Stations, King Streetcar Stops and Green P Parking Lots within the City of Toronto

The procedures used in section 4.4 were modified to allow for the estimation of the total 2018/19 Cl^- savings that could have occurred if brine was used on all areas of Ryerson campus, and for the case study expansion scenarios for the 2018/19 winter season. This was done by simply replacing the area value used in the ACT and BAU calculations in section 4.4 with the total area of Ryerson campus, and subsequently with the total areas of the expansion case studies. These BAU and ACT estimations were then used to generate the various Cl^- savings estimations.

4.51 Expansion Zones Area Calculation

i. **Ryerson Campus**

The 2018 Ryerson campus site map was obtained from campus facilities and was subsequently digitized. This map describes detailed information about all campus property, including the locations of walkways, curb lines, sidewalks, roads etc. The 2018 City of Toronto Property Map Data (City of Toronto Works and Emergency Services, 2018) was also added to the GIS. This data possesses current locations of curb lines, sidewalks, and property boundaries of all areas of Toronto. Using these two data sources, a shapefile was created cataloguing all impermeable surfaces under the jurisdiction of Ryerson's maintenance team (Figure 4). Finally, Ryerson's maintenance manager was consulted to verify all areas that fall under the jurisdiction of the Ryerson maintenance team were accounted for.

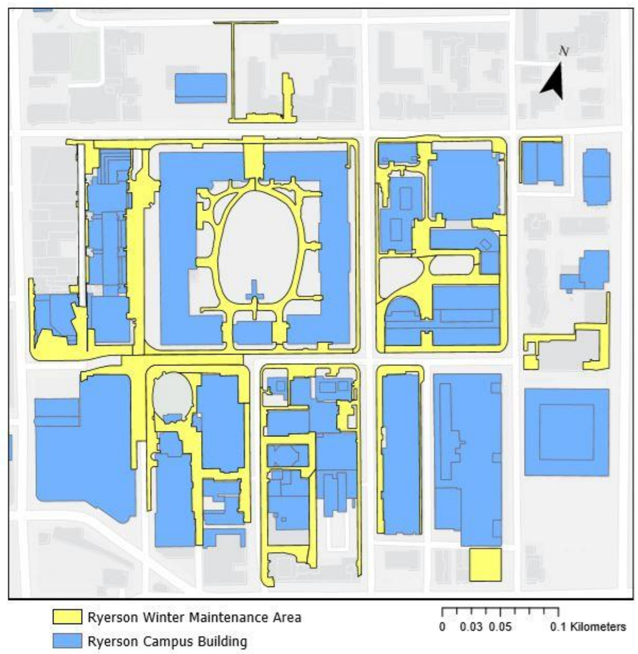

Figure 4. Impermeable Surfaces under the jurisdiction of Ryerson's Facilities Maintenance Team.

ii. Metrolinx Go Stations

To isolate the impermeable surfaces associated with each Metrolinx Go Station along the East and West Lakeshore line within the Metropolitan of Toronto (Figure 5), the City of Toronto 2018 Orthographic Imagery data (City of Toronto Survey and Mapping Services, 2018) was utilized in conjunction with the 2018 City of Toronto Property Map Data property boundaries (City of Toronto Works and Emergency Services, 2018) to determine which property polygon belonged to each station. The curb line, sidewalks, and pathways information from the 2018 Property Map dataset was then used to isolate the areas that most probably require winter salting. These included uncovered platform areas, walkways, and designated station parking lots on Metrolinx property. Union Station was not considered in this analysis as the majority of the station is indoors.

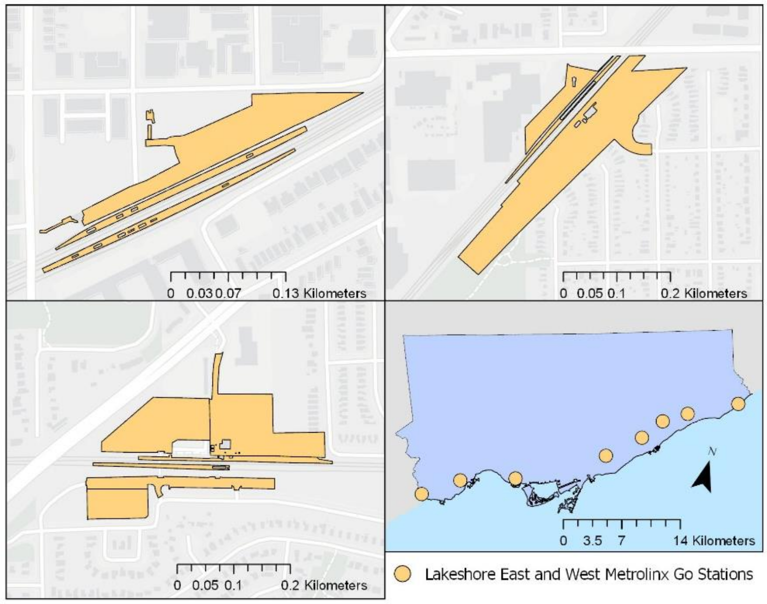

Figure 5. Mimico Station (Top Left), Scarborough Station (Top Right), Guildwood Station (Bottom Left), and the locations of all Lakeshore East and West Metrolinx Go Stations within the Metropolitan of Toronto.

iii. King Street Streetcar Stops

Waiting areas at streetcar stops within the City of Toronto vary from explicitly designated areas, to simple signs posted on sidewalks (Figure 6.). To quantify the total waiting area of all the streetcar stops along the King Street 504 streetcar line, an average waiting area of 8.82 m^2 was assumed for each stop. This corresponds to the total area of two sidewalk slabs (City of Toronto, 2017). This area value was multiplied by the total number of streetcar stops on this route to generate the total area of all streetcar stops

Figure 6. Example of King Street Bus/Streetcar Transit Stop (Urban Toronto, 2017).

iv. **Green P Parking Lots**

The City of Toronto Green P parking lot dataset describes the location, capacity, and characteristics of every public "Green P" parking lot in the City of Toronto (Toronto Parking Authority, 2019). The point location of each Green P parking lot was used in an overlay analysis with the 2018 City of Toronto Property Map Data property boundary shapefile (City of Toronto Works and Emergency Services, 2018) to determine which property polygon contained each parking lot point. Only outdoor parking lots were considered. Subsequently, the 2018 City of Toronto Property map information was used to isolate all parking lot area on Green P property (Figure 7).

Figure 7. Green P parking lots within the Metropolitan of Toronto

4.52 Scaling Chloride Reductions to Case Studies

To provide an estimate of the potential material and cost savings experienced from the hypothetical adoption of DLA throughout Ryerson and the case study areas during the 2018/19 winter season, the historic 2018/19 brine and rock salt events identified in section 4.4 and their associated brine and or rock application rates were used to estimate an ACT and a BAU scenario for each expansion case study. The methods used to compute the BAU and ACT Cl^- estimations were identical to section 4.4, with the exception that the NaCl and Cl^- mass calculation for each case study scenario considered the entire area of that expansion case study, rather than the Ryerson pilot zones. The NaCl savings were then used to estimate monetary savings for each expansion scenario using the average price of $5.18 per 20 kg bag of NaCl (D. Batko, pers. comm.).

It is very important to note that the savings estimations for the TTC, Green P and Metrolinx are based on observed road salt and brine application rates used by the Ryerson facilities team. The standard rates utilized by these organizations and the Ryerson facilities team likely differ, and any major difference will result in discrepancies between the predicted Cl^- savings values, and those that would occur from the actual adoption of DLA by these organizations. Therefore, the estimated Cl^- savings produced by this analysis should be considered as example of the savings that could occur if the case study organization utilized similar winter maintenance practices as Ryerson.

4.6 Sampling Error Calculation

For each Cl^- reduction estimation, the associated error was calculated. This was done by propagating the error associated with each mean event Cl^- application rate through any and all calculations using these rates. For any operation involving the addition or subtraction of an estimated Cl^- mass, for example the subtraction of the ACT from the BAU, the standard error associated with each Cl^- mass estimate was summed in quadrate. Additionally, for any operation involving the multiplication of an estimated Cl^- mass by a constant, such as an area value, the standard error of the Cl^- mass estimate was also multiplied by that constant.

4.7 Historical analysis of DLA incorporation

The 2018/19 winter was characterized by abnormally large snowfalls and cold temperatures. These conditions are not optimal for DLA, and surely reduced its utility in 2018/19. A more moderate winter with more ideal weather conditions for DLA could have seen more frequent use of brine, and therefore higher NaCl and Cl^- reductions. To evaluate whether the Cl^- reductions experienced during the 2018/19 winter season were representative of typical Toronto winters, and to quantify the typical Cl^- savings that could be experienced over time, the historic climate data was utilized to assess the winter season characteristics and Cl^- reduction values for each winter season between 1938 and 2018. Each year was queried for likely rock and brine application events utilizing the same methods employed in section 4.52. These records were used to generate the total number of application days, the proportion of those events which required brine (according to criteria outlined in section 4.1), and the percent Cl^- reduction as a result of the use of DLA for each winter season. These values were then used to estimate the benefit of DLA in Toronto for the average winter conditions.

Climate change has and will continue to alter the climatic conditions in Canada. These changes may or may not impact the number of brine events experienced annually and may therefore have implications for the utility of DLA use in the future. To assess the impact of these changes, the historic climate data was also utilized to assess whether the number of events which qualify for a brine application has changed over time. The total number of brine events, and the proportion of events that required brine were computed and compared over time.

5. Results

5.1. Brine Application Rates

The brine Cl^- application rates observed in 2018/19 were generally much lower than the observed rock salt application rates, as the brine was found to have a mean and ± standard error Cl^- application rate of 0.014 ± 0.001 kg Cl^-/m^2, while rock salt had a mean and ± standard error of 0.0029 ± 0.003 kg Cl^-/m^2. The Shapiro- Wilks test of normality indicated that the mean rock and brine event Cl^- application rates were normal (P= 0.04), and the Levene's Test for equality of variances indicated homogeneity of variance. It was found that the two application methods had significantly different Cl^- application rates, with brine having significantly lower rates ($T_{(8)}$ = -4.083 , P= 0.004). Weather was also found to have a predictable and expected effect on Cl^- application rates. Application rates were consistently lower in conditions with less snow accumulation and the presence of rain typically increased the Cl^- requirements (Table 3).

Table 3. Mean Cl^- application rate of brine and rock salt application events grouped by weather categories.

Classification	**Brine Cl^- Application Rate (Kg Cl^-/m^2)**	**Rock Salt Cl^- Application Rate (Kg Cl^-/m^2)**
Snow	0.011	0.027
Rain	0.017	0.025
Light Snow - Rain		0.033
Moderate Snow - Rain	0.020	0.036

The interzonal variation of brine and rock Cl^- application rates were found to be insignificant. There was found to be overlap between of the majority of the medians, and as there was overlap between the spread of all box plots this suggest that no one zone received significantly higher or lower Cl^- application rates (Figure 8).

The brine Cl^- application rates observed at Ryerson in 2018/19 were found to be larger than the rates utilized or recommended by organizations in Toronto, or within Canada. The City of Toronto states that its standard application rate of 0.0056 kg Cl^-/m^2 is utilized during brine applications (City of Toronto, 2016). The City of Winnipeg utilizes a brine application rate of 0.0064 kg Cl^-/m^2 (Transportation Association of Canada, 2013). Several advocacy groups such as the Salt Vulnerable Areas Working Group and Clear Roads recommend rates between 0.0045 and 0.0105 Kg Cl^-/m^2 (Crewe & Gowda, 2018; Nixon

& DeVries, 2015). Additionally, in 2014 Hossain determined that as little as 0.0021 kg Cl^-/m^2 is required to achieve optimal levels of service (S. M. K. Hossain, 2014)

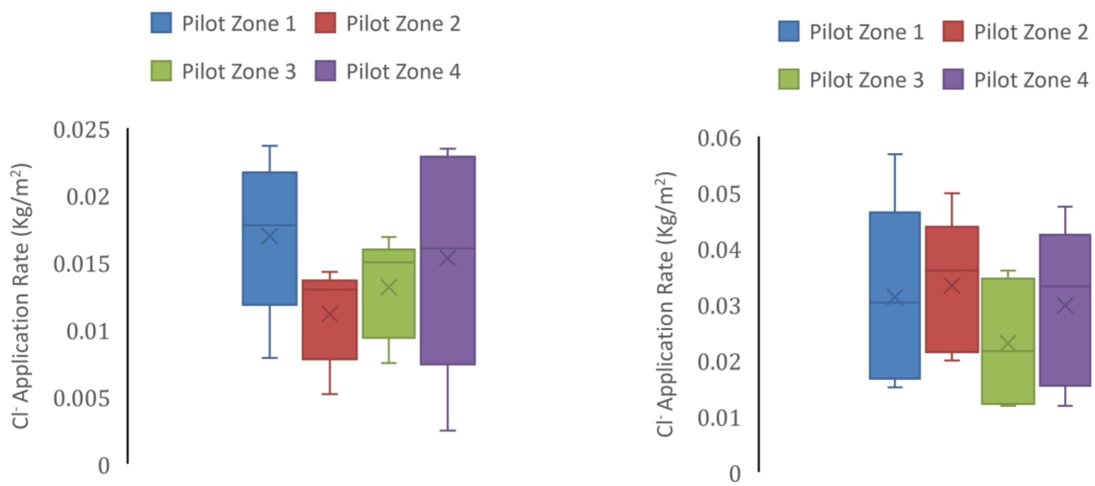

Figure 8. Interzonal Variation in Brine (left) and Rock Salt (right) Cl^- application rates.

Additionally, the rock salt application rates observed at Ryerson were found to be within the accepted range of rock salt application recommended by organizations and acedemic literature in Canada. The Transportation Association of Canada recomends rock salt application rates that correspond to Cl^- application rates between 0.015 and 0.024 Cl^- kg/m^2 (Transportation Association of Canada, 2013). The City of Toronto utilized rates beteen 0.014 and 0.037 kg/m^2(City of Toronto, 2016). Additionally, a study at the University of Waterloo found that in terms of performance, a rock salt application rate that applies 0.015 Cl^- kg/m^2 was optimal (K. Hossain & Fu, 2016). Although select observed rock salt application rates were found to be larger than these recomeneded rates, the mean Ryerson rock salt application rate does fall within these recomedned rates (Figure 8).

5.2 Estimation of Chloride Reduction at Pilot Zones Ryerson 2018/19

The results of the weather specific analysis suggest that approximately 544.33 ± 82.26 kg of Cl^- were diverted from the environment as a result of the use of DLA at Ryerson over the 10 recorded salting events (Figure 9). This corresponds to a total mass of 879.26 ± 132.88 kg of NaCl, a total financial savings of $232.89 ± 35.12 and a total overall reduction of Cl^- output of 23.53 ± 3.56 % (relative to BAU levels). The non- weather specific analysis suggests slightly higher saving values at 636.34 kg ± 122.39 of Cl^-, 1048.93 ± 201.75 kg of NaCl, a total financial savings of $271.67 ± 52.254, and a total overall Cl^- reduction of 26.46 ± 5.09%.

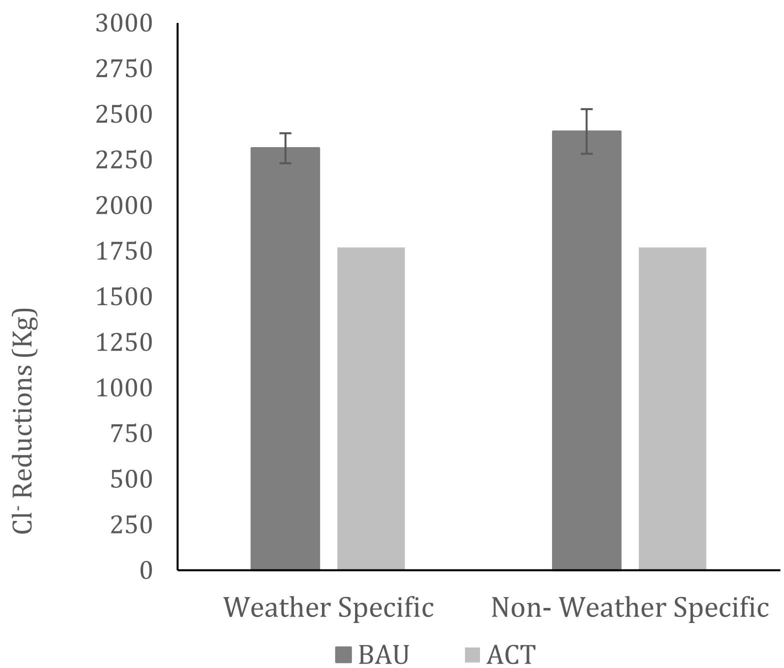

Figure 10. Estimated Weather Specific and Non- Weather Specific Cl^- reductions that occurred during 10 observed salting events.

The querying of the 2018/19 historic climate data identified 20 likely brine application events, and 14 likely rock salt application events. The chloride reduction estimation utilizing the weather specific replacement masses indicated that approximately 2589.06 ± 318.49 kg of Cl^- was diverted at Ryerson over the 2018/19 winter season, a total Cl^- reduction of 37.5 ± 4.61 % (Figure 10). This corresponds to a

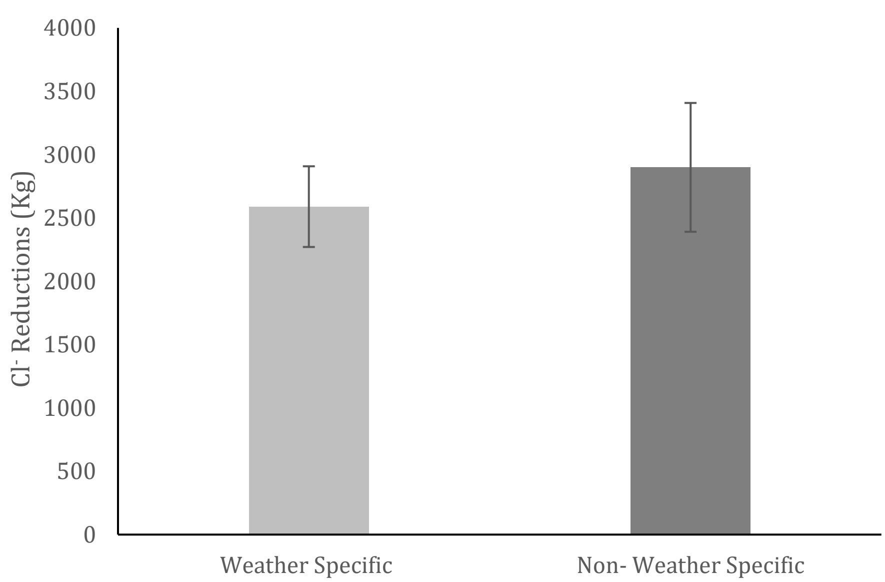

Figure 9. Weather and Non- Weather Specific Cl- reduction estimations for DLA use at Ryerson Pilot Zones throughout 2018/19 winter season.

total NaCl reduction of 4267.76 ± 525kg and a total material costs savings of $1105.04 ± 135.94. The non- weather specific Cl^- saving estimation resulted in a Cl^- reduction of 2899.06 ± 508.55 kg and a NaCl reduction of 4778.76 ± 838.29 kg. This represents a 40.14 ± 7.04 % reduction in Cl^- use and material cost savings of $1237.36 ± 217.01. The error associated with these estimations were found to be fairly large, as these error values varried from 12 % to 17 %.

5.3 Estimation of Chloride Reduction due to Brine Expansion to all Ryerson Campus and Case Studies

For all areas of Ryerson campus, the weather specific analysis found reductions of 9930.84 ± 1221.67 kg of Cl^-, 16369.81 ± 2013.77 kg of NaCl and $4238.60 ± 521.43. The non- weather specific analysis estimated reductions of 11119.92 ± 1950.67 kg of Cl^-, 18,329.85 kg of NaCl and $4746.12 material cost savings (Figure 11). The savings estimation experienced by Green P and Metrolinx were much larger than that of Ryerson, as the weather specific analysis estimated Cl^- reductions of 254,785.80 ± 31,343.09 kg and 63,199.25 ± 774.61 kg respectively, and the non- weather specific analysis estimated Cl^- reductions of 285,292.70 ± 50046.06 kg and 67,748.78 ± 11,884.49 kg respectively (Figure 11). These masses correspond to a material cost savings of $108,745.80 ± 13,377.63 - $121,766.50 ± 21,360.29 for

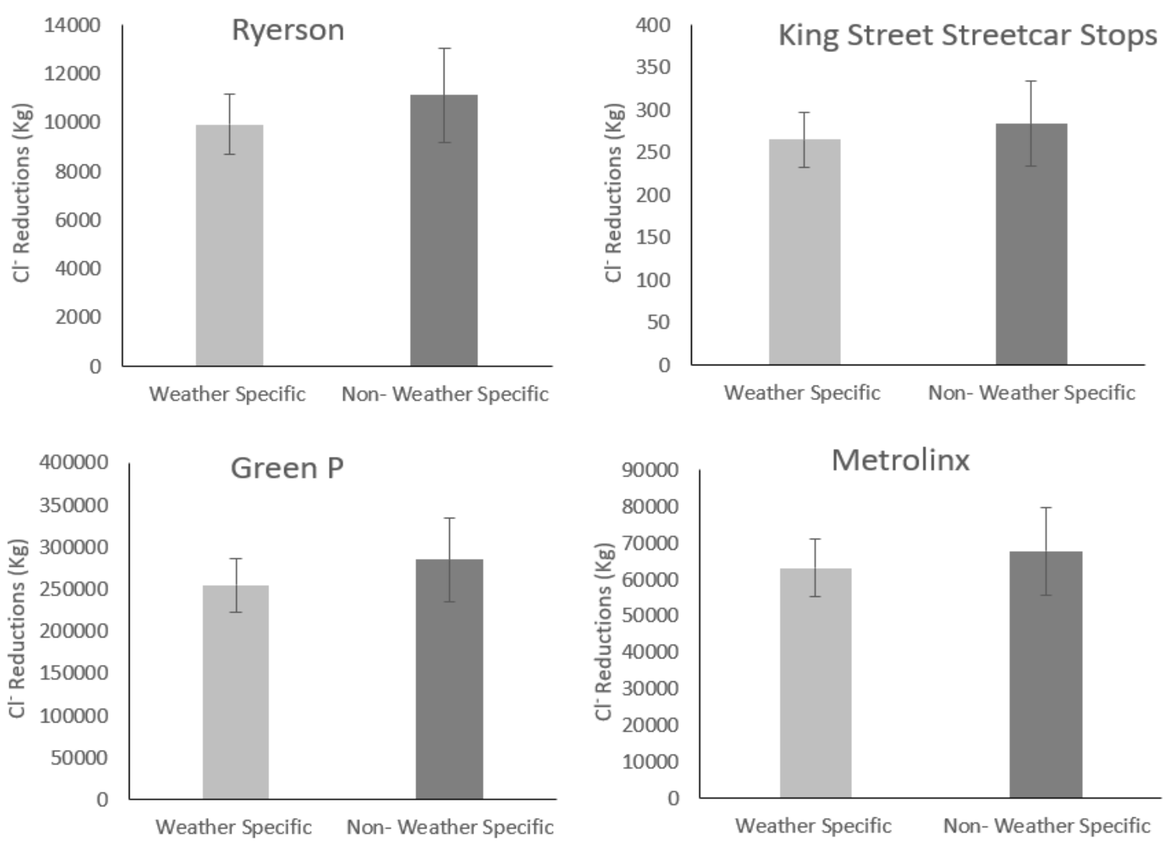

Figure … olinx
Go Stations, and TTC King Street Transit Stops

Green P and $26,974.23 ± 3318.30 - $28,916 ± 5072.45 for Metrolinx. The saving estimations for the King Street Streetcar case study produced consider ably smaller saving estimations, as reductions of 265 ± 32.61 - 284.15 ± 49.85 kg of Cl^- were found (Figure 11). However, similar to section 5.2, the error associated with these Cl^- estimation values were found to be large.

5.4 Historical Analysis of DLA Incorporation

Between the winters of 1938 and 2018, the mean number of events that met de-icing standards per winter season was found to be 34.9 (min 18, max 56). Of those events, on average 61 % (min 31.7 %, max 88.5 %) 'qualified' for brining. The winter of 2018/19 had 37 events that met de-icing standards and is therefore slightly above the average. Of those events, a below average 54 % 'qualified' for brine applications. As a result, there was an above average proportion of rock salt applications in 2018/19 when compared to previous years.

Table 4. Summary Statistics of Historic Climate Data Analysis

	Number of Brine Application	**Number of Rock Salt Applications**	**Number of Salting Events**	**Percent Brine Applications (%)**
Mean	21.4	13.5	34.9	61.4
Min	11.0	3.0	18.0	31.7
Max	39.0	28.0	56.0	88.5
2018/19	20.0	17.0	37.0	54.1

The assessment of the number of brine events per year shows a slight increase in the total proportion of events that required brine between 1938 and 2018 (Figure 12). This increase suggests that the utility of brine has increased over that same time period.

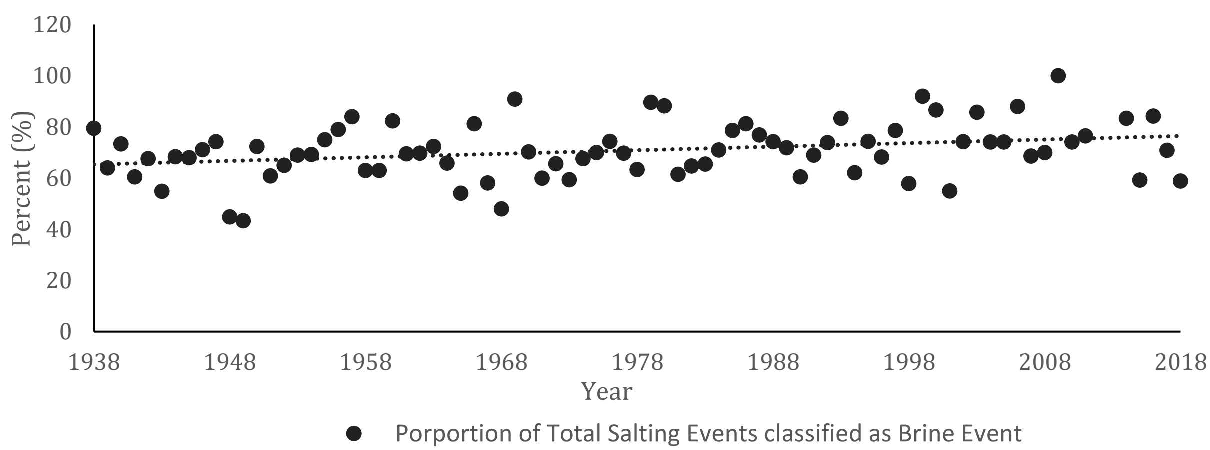

Figure 12. Increase in proportion of total salting events requiring brine between 1938 and 2018

6. Discussion

6.1 Effectiveness of DLA at Reducing Chloride Inputs to the Environment from Ryerson University

The statistical analysis of the brine and rock salt application rates observed during the 2018/19 Ryerson Road Salt Reduction pilot showed that DLA required significantly less Cl^- than conventional rock salt. This on its own suggests that Ryerson did experience Cl^- reductions due to the incorporation of DLA into its winter maintenance program. Additionally, although the results were accompanied by large error values, the Cl^- saving estimations suggest that over the 10 recorded brine events and throughout the 2018/19 winter season, DLA use did result in significant Cl^- reductions. These results do suggest that the incorporation of DLA was an effective approach for reducing Cl^- inputs to Ryerson Campus.

It was also found that the percent Cl^- reduction was larger throughout the entire 2018/19 winter season than during the 10 observed salt application events. This is an interesting result and may be a result of the inclusion of the shoulder seasons into the Cl^- reduction analysis for the entire 2018/19 winter season. DLA is more beneficial during the shoulder seasons (i.e., early and late winter) as these periods of time typically experience greater numbers of precipitation events with require brining (i.e., lighter snow events). The Cl^- estimation for the entire 2018/19 winter season would have captured the shoulder seasons, whereas the observed salt application events were mostly recorded outside of these shoulder seasons. This conclusion is aligned with testimony from Ryerson's Maintenance team, who have stated greater Cl^- savings occurred early and late in the winter season (D. Batko, pers. comm.).

The results of section 5.3 provide a strong justification for the expansion of the pilot project to all areas of campus, as the weather specific analysis estimated that this could result in significantly greater Cl^- reductions.

6.2 Cost Savings Associated with the Use of DLA on Ryerson University Campus

The monetary savings associated with NaCl reductions at Ryerson in 2018/19 were estimated at approximately $969.16 to $1241.88. Additionally, Dan Batko, Ryerson Facilities manager estimates that the increased ease of snow removal, due to increased ease of snow removal and more effective snowfall melt, reduced labour costs by approximately 3-4 hours per precipitation event. At a labour cost of 26-59$ an hour, this suggests that an additional $1560-4720 was saved due to the use of brine at Ryerson in 2018/19 (D. Batko, pers. comm.). The total cost of the brine equipment was $9976. Therefore, even if the project is not expanded and the material cost savings remain similar to 2018/19, the labour and material financial savings should cover the equipment cost in at least 4 years. This however does not take into account any degradation of the brine equipment over that period of time.

Dan Batko also stated that the current Ryerson brine vehicle could be used on a larger area of campus, possibly up to 50 % of campus or 15885.5 m^2. During the pilot, the total area of the pilot zones was 8283 m^2. If the area that the brine machine is responsible for was increased to 50 % of campus, the total material and financial savings would nearly be doubled. This would also greatly reduce the equipment payoff period.

6.3 Chloride Diversion and Cost Savings Associated with Case Studies

Despite the error associated with the results, the estimation of Cl^- and monetary savings that would occur from the adoption of DLA by external organizations was successful in illustrating the potential for DLA adoption by Green P and Go Metrolinx. If DLA was adopted by these two organizations, that would represent a reduction in emitted Cl^- equivalent to nearly 75 % of the salt usage for the municipality of Brockville, a city of nearly 22,000. Additionally, these reductions correspond to total material cost reductions of between \$108,745.80 ± 13,377.63 and \$121,766.50 ± 21,360.29 for Green P, and between \$26,974.23 ± 3318.30 and \$28,916 ± 5072.45for Metrolinx Go.

Additionally, many Metrolinx stations and Green P Parking lots analyzed in this study would be ideal for DLA adoption. Seven of the nine Go Stations, and 25 of the 214 Green P parking lots have areas above 8283 m^2, the size of the Ryerson Pilot Zones. These stations could therefore each support at least one brine machine and experience similar Cl^- and cost reductions than those experienced at Ryerson in 2018/19. The geographic layout Metrolinx Go Stations may also ideal for brine adoption as the areas are very localized, and the on-site facilities would likely have space for brine equipment. The 25 parking lots with areas of over 8283 m^2 also represent 53.2% of the total Green P Parking area. Therefore by adopting DLA in this relatively small number of parking areas, Green P could experience over half the estimated Cl^- and cost reductions estimated by this study. These Go Stations and Green P parking lots would therefore be ideal for test or pilot projects.

The total Cl^- and monetary savings estimated for the TTC king Streetcar line were less impressive due to the small total area of the king street streetcar line stops. However, anecdotal evidence suggests that BAU road salting rates at these sites is far in excess of the rates we measured on Ryerson campus, so further research is needed to more accurately estimate potential Cl^- savings.

6.4 Historical Comparison of DLA Utility

The utility of DLA in 2018/19 in terms of proportion of weather events that required brine was below average for the typical winter season. This suggest that the relative utility of DLA was reduced in

2018/19, and Ryerson's Facilities staff should expect to utilize DLA for a greater proportion of winter events in the coming years. Additionally, the examination of the historical analysis of DLA utility suggests that since 1938, there has been a slight rise in the number of brine events, and therefore the utility of DLA may continue to increase in the future. However, historic weather data was acquired from only one station in Toronto, and more research is needed to determine if this pattern is consistent across all geographic areas and is likely to continue with the effects of climate change.

6.5 Limitations and Recommendations

Although this study was able to produce estimates of the mass of Cl^- that was diverted from the environment as a result of the Ryerson Road Salt Reduction Project, and the hypothetical adoption of DLA by the case study scenarios, the large uncertainties surrounding these values suggests that future research is needed to verify the results. Ryerson's Facilities team is currently planning the adoption of an electronic recording system which will allow for the recording of every brine and rock salt application event. If this program is successful, the number of observed salting events would be dramatically increased, and the uncertainties associated with the brine and rock salt applications rates could be significantly reduced. Therefore, following the 2019/20 winter season, this methodology could be used to provide valid Cl^- savings estimations.

The small sample size also reduced the ability of this analysis to account for weather conditions, as several weather classification categories needed to be amalgamated. This lack of recorded events for the entire winter season also forced the use of the historic daily weather data to estimate the total savings experienced during entire 2018/19 winter season.

Although increasing the total number of observations could increase the precision of Cl^- reduction estimation and eliminate the reliance on historic daily weather data, lessons learned through this analysis provide strong justification for the altering the structure of the pilot project's recording system. As previously mentioned, during the winter of 2018/19 brine and rock salt were never utilized at the same time, during the same conditions. This made it necessary to estimate the BAU values with rock salt application rates observed in different environmental conditions than the brine event being replaced. This source of error could be avoided if one or more control areas in which only rock salt were utilized was established on Ryerson campus. This would nullify the need to classify and match the application rates based on observed weather conditions as the replacement mass for each brine application event could be derived using the rock salt application rate or rates observed during the associated brine application event. This would also likely reduce the error associated with the Cl^- reduction estimations as a single application rate would be used for the generation of the replacement masses, or if multiple control areas were established there would likely be much less variance between the rock salting applications observed during a single event than the rock salting application rates observed during different storm events that are classified as the same storm type.

Ryerson, and other pilot projects, may also be interested in the addition of a performance measure into the brine pilot project. Ryerson's facilities team does record the number of slip and falls that occur during the winter season, and there were no reported increased number of falls following the implementation of DLA use on Campus. However, as health and safety standards must be met, the performance of brine should be assessed as the pilot project continues. Assessing the performance of the brine and rock salt, such as time to bare pavement or friction coefficient, would allow the facilities team to determine if DLA is performing worse, better or to the level of rock salt. This may also allow for an assessment of optimal application rates and the impact of environmental conditions such as surface type, foot traffic, shade levels etc. This could be done by establishing different treatment areas on campus, in which the performance of various brine and rock salt application rates are assessed. Treatments of alternative de-icers and anti-icers, such as beat juice and brine mixtures, could also be established. This would however require additional coordination and sampling efforts.

Finally, as seen in section 8.1 the brine Cl^- application rates utilized in the Ryerson Road salt reduction pilot project were found to be generally larger than brine Cl^- application rates utilized or recommended by other organizations, municipalities, and academic researchers. This suggests that in the future, the application rates of brine to Ryerson campus could be slightly reduced to better reflect these recommended rates. This would further increase the Cl^- savings experienced as a result of DLA use.

7. Conclusion

The widespread application of road salts for winter maintenance safety causes extensive damage to natural and urban environments. Although anecdotal evidence suggested that the Ryerson Road Salt Reduction Pilot Project, which saw the incorporation of DLA at Ryerson University, resulted in significant Cl^- reduction, this study empirically quantified those savings and investigated whether the savings experienced in 2018/19 were representative of the savings that will be experienced in the coming years. Additionally, this study used recorded rock and brine application rates to estimate the savings that would occur from the expansion of this Pilot project, and from the use of DLA by all Metrolinx Go Stations on the Lakeshore East and West lines within the City of Toronto, all Green P parking lots within the City of Toronto, and all King Street streetcar stops. Although the results were accompanied by a degree of uncertainty, this research suggests that DLA was an effective approach for reducing Ryerson Cl^- use during the 2018/19 winter season. However, it was also concluded that lowering the application rates and increasing the total pilot area could further increase the Cl^- savings experienced at Ryerson and the monetary benefit of adopting DLA. The extrapolation of the results to all areas of Ryerson, to Green P parking lots and to Metrolinx Go Stations also illustrated the environmental and monetary incentives for the use of DLA in those areas. The methodological design used in this study may provide more accurate Cl^- savings estimations with increased number of observed salting records. These findings also provide advocacy groups, such as the WWF, with positive case studies which these groups can use to support their efforts to influence organizations to adopt road salt reduction strategies. The results also suggest the utility experienced in 2018/19 were fairly representative of the savings that will be experienced in the coming years. Lastly, the recommendations developed through this analysis may prove useful for improving the methodological design, data recording practices, and ultimately the Cl^- reductions of the Ryerson Road Salt Reduction Project and road salt reduction projects in general.

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