Effect of Road Salt on Soil and Water Properties in Halifax, Nova Scotia

By

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Abstract

Road salt is a crucial public safety tool to protect people on winter roads, but it disperses from roads and impacts the environment. Increased salinity affects both soil and water systems with adverse effects observed on vegetation, nutrient cycling, and aquatic organisms. Nova Scotia applies the most road salt of all the Canadian provinces per unit area with a total of 230,182 tonnes. I compiled and analyzed water conductivity data for the Halifax Regional Municipality (HRM) from datasets provided by the Department of Fisheries and Oceans and Halifax Water to determine the spatial and temporal trends in conductivity. Conductivity has been increasing in most HRM lakes since at least 1980, but seasonal trends were inconsistent. To better understand salinity of soil and lakes, fieldwork was conducted at five lakes in Dartmouth, Nova Scotia that represented sites exposed to or protected from road salt. At each lake, we sampled water and soil on a side that was closer to roads/road salt application, and on another side further away. Statistical analysis showed no significant effect of proximity to road salt application on water conductivity ($P = 0.834$). There was a significant difference between protected and exposed sites ($P = 0.0187$). Soil electrical conductivity was also measured on both sides of the lakes at distances of 0, 10, and 20 m from the lake before (fall) and after (winter) road salt application. Soil conductivity was significantly higher at 0 m (compared to 10 m, $P = 0.020$, and compared to 20 m, $P < 0.001$) and before road salt application ($P = 0.014$). There was no significant effect of protection ($P = 0.079$) or proximity to road salt application ($P = 0.184$) on soil conductivity. Based on these results, I concluded that road salt is negatively impacting many lakes in the HRM.

April 26th, 2021

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This research took place in K'jipuktuk on the traditional and unceded territory of the Mi'kmaq.

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Lastly, my thesis would not have been completed without the love and support of my family and friends.

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1. Introduction

1.1 Road Salt Use

Applying road salt to roads, sidewalks, and parking lots is a common method in North America to increase the safety of travel during the winter months (Halifax Regional Municipality (HRM), 2020). Snowfall and low temperatures resulting in ice formation can create dangerous conditions for cars and pedestrians by reducing surface traction. Road safety is a significant public safety issue and as such, there is a duty of care to provide a safe environment that limits the dangers of travel within reason (Environment Canada, 2004). A variety of salting materials can be applied to the road to reduce freezing and increase traction, however, in my study the term "road salt" will be used to refer to sodium chloride (NaCl), which composes 97% of the road salt used in Canada (Canadian Council of Ministers of the Environment (CCME), 2011). Salt is a common material that is easily sourced and transported, effective, and relatively cheap (Corsi et al., 2015; Toronto and Region Conservation Authority, 2019). While winters in the HRM, Nova Scotia (NS) are milder than those in other parts of Canada, the fluctuations in temperatures around the freezing point of water result in frequent snow melt, freezing rain, and ice formation. As a result, NS has the highest loading of road salt per unit area of all the Canadian provinces at 230,182 tonnes (CCME, 2011).

The general approach to road salt use focuses on human safety, with adaptations for environmental protection made after toxic effects have been observed (Environment Canada, 2004). While road salt is an effective method for improving road safety, it enters the environment as a pollutant with negative ecological effects. Pollutants cause habitat degradation and can result in the loss of ecosystem services. In the HRM, road salt runoff is not monitored and the runoff that does not run into water bodies and is not absorbed by the soil simply enters the stormwater drainage system, which runs into the harbour (York pers. comm., 2020). Although road salt is only applied from November until April, elevated chloride levels have been observed throughout the year in urban and suburban environments (Environment Canada, 2001). There can also be negative impacts of road salt on human health; increasing risk for chronic diseases through increased consumption of sodium, and chloride-corroded pipes that release metals into the drinking water system (Madison Metropolitan Sewerage District, 2020). Salt is a corrosive material that damages vehicles, concrete, brick, and stone resulting in monetary costs (Madison Metropolitan Sewerage District, 2020). The cumulative effects of road salt being used over previous decades means that impacts will continue to persist in the ecosystem for subsequent decades even with changes in anthropogenic road salt use (Environment Canada, 2001).

1.2 Impacts of Road Salt

While road salt has been extensively used throughout the HRM, the potential environmental impacts on the soil and water in the region have been vastly understudied (but see Collins and Russell, 2009). A report prepared by Environment Canada (2001) concluded that there were negative environmental impacts on freshwater ecosystems, soil, vegetation, and wildlife due to the high release of road salts. These potential toxic effects have resulted in limits being placed on the short- and long-term concentrations of Na^+ and Cl^- levels to balance the need for road safety with environmental protection. In freshwater aquatic systems, the recommended short-term exposure limit is 640 mg Cl^-/L, and the long-term limit is 120 mg Cl^-/L, as determined using both $CaCl_2$ and NaCl salts (CCME, 2011).

These limits are not legally enforceable, existing solely as recommendations for best anthropogenic practices to ensure the ongoing protection of the most sensitive life stages of the most sensitive aquatic organisms (CCME, 2011).

More immediate impacts of toxicity are seen in water bodies as surface runoff allows salt to directly dissolve into the water, thereby increasing salinity. Waterways contain chloride naturally at varying levels; however, there can be a significant increase in chloride concentrations due to anthropogenic impacts (Khazaei and Milne-Home, 2017). Nova Scotia's ambient chloride concentrations are typically <10 mg/L for inland lakes, with lakes in coastal areas such as HRM ranging from 20 to 40 mg/L (CCME, 2011). Chloride is considered a hydrologically and chemically inert substance as it does not biodegrade, readily precipitate, volatilize or bioaccumulate (CCME, 2011). Chloride concentrations are high in surface water compared to sediment as chloride does not absorb readily onto mineral surfaces (CCME, 2011). Salts applied to the roads can be easily mobilized by rainwater, allowing movement into shallow groundwater systems, rivers, and lakes (Khazaei and Milne-Home, 2017). Other pathways by which chloride contaminates water bodies include through wastewater effluents, stream inflow, and leaching from contaminated soils (CCME, 2011).

Dissolved salt can change the density gradients in a lake and hinder vertical mixing as layers with salt are denser and settle at the bottom (CCME, 2011; Novotny and Stefan, 2012). Small, deep lakes are particularly vulnerable to this condition, known as meromixis, that can leave the deeper layers oxygen-deprived and nutrient-depleted (Environment Canada, 2001; Scott et al., 2019). Salt can be retained by groundwater for decades, taking from a few years to hundreds of years to reach an equilibrium where the output of salt is balanced with salt inputs (Environment Canada, 2001). In inland waters, salinization is a factor resulting in low abundance and diversity of freshwater organisms (Environment Canada, 2001). Increased salinization of freshwater results in toxic effects on aquatic organisms as they experience a reduced ability to osmoregulate (Cañedo-Argüelles et al., 2019). Many types of organisms are vulnerable to salinization, and as water bodies get saltier salt intolerant species are excluded, effecting changes in community composition (Collins and Russell, 2009). Data regarding salt sensitivity of particular organisms is limited (Cañedo-Argüelles et al., 2019), however, zooplankton have shown to be particularly sensitive with increases in salinity resulting in decreased reproduction and increased mortality (Arnott et al., 2020). High salinity can trigger a trophic cascade that has implications for ecosystem services and functions (Hintz et al., 2017). Seasonal trends have been observed in water salinity in the HRM, with a low in the autumn pre-salting season and a high in April (Scott et al., 2019).

Although less is known about the impact of road salt on soil, there is cause for environmental concern. The threshold tolerance for NaCl in the soil is 60 mg Na^+/L and 90 mg Cl^-/L, with adverse effects not being observed in soil integrity, soil organisms, and vegetation at these limits (Environment Canada, 2001). Accumulation of NaCl in soil results in reduced water permeability, poor aeration, surface crusting, and increased alkalinity (Equiza et al., 2017). Increased salinity can further compound these effects by increasing pH, which affects plant health by preventing them from absorbing important nutrients from the soil (Equiza et al., 2017). Na^+ causes particular concern as the cation reacts to displace Ca^{2+} and Mg^{2+} in the soil, allowing those ions to also leach into water systems (Guesdon et al., 2016; Jamshidi et al., 2020). NaCl ions in the soil likely contaminate groundwater (Watmough et al., 2017; Novotny and Stefan, 2012), entering lakes and the drinking water supply.

1.3 Road Salt Use in the HRM

While safety remains the priority, best management practices can increase the efficiency of road salt use while limiting the environmental impacts (Environment Canada, 2004). There are several methods of road salt application in use in the HRM, including direct application to surfaces as salt, mixed with water to create a brine, or mixed with sand (HRM, 2020). Application typically begins in November and is based on predicted snowfall or freezing events that require intervention to maintain road safety (HRM, 2020). Weather patterns in the HRM often see rainfall events soon after snow, which creates more hazardous conditions due to ice formation (HRM, 2020). Rainfall intensity is known to play a role in the release of pollutants into the environment. Rainfall events that happen soon after road salt application greatly contribute to the dislodgement of road salt, with rainfall and runoff peaking at the same time (Trenouth and Gharabaghi, 2016). Road salts are also known to be displaced through snowmelt, as windborne powder, and through spray from vehicles (Environment Canada, 2001).

Road salt is applied mainly on roads, sidewalks, and parking lots by both the municipal government and by the private sector, such as businesses and homeowners. The effectiveness of road salt is highly dependent on applying the right amount in the right place at the right time. While private applications of road salt account for significant use (CCME 2011), this study will focus on the role that municipal application rates of road salt have on the local ecosystem. Road salt began being used in NS in 1958 (Ginn et al., 2015). The salt used in the HRM is sourced from Canadian Salt Co. Ltd. in Pugwash, NS (HRM, 2020). The municipality has access to 18,000 to 20,000 tonnes of salt at any given time, with three salt domes available within the region (HRM, 2020). Using road salt as an anti-freeze method can have negative environmental impacts as very little salt can be held in ice, concentrating it in the liquid phase (Environment Canada, 2004). This aids in salt being dispersed into the environment where it is able to enter water systems and soil. It is necessary to quantify the impacts of road salt usage on the local environment to protect ecological systems as well as human safety. A reduction in road salt usage does not necessarily mean an increase in danger, as it has been shown that "smart use" is more effective than quantity (Environment Canada, 2001). Additional benefits of smart salt use are more efficient operations, savings in material usage, and improved road safety (Environment Canada, 2001).

1.4 Objectives

The main objective of this study was to quantify the impact of road salt runoff on soil and lakes in the HRM. The impact of road salt on both water and soil has been largely understudied in the HRM (but see Ginn et al., 2015; Scott et al., 2019), with a lack of data on the environmental impacts of road salt available to inform decision-making regarding road salt use. Conductivity was used as a proxy for salinity because strong correlations have been found between sodium and conductivity, and chloride and conductivity (Wyman and Koretsky, 2018). This thesis combined field data collection (water and soil) with water conductivity data from additional sources (Clement and Gordon, 2019; Halifax Water, 2020). These datasets were used to examine historical and current spatial and temporal trends in water conductivity in relation to road salt application. Sample sites were selected in Dartmouth, NS from both protected and exposed sites, to compare the impact of road salt based on application rates and watershed boundaries. I also examined how distance from road salt application affects soil. The impact of road salt on the sampling sites was measured through water and soil conductivity. I predicted that lakes with a higher exposure to road salt would have higher conductivity. I also predicted there would be a higher soil conductivity closer to road salt application.

2. Methods

2.1 Historical Data Sources

Historical water data was provided by Fisheries and Oceans Canada (DFO) and Halifax Water. The Synoptic Lake Study includes data on 51 HRM lakes collected in the fourth synoptic survey of water quality conducted by the DFO (Clement and Gordon, 2019). This database has a standardized sampling effort, with all samples collected on one day using a multiparameter instrument. The same sampling was undertaken in 1980, 1991, 2000, and 2011. Although the dataset contains many variables related to water quality, this thesis is primarily concerned with water conductivity data. Sodium and chloride levels were individually measured, making it possible to compare how trends in these ion concentrations compare with trends in conductivity. Comparisons were made with findings from the HRM Water Quality Monitoring Program (Stantec, 2012) to assess long-term trends in relation to the Canadian Council of Ministers of the Environment (CCME) water quality guidelines.

Halifax Water also provided conductivity data from the fall of 2009 to 2019 for conductivity from the Lemont and Topsail watershed (Halifax Water, 2020). Sampling occurred at three sites within the watershed, although not all sites were sampled each time. This dataset included values from every month of the year so temporal trends could be analyzed to better understand how road salt application and mobility impacts the environment year-round.

Soil sampling has been done in some areas of the HRM (e.g., Desjardins, 2015), but as it is patchy, it was difficult to compile this data for the purposes of this study. For example, SoilGrids and the Nova Scotia Detailed Soil Survey do not include salinity or conductivity data. Thus, I only looked at soil conductivity at sites where I conducted fieldwork.

2.2 Site Selection

Sampling sites were chosen from urban lakes in Dartmouth, HRM. The sites were designated as exposed to or protected from road salt based on adjacent roadways, road salt application rates, and land use. At each site, the roadways covered a variable amount of area within the watersheds due to land use and urbanization. The assumption was made that as the area where road salt is applied increases, a larger amount of road salt leaches into the watershed. Areas that receive more frequent and higher loads of road salt will also experience increased contamination from road salt due to its high mobility. Besides exposure to road salt, factors such as accessibility and watershed usage were considered when selecting the sites.

We selected five lakes for sampling, ranging from higher to lower road salt exposure: 1) Black Lake, 2) Spectacle Lake, 3) Oathill Lake, 4) Lemont Lake, 5) Topsail Lake. Black Lake is adjacent to the HRM Salt Storage Depot in Dartmouth. No historical data was available for the site. However, the small size of the watershed and frequent passage of trucks carrying road salt have likely led to high levels of salt contamination. The two nearby salt domes are built on concrete and left open year-round. Salt that leaches into the soil also likely makes its way into the watershed. Spectacle and Oathill Lakes have moderate exposure to road salt. They are both urban lakes with watersheds that include residential and commercial developments. Lemont Lake and Topsail Lake share a protected watershed that is regularly monitored by Halifax Water, as they are part of the city’s water supply. Historical conductivity data for this watershed was included in the analysis. These sites are expected to have a lower exposure to road salt as there is no road within the watershed (Scott et al., 2019). However, there is a major road just on the edge of the watershed boundary and some construction was ongoing during the sampling period. As these two sites are protected from road salt, a grouped comparison was made with the exposed lakes (Black Lake, Spectacle Lake, and Oathill Lake).

The sites were mapped in ArcGIS (ESRI. 2019; Figure 1) by Greg Baker (SMU, Department of Geography). Layers of infrastructure data from Halifax Water and the HRM Open Data Catalog depicting catch basins, storm water lines, sanitary sewer lines, combined sewer lines, and access points were used. LiDAR elevation (LiDAR DEM, 2007; 2018) was considered along with the watershed boundary, natural watercourses, ditching, and underground stormwater infrastructure to visualize the sample sites (NS Topographic Database 1982; 2020; NS Orthophoto Database, 2017; NS Property Records Database, 2019). Road salt application rates and the road priority maps were obtained from the Superintendent of Winter Operations, Steven York (HRM, 2020). These layers were also added to the maps to compare the location and frequency of road salt application.

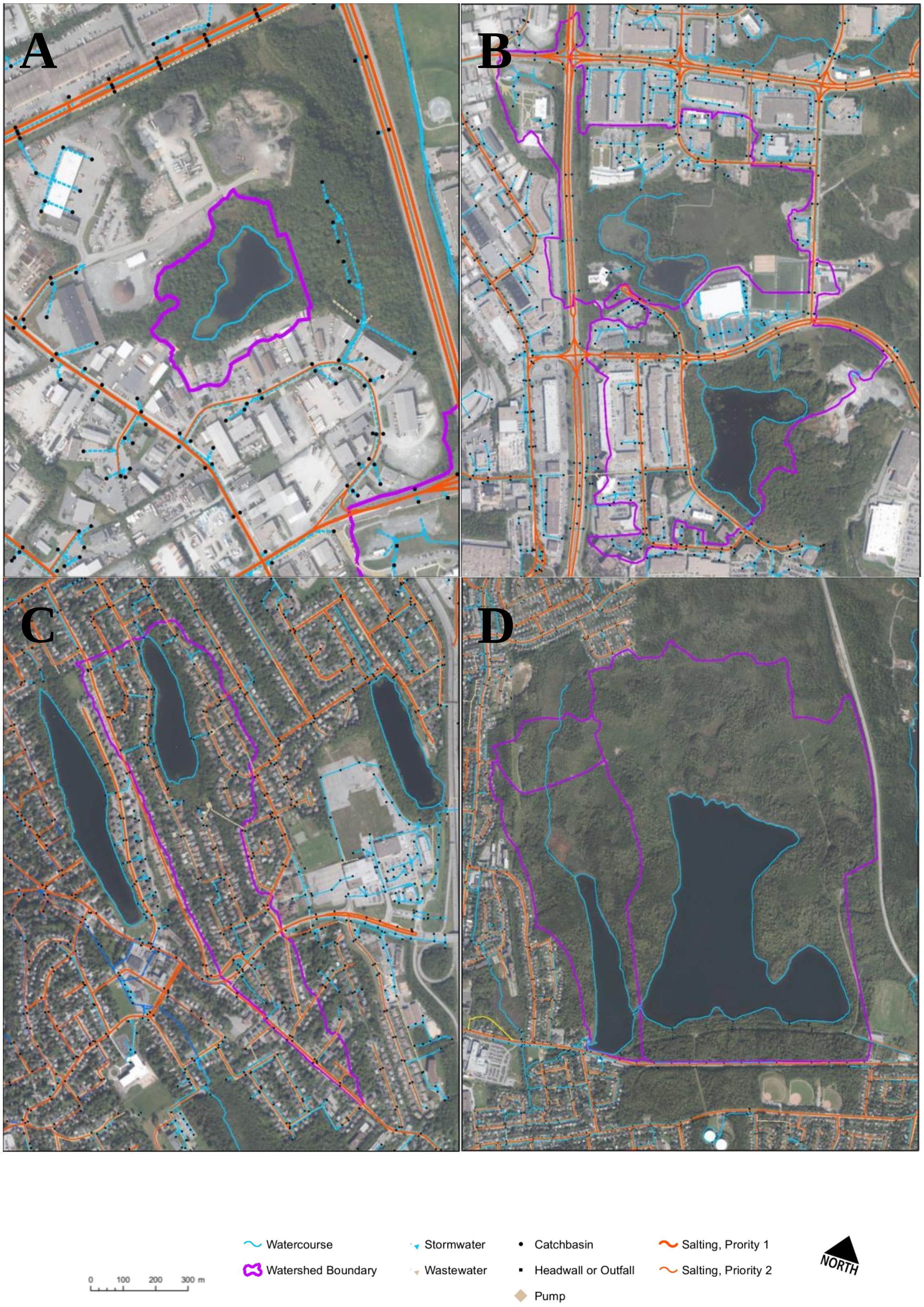

Figure 1. Watershed imagery of sites sampled in Dartmouth, NS. A) Black Lake; B) Spectacle Lake; C) Oathill Lake; D) Lemont and Topsail Lake. Topographical layers show

the natural watercourse, watershed boundaries, catch basins, storm water lines, sanitary sewer lines, combined sewer lines, ditching and access points. Above and belowground infrastructure data was provided by Halifax Water and the HRM Open Data Catalog. Roads are coloured to indicate their salting priority, as designated by the HRM. Stormwater and wastewater drainage systems are also depicted.

2.3 Field Data Collection

The first round of sampling occurred prior to road salt application on October 17th and 20th, 2020. As the mild fall weather meant that road salt application did not begin until late December 2020, the second round of sampling occurred on January 24th and 30th, 2021. The same methods were followed to make a comparison between soil conductivity at sites sampled before and after road salt application. Sampling was done on a “close” side adjacent to the road and on an opposing “far” side to compare the effect of distance on conductivity. Water sampling was not repeated in the post-road salt application period as the lakes were frozen.

Approximate Global Positioning System (GPS) coordinates based on observed proximity to roads and road salt were used to determine which sides of the lake would be sampled. The precise coordinates of the sample site were taken from the lake edge while sampling. A bucket was filled with lake water to stabilize the pH reading of the YSI sonde probe before the reading was taken in the lake at the shoreline just under the water’s surface without disturbing the sediment. Immediately after taking field measurements, the probe was rinsed with distilled water.

Table 1. GPS coordinates of sites sampled in Dartmouth, NS

Lake	Proximity to road salt application	
	Close	Far
Black	44.71079ºN, 63.59322ºW	44.70964ºN, 63.59299ºW
Lemont	44.68683ºN, 63.51912ºW	44.68760ºN, 63.52092ºW
Oathill	44.67220ºN, 63.54981ºW	44.67538ºN, 63.55114ºW
Spectacle	44.70198ºN, 63.58199ºW	44.70297ºN, 63.58148ºW
Topsail	44.69909ºN, 63.51570ºW	44.69297ºN, 63.50722ºW

Soil samples were collected with a soil corer taking five 5 cm cores within a 1 m^2 quadrat. All five samples were combined for laboratory analysis. Some of the lakes were rocky right by the shore, so the closest available location with soil parallel to the shore was sampled. The process was repeated at 10 and 20 m from that first point, along a transect running perpendicular to the shore so that soil cores were still taken at the same distance from the shore. If the ground was too rocky or frozen, the quadrat was moved slightly parallel to the shore so that soil cores were still taken at the same distance from the shore. The cores were stored in paper bags and laid out to dry in the lab for one week.

The dry soil samples were sieved with a 2 mm mesh filter to remove non soil particles. Next, 5 g of each sample was weighed out and mixed with 50 mL of deionized water in a 50 mL high-density polyethylene plastic vial. The mixture was left to saturate for at least 20 minutes and was frequently mixed to resuspend settled solids. The electrical conductivity (EC) of the mixture was measured using a Thermo Scientific Orion Star A215 pH/Conductivity Benchtop Multiparameter Meter (range, 0.001 µS/cm to 3000 µS/cm).

The meter was calibrated by a one-point calibration at the beginning of the processing period using a 1413 µS/cm standard.

2.4 Statistical Analysis

Conductivity in lakes across the HRM was compared across spatial and temporal scales. Tables were compiled in Microsoft Excel, and figures and all statistical analyses were performed using R 4.0.2 statistical software within the RStudio Integrated Development Environment 1.3.1073 (R Core Team, 2020; RStudio, 2020). The full reproducible code is available in Appendix A.

Conductivity, sodium, and chloride data from the DFO synoptic lake study was displayed in maps to determine the relationship between proximity to road salt application and level of conductivity and road salt ion concentration. Road salt and sand application data was provided by the HRM and Nova Scotia Transportation and Infrastructure Renewal (NSTIR). Sodium and chloride ion concentrations were compared with existing environmental protection recommendations. Trends in conductivity, sodium, and chloride did not show a normal distribution. Therefore, a sign test was used to analyze temporal trends in conductivity, sodium, and chloride throughout the HRM. Changes in conductivity, sodium, and chloride over time were displayed in scatterplots.

The Halifax Water dataset was used to display the temporal trends in conductivity in Lemont and Topsail Lakes. The mean conductivity across the lake was analyzed using a sieve bootstrap t-test to determine if there was a linear trend in conductivity over time. Temporal trends in conductivity were also displayed by year in a time series.

Water conductivity data collected from close and far sides of the lake during fieldwork had no outliers and was not normally distributed. A one-sample Wilcoxon signed-rank test was used to compare conductivity and proximity to road salt application, and conductivity and protection.

Soil conductivity data across site, distance, proximity and round of sampling was logarithmically transformed to make the distribution more normal. A linear mixed model using site as a random effect compared soil conductivity across different variables.

3. Results

3.1 Overview

Water conductivity and sodium and chloride ion concentration data was compiled from datasets provided by the DFO Synoptic Lake Study (Clement and Gordon, 2019). This data was analyzed for temporal trends. Over time water conductivity, and sodium, and chloride ion concentrations have significantly increased. Halifax Water provided data for the protected Lemont and Topsail watershed (a site included in the fieldwork). Seasonal trends in conductivity varied across years. Water and soil conductivity was also collected from five sample sites in Dartmouth, NS. Conductivity was measured on a side of the lake close to road salt application and an opposing far side. Proximity to road salt application has a non-significant effect on water conductivity but protection did lead to significant differences. Soil conductivity was significantly higher before road salt application and at the shoreline.

3.2 Synoptic Lake Study Data

The Synoptic Lake Study (Clement and Gordon, 2019) gives an overview of the trends in conductivity throughout lakes in the HRM. Lakes with a higher conductivity are normally concentrated in urban areas with higher road salt application rates (Canvec, 2017; Shaded Relief Images, 2006; Figure 2A). Lakes that are outside the urban core and away from roads and highways tend to have lower conductivity. Sodium and chloride concentrations follow a similar trend (Figure 2B; 2C), although sodium levels are consistently lower than chloride. The sodium concentrations were compared with the tolerance threshold for soil of 60 mg Na^+/L. Chloride concentrations were compared with the aquatic long-term exposure limit of 120 mg Cl^-/L. Chocolate, Frog, Whimsical, Frenchman, Cranberry, Settle, Bissett, Russell, Oathill, and Penhorn Lakes had chloride levels above the recommended 120 mg Cl^-/L (Canadian Council of Ministers of the Environment (CCME), 2011). The same lakes as well as First, Governor, and Bayers Lakes had sodium levels above the CCME recommended threshold for soil of 60 mg Na^+/L.

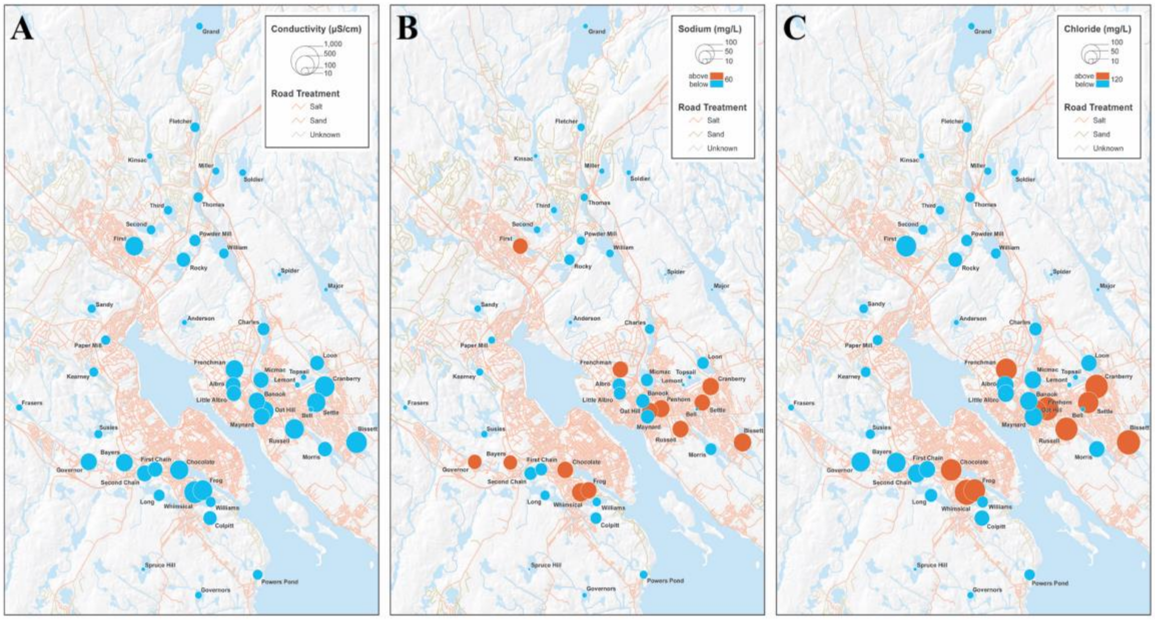

Figure 2. (A) Conductivity (µS/cm), (B) sodium (mg/L), and (C) chloride (mg/L) measured in lakes throughout the HRM in 2000 (A n=50, B n=51, C n=51). Roads where salt or sand is applied are differentiated by colour. Larger circles represent higher concentrations. Orange circles indicate lakes where ion concentrations are above the CCME recommended limits (60 mg Na^+/L and 120 mg Cl^-/L).

The mean conductivity of HRM lakes generally increased from 1980 to 2000 (Figure 3). The conductivity of Whimsical Lake in 1991 was a non-extreme high outlier and the distribution of the data was not normal (Shapiro-Wilk test, W=0.883, $P < 0.001$). Using a one-sample Wilcoxon signed-rank test the distribution was determined to be asymmetrical. There was a significant difference in conductivity between 1980 and 1991 (Sign test, n=49, $P < 0.001$), 1980 and 2000 (Sign test, n=48, $P < 0.001$), and 1991 and 2000 (Sign test, n=48, $P < 0.001$).

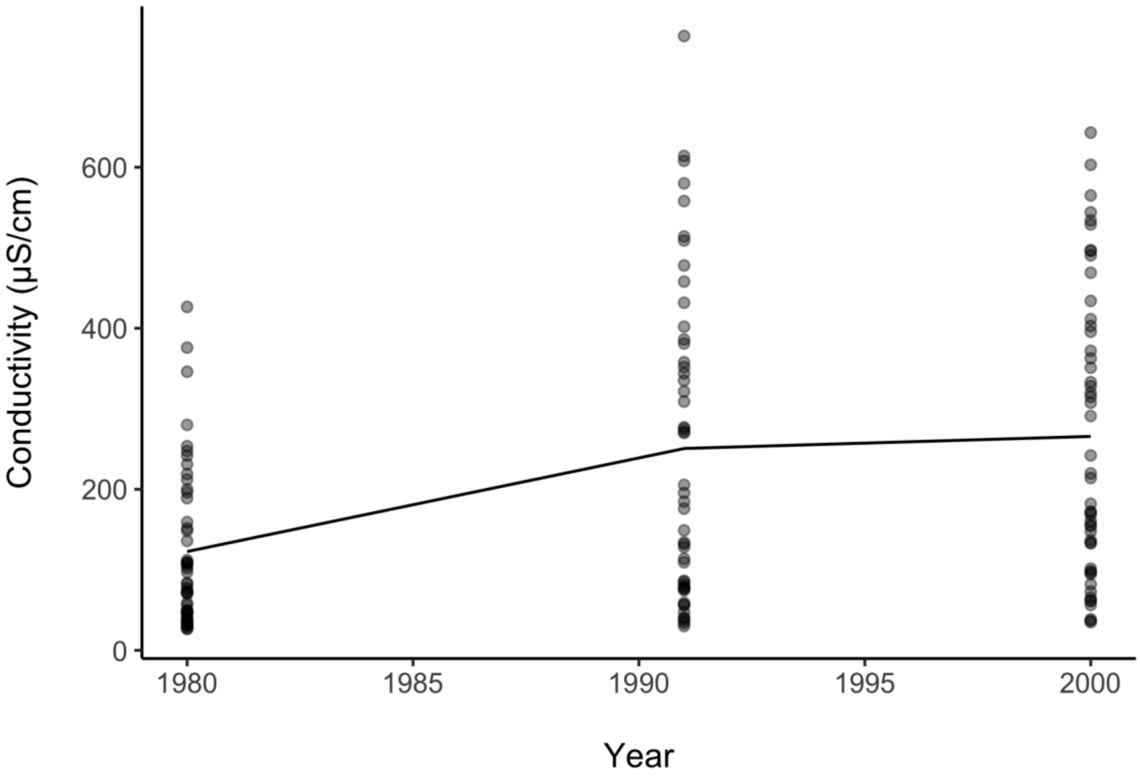

Figure 3. Conductivity (µS/cm) of 51 lakes in the HRM measured in 1980, 1991, and 2000 with mean trendline (1980 n=49, 1991 n=49, 2000 n=50). Conductivity values were not available for 2011.

Mean sodium and chloride ion concentrations increased over the 31-year observation period in lakes throughout the HRM (Figure 4). Frenchman Lake in 2011 was a high extreme outlier for both sodium and chloride. Sodium concentrations did not have a normal distribution (Shapiro-Wilk test, $W=0.751$, $P < 0.001$). Chloride concentrations also did not have a normal distribution (Shapiro-Wilk, $W=0.859$, $P < 0.001$). Using a one-sample Wilcoxon signed-rank test the distribution was determined to be asymmetrical for both sodium and chloride concentrations. There was a significant difference in the increase in sodium and chloride in 1980, 1991, 2000, and 2011 (Sign test, n=199, $P < 0.03$; Table 2).

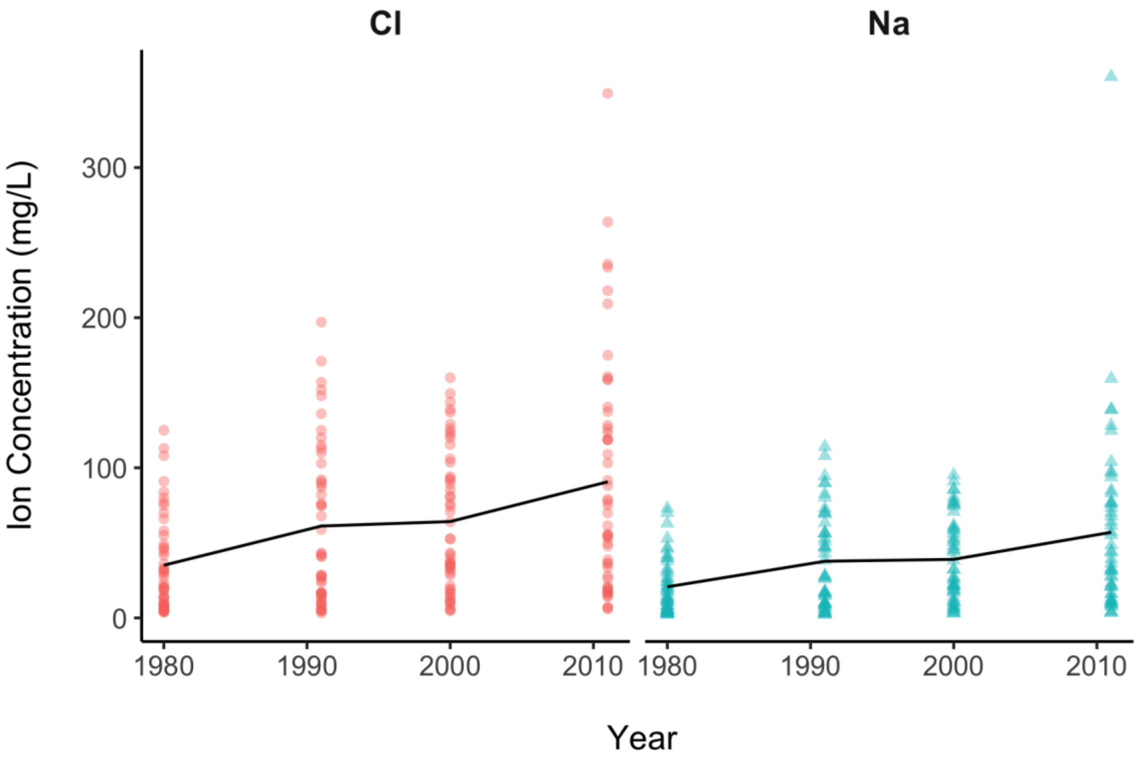

Figure 4. Chloride (mg/L) and sodium (mg/L) concentrations in lakes in the HRM with mean trendline, measured in 1980, 1991, 2000, and 2011 (1980 n=48, 1991 n=49, 2000 n=51, 2011 n=51). Frenchman Lake was an extreme high outlier in 2011 for both chloride and sodium.

Table 2. Significance values (p-values) of one-sample Wilcoxon signed-rank test for sodium and chloride from 1980 to 2011.

	Year	1980	1991	2000
Sodium	1991	<0.001	-	-
	2000	<0.001	0.029	-
	2011	<0.001	<0.001	<0.001
Chloride	1991	<0.001	-	-
	2000	<0.001	0.013	-
	2011	<0.001	<0.001	<0.001

3.3 Halifax Water Data

Halifax Water provided water conductivity data collected from three sites from the Lemont and Topsail watershed from 2009 to 2020. The conductivity of each month with mean trendline is displayed in Figure 5. The data did not have a normal distribution (Shapiro-Wilk test, W=0.778, $P < 0.001$) and the sample sizes for each year and month were not equal. Therefore, a sieve bootstrap version of the t-test was used, which does not require the assumption of normality and independence. It indicated that there was no linear trend over time (t-value=0.67703, $P = 0.345$).

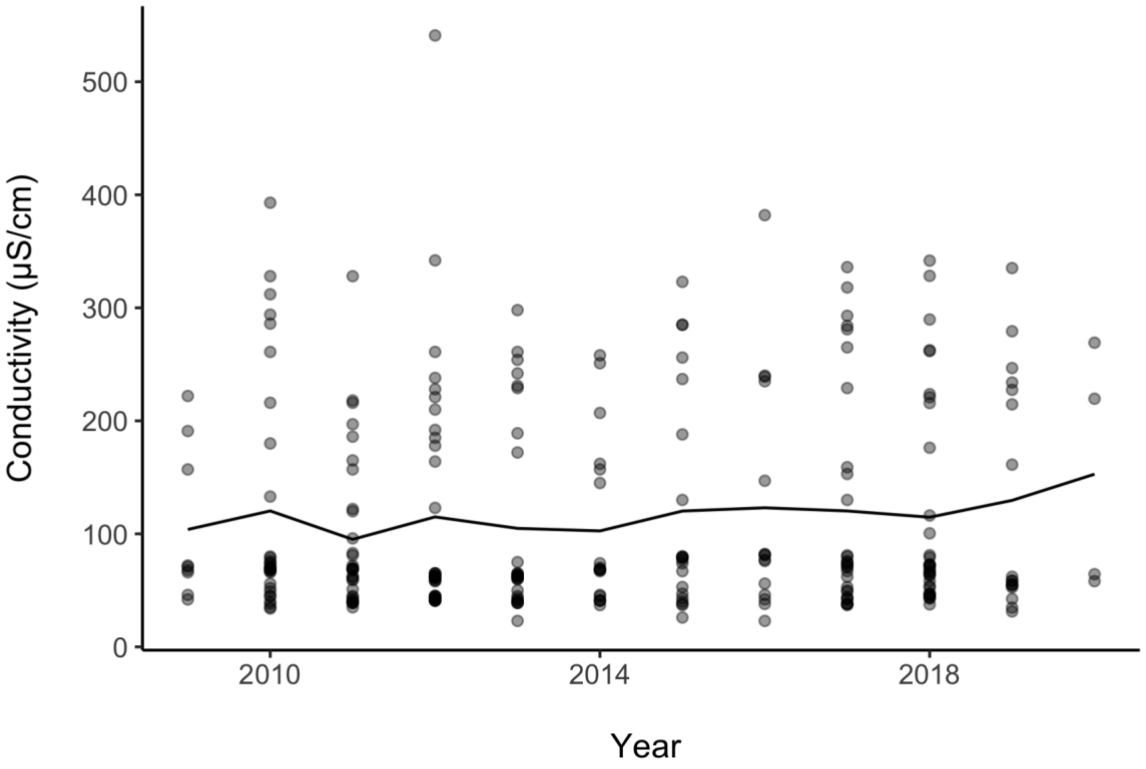

Figure 5. Conductivity from 2009 to 2020 measured at three points from Lemont and Topsail Lake with mean trendline. Data provided by Halifax Water (2020).

Halifax Water conducted water quality monitoring throughout the year at Lemont and Topsail Lake to observe seasonal trends in conductivity (Figure 6 and Figure 7). There is variation in water conductivity within this lake over time though the fluctuations have not been as large in recent years (Figure 6). Within any year, water conductivity does not show a consistent trend, but the highest peaks are seen in January and February, and the lowest in July (Figure 7). Further statistical analysis was not conducted as there was large variation in the sample sizes across year and month.

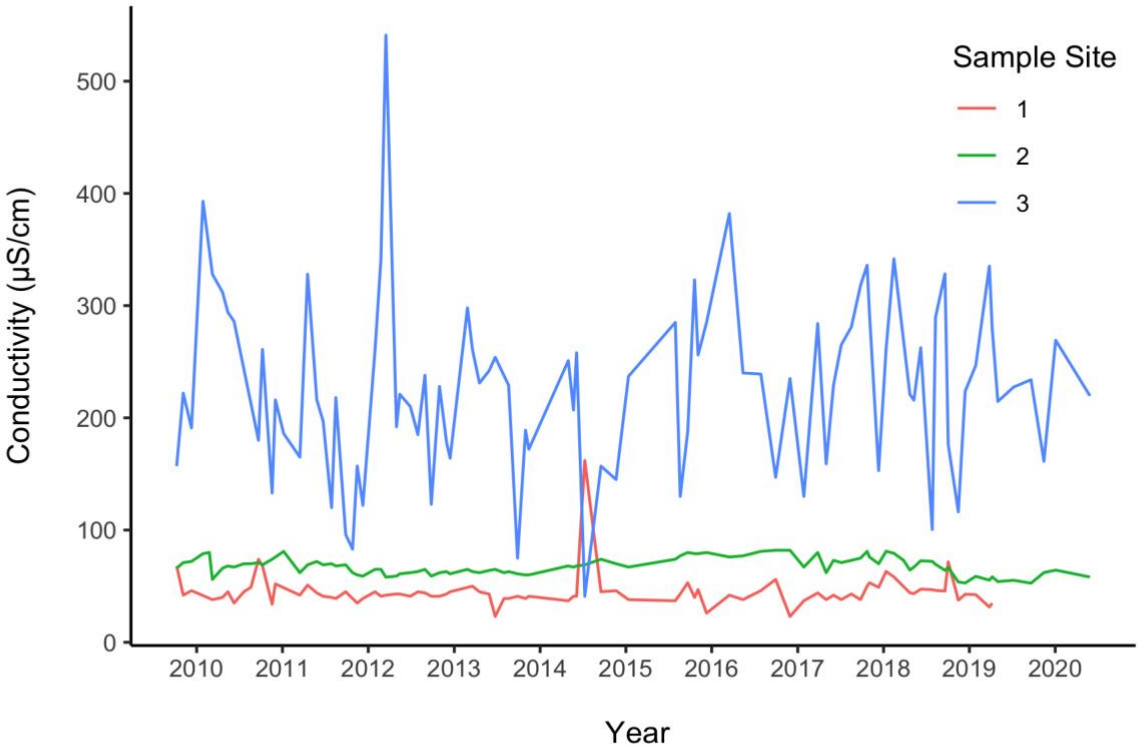

Figure 6. Temporal trends in conductivity in the Lemont and Topsail watershed from 2009 to 2020, separated by sample site. Data provided by Halifax Water (2020).

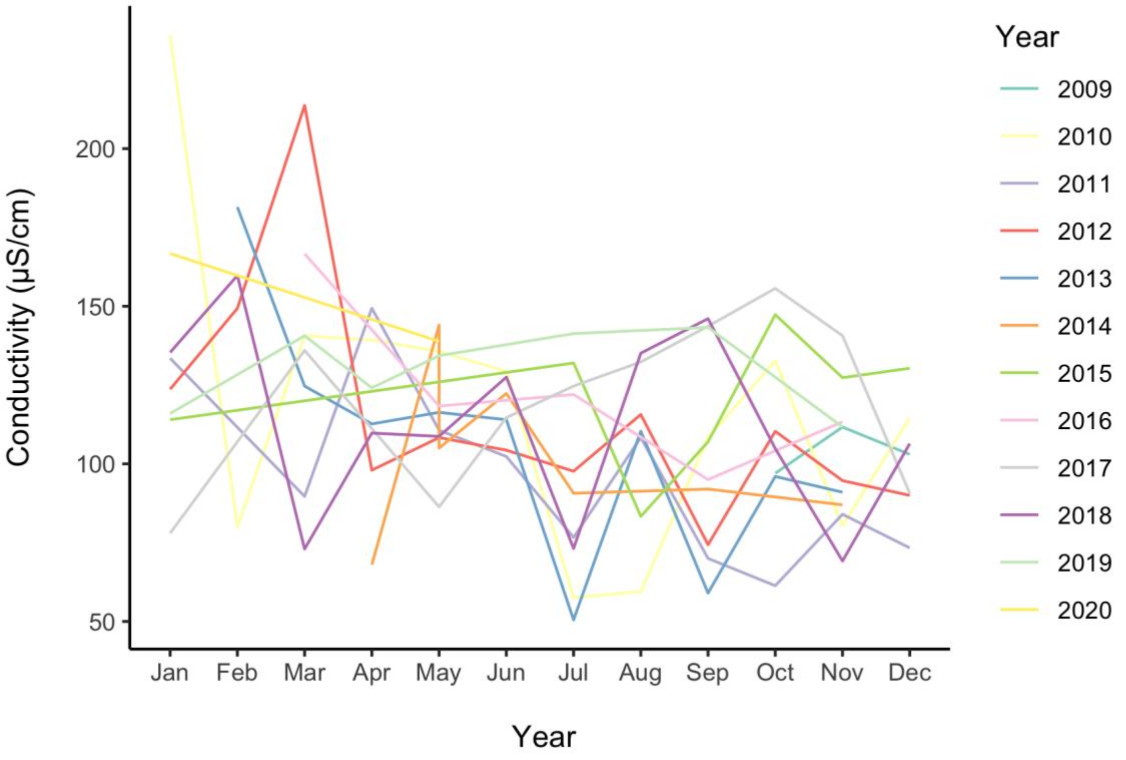

Figure 7. Conductivity in the Lemont and Topsail watershed from 2009 to 2020, separated by year and month. Data provided by Halifax Water (2020).

3.4 Fieldwork - Water Conductivity

Water conductivity was measured at five sample sites in the HRM in the fall, on the sides of the lake close and far from road salt application. The lakes were also assigned as protected or exposed. Halifax Water manages Lemont and Topsail Lakes (protected sites) while the other lakes sampled (Black Lake, Spectacle Lake, and Oathill Lake) are considered to be more exposed to road salt. The data had no outliers and was not normally distributed (Shapiro-Wilk test, W=0.804, P = 0.0162). A one-sample Wilcoxon signed-rank test was used as the data distribution was symmetrical. A comparison was made between conductivity and proximity (close or far) to road salt application, and conductivity and protection (Figure 8). There was no significant effect of proximity to roads on water conductivity (Wilcoxon signed-rank test, W=11, n=10, P = 0.834). However, there was a significant difference between protected (Lemont and Topsail Lakes) and exposed lakes (Black Lake, Spectacle Lake, and Oathill Lake), with exposed lakes having higher water conductivity (Wilcoxon signed-rank test, W=0.5, n=10, P = 0.0187). As multiple comparisons were made, the alpha value was lowered using the Bonferroni correction (α=0.025).

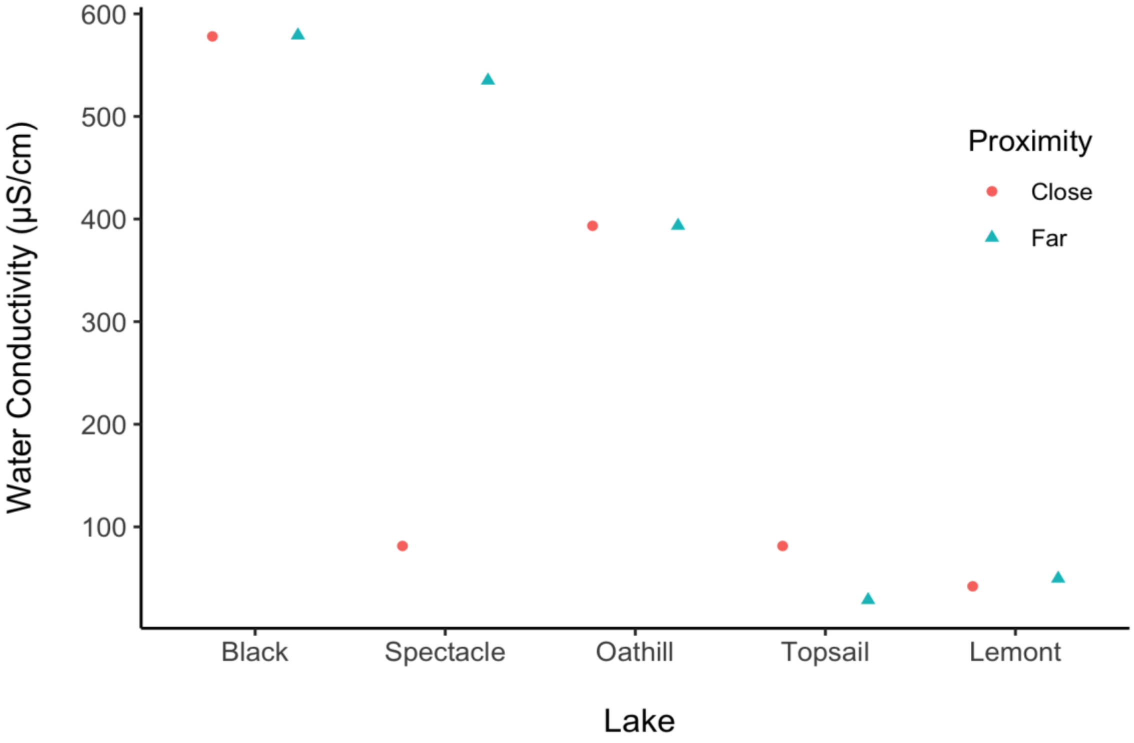

Figure 8. Water conductivity (µS/cm) of HRM lakes by proximity to road salt application (n=1/side of lake). Lakes were sampled on a side close to a road and an opposing, far, side. Lakes were assigned as being exposed to (Black Lake, Spectacle Lake, and Oathill Lake) or protected from (Lemont and Topsail Lake) road salt.

3.5 Fieldwork - Soil Conductivity

Soil conductivity analysis was completed in the lab using the five 5 cm depth soil cores collected at 0, 10, and 20 m from the shoreline (Figure 9). Soil cores were combined to produce one conductivity value. The only extreme outlier was Spectacle Lake, for soil sampled at 0 m close to road salt application in the fall. The data was logarithmically transformed, and the transformed distribution was not significantly different from normal (Shapiro-Wilk test, W=0.9812, P = 0.4813).

A linear mixed model compared level of protection, sampling time (round: pre or post road salt application), proximity to road (side: close or far), and distance (0, 10, and 20 m from the shoreline), with site as a random effect (Table 3). Soil from exposed sites had a non-significantly higher conductivity than soil from protected sites. Soil conductivity was higher before road salt application (in the fall). Conductivity at 10 and 20 m was lower than 0 m, right at the shoreline.

Table 3. Results of linear mixed model on soil conductivity, using site as a random effect (n=6/lake) and road proximity (close or far) and distance from lake shore (0, 10, and 20 m) as fixed effects.

Variable		Estimate	Standard error	t-value	p-value
Intercept		1.82689	0.13551	13.482	0.256
Protection	Exposed	0.18188	0.16000	1.137	0.079
Round	Before	0.09626	0.05479	1.757	0.014
Side	Far	0.13485	0.05479	2.461	0.184
Distance	10	-0.08923	0.06710	-1.330	0.020
	20	-0.15702	0.06810	-2.340	<0.001

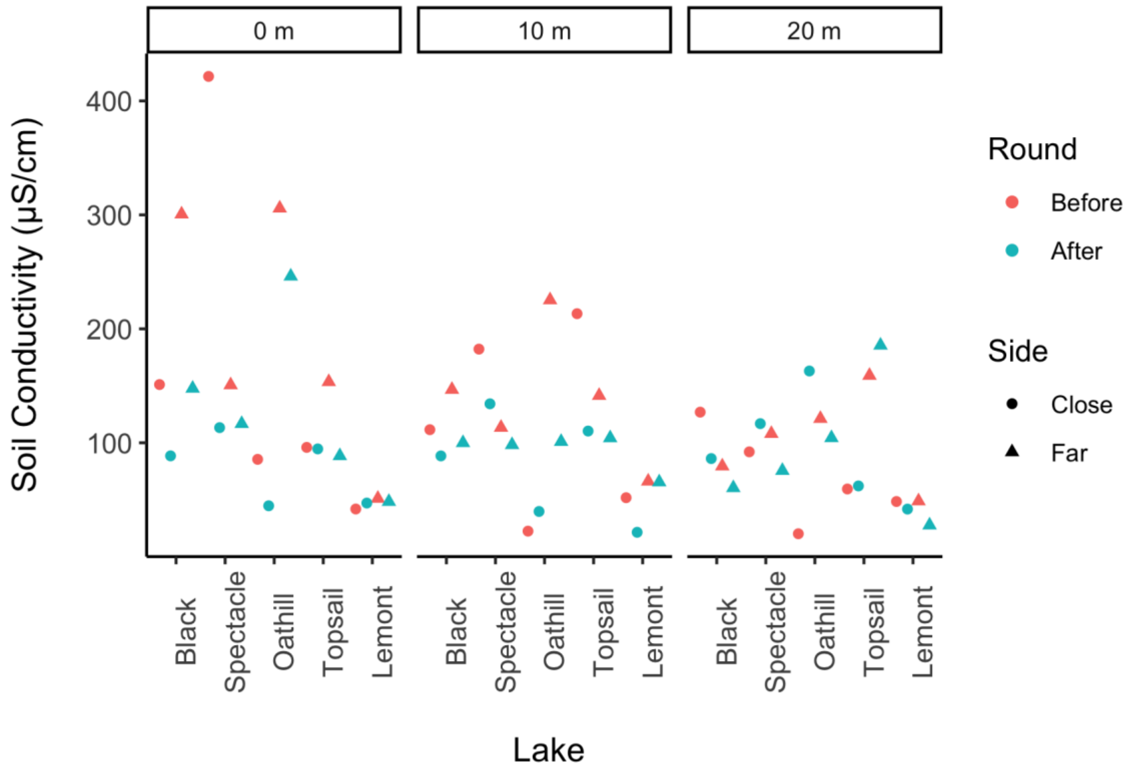

Figure 9. Soil conductivity (µS/cm) measured at 0, 10 and 20 m from the shoreline (n=6/lake). Five soil cores of 5 cm were taken at each distance and combined for lab analysis of conductivity. Sampling was done in the before (fall) and after (winter) road salt application, on sides close and far from a road where road salt was applied. On both sides of the lake samples were taken from 0, 10, and 20 m at the shore. Lakes were assigned as exposed to (Black Lake, Spectacle Lake, and Oathill Lake) or protected from road salt (Lemont and Topsail Lake).

4. Discussion

4.1 Overview of Water Conductivity in the HRM

Despite NS being the Canadian province that uses the most road salt per area, there is little awareness about the impact that road salt is having on the ecosystem. By demonstrating how salt is accumulating in the environment, this can drive action to minimize the adverse effects of freshwater and soil salinization. Results from the Synoptic Lake Study show how conductivity has significantly increased from 1980 to 2011 in the HRM (Figure 3). This trend has been observed since road salt began being used in the HRM. From 1958 to 1977, there was an average increase in chloride concentration by 172% in HRM lakes (Ginn et al., 2015). This correlates with an increase in sodium and chloride ion concentrations (Kelly et al., 2019; Figure 4). Sodium and chloride are not the only ions that would increase conductivity; however, the increase in conductivity is concentrated in areas where road salt is applied. Clement and Gordon (2019) reported extensively on the changes in water quality parameters in the 4th Synoptic Lake Study, but this study compares only a narrow range of water quality parameters with road salt application.

Lakes in more urban areas, where more road salt is applied generally have higher conductivity compared to lakes outside of the urban core (Environment Canada, 2001). Lakes in coastal areas, such as Halifax, also generally have higher conductivity due to infiltration of higher salinity sea water (Canadian Council of Ministers of the Environment (CCME), 2011). Protected lakes, such as Lemont and Topsail, did not have a significant increase in conductivity over time (Figure 5) by blocking potential pathways of contamination. Urban areas experience greater road salt application but also have more pavement where sodium and chloride cannot be absorbed, thus increasing runoff into water bodies (Hunt et al., 2012; Jamshidi et al., 2020). Water bodies draining major roadways or urbanized areas are normally more greatly affected by road salt use (Environment Canada, 2001). Release of environmental pollutants has a positive correlation with average annual daily traffic (Trenouth and Gharabaghi, 2016), suggesting that roads with high use promote particulate material dislodgement (Trenouth and Gharabaghi, 2016). High speed roads pose a greater risk of contamination as the faster a vehicle is moving the further it can spray road salt (Environment Canada, 2001; Hunt et al., 2012), so speed limit as well as distance from the road can impact road salt contamination. The slow turnover rate of groundwater means it will take a long time after the discontinuation of road salt to see reductions in mean conductivity (Kelly et al., 2019).

First, Governor, Bayers, Chocolate, Frog, Whimsical Frenchman, Cranberry, Settle, Bissett, Russell, Oathill, and Penhorn Lakes had sodium and/or chloride levels above the recommended limits for water and soil (Figure 2). As expected, these lakes are concentrated in the urban core or are surrounded by many salted roads. Salt input is a determinant of long-term mean ion concentrations (Kelly et al., 2019). Anywhere from 28 to 77% of the chloride from road salt is retained in water annually (Oswald et al., 2019). Runoff first mixes with groundwater (Jamshidi et al., 2020), where chloride is stored and released into water bodies over years (Snodgrass et al., 2017). Chloride levels continued increasing with development and stabilized after cessation of development but remained at higher levels in most lakes (Clement and Gordon, 2019; Scott et al., 2019). Only 25% of the land needed to be developed for chloride levels to exceed guidelines (Scott et al., 2019) for 14 days per year (Corsi et al., 2015). This is cause for concern as it remains unclear how specific HRM lakes are being detrimentally impacted by consistently high sodium and chloride levels.

As sodium and chloride levels have continued increasing throughout the HRM since 2000 (Figure 4) there is a risk of adverse effects in these lakes, such as changed community composition (Hintz et al., 2017; Novotny and Stefan, 2012). Hintz et al. (2017) found that over the course of eighty-three days, dissolved oxygen significantly decreased as experimental freshwater environments were exposed to high levels of salt. Freshwater benthic communities show decreased diversity in response to elevated chloride as salinization promotes anoxic conditions in lower lake strata (Novotny and Stefan, 2012). A wide range of salt intolerant species will be excluded from lakes and ponds where salinization has occurred (Collins and Russell, 2009). Salinization of freshwater can alter ecosystem functioning through a reduction in quantity and quality of organic matter processing (Cañedo-Argüelles et al., 2019). The effect on ecosystem functioning has been similar across regions although the effect on organism groups can differ, as groups such as microbes have exhibited buffering capabilities (Cañedo-Argüelles et al., 2019). Vegetation is also affected, as road salt application has been linked to a decline in urban trees through salt stress from high uptake of salt through the soil and salt spray damage (Equiza et al., 2017).

In general, chloride levels are higher in the water than sodium. Sodium ions are more easily held in soil due to cation exchange reactions (Guesdon et al., 2016; Jamshidi et al., 2020) and chloride is also easier to trace (Snodgrass et al., 2017). Chloride levels are studied as an indicator of watershed pollution levels as chloride can come from a variety of anthropogenic sources. The northeastern United States has seen chloride concentrations approximately doubling from 1990 to 2011 where there is comparable use of road salt (Corsi et al., 2015; Shetty et al., 2020). Besides being released through road salt, chloride can enter watersheds through fertilizers made with potash, water softener discharge, and sewage contamination due to increased human consumption of salt (Hunt et al., 2012; Khazaei and Milne-Home, 2017). In the HRM, the stormwater drainage system runs into the harbour (York pers. comm., 2020) so pollutants in this system are likely only minimally impacting freshwater lakes. The impact of these other sources of Cl^- should be considered in future studies, as road salt was the only contaminant considered in this study, to determine how various anthropogenic activities have contributed to the significant increases in conductivity, sodium, and chloride over time.

For the few sites sampled to examine the effects of proximity of road salt application and protection from road salt application on water conductivity there was a non-significant effect of proximity to roads on conductivity but a significant effect of lake protection on conductivity (Figure 8). For most lakes in this study, there was a negligible difference between conductivity on the close and far side. Although one side was designated as “far”, the exposed sites (Black Lake, Spectacle Lake, and Oathill Lake) had high levels of development on all sides, so it was expected that conductivity would be similar on the close and far side. For the protected sites (Lemont and Topsail Lake), the similarities in conductivity on the close and far side can be attributed to a lack of development on all sides of the lakes. The internal mixing of a lake (Scott et al., 2019) and ion movement (Watmough et al., 2017) means that the impact of road salt will not be localized to just one side. Conductivity on the far side of Spectacle Lake was 453.6 µS/cm higher than the close side (Figure 8). Spectacle Lake shares a watershed with Frenchman Lake (an extreme outlier in the Synoptic Lake Study), so the large difference in conductivity is more likely the result of internal cycling patterns that warrant further investigation.

Lakes that were protected (Lemont and Topsail Lake) likely had significantly lower conductivity due to the lack of development within the watershed (Scott et al., 2019). These results were consistent with expectations from visually identifying levels of development and roads within the watershed. The protected sites in this study were next to a major highway, however this section of the highway has sand application (instead of salt) to limit salt spray and contamination. By limiting the presence of salt into the local environment, these lakes have been less impacted by road salt than other lakes in the HRM. In contrast, Black Lake, which was next to the two salt storage domes, had the highest conductivity out of the lakes sampled. A similar strong negative correlation between distance from salt storage barns and chloride levels was also found in New York state (Pieper et al., 2018). As well, in the same study, lakes within 30 m of a major roadway had higher median chloride concentrations than lakes only close to minor roads (Pieper et al., 2018). Likewise, in the HRM, it was found that lakes near major roads had higher conductivity than lakes near only minor roads (Figure 2).

4.2 Seasonal Trends in Water Conductivity

Seasonal trends in Lemont and Topsail Lake were inconsistent (Figure 6 and 7). The highest peaks in conductivity in Lemont and Topsail Lake were in January and March, coinciding with the months when road salt application rates are generally higher (York pers. comm., 2020). However, as sampling did not occur in every month of every year and the dataset used only consists of one watershed, it is not possible to make generalizations about seasonal trends in lakes throughout the HRM. While Scott et al. (2019) found that lakes in the HRM did exhibit seasonal trends linked to road salt application, various studies in other regions have shown that elevated water conductivity at any time of the year may be the result of road salt application (Perera et al., 2013; Hintz et al., 2017; Snodgrass et al., 2017; Wyman and Koretsky, 2018; Shetty et al., 2020). Equiza et al. (2017) found that conductivity generally decreases throughout the spring and summer. Chloride levels can remain elevated throughout the year (Environment Canada, 2001), as the impact of road salt is not temporally limited. Furthermore, as road salt can be retained in groundwater and watersheds for decades (Kelly et al., 2019; Snodgrass et al., 2017) conductivity levels can fluctuate based on the slow release of retained ions.

Precipitation can affect conductivity, with years that have lower discharge (drier climate) having higher mean sodium and chloride ion concentrations (Kelly et al., 2019). Comparing seasonal trends in the HRM with rainfall data from Environment Canada (2021) shows that precipitation rates are on average, lowest in the summer during July and August. The highest peak was seen in January 2010, when precipitation was 92.3 mm. In March 2012 conductivity was similarly high, with precipitation only 64.5 mm. Lower precipitation concentrates water, resulting in higher conductivity. Summer months can experience a peak in conductivity when the evaporation rate exceeds precipitation (Hunt et al., 2012). However, the lowest mean conductivity was in July 2013. Precipitation was higher this month at 110.9 mm, which had a dilution effect. October 2017 and September 2018 had similar conductivity, however, precipitation levels differed at 66.8 mm and 101.8 mm respectively. Rainfall could also introduce other pollutants besides road salt into water bodies (Trenouth and Gharabaghi, 2016), which would also contribute to increasing conductivity. To understand the local relationship between road salt application, conductivity, and season, would require combining precipitation data, microclimate data, and monthly water quality data from lakes within the HRM.

4.3 Soil Conductivity

Sampling was done before and after road salt application to compare the effect of acute road salt application on soil electrical conductivity. Trends in soil conductivity were inconsistent across the sites. It was surprising that soil conductivity was significantly higher before road salt application. The winter of 2020-2021 was relatively mild (Environment Canada, 2021) and thus road salt application was limited in the HRM so there was expected to be a large increase in conductivity during the winter. Shetty et al. (2020) found that in New York salt had not been sufficiently removed from soil by spring suggesting that higher conductivity can be observed year-round. As road salt can be held in the soil (Guesdon et al., 2016; Jamshidi et al., 2020), it can be expected that soil conductivity fluctuates throughout the year in less predictable patterns.

Soil conductivity was highest at 0 m, at the shoreline. Equiza et al. (2017) found that sodium concentration decreased with distance from the road, and it was expected that conductivity would be higher closer to the road due to higher exposure. The sites used by Equiza et al. (2017) were mainly impacted by salt runoff and spray from roads and sidewalks, whereas sites used in this study had various land uses (such as unpaved walking trails) that can explain some of the variation in the effect of distance on soil conductivity. When conductivity was highest at 0 m, water conductivity was generally higher, so the soil at that distance could be more saturated with ions. Ions move through the soil into groundwater and water bodies (Watmough et al., 2017), so it is possible that the effect of distance on conductivity will not have consistent spatial and temporal trends. At sites with higher conductivity at 10 or 20 m, there were walking paths where salt contamination could come from shoes while the shoreline was not frequently passed over resulting in lower conductivity. As a distinct temporal pattern was not present among the sites with a small sample size, I recommend more frequent sampling of a broader range of sites to determine the long-term temporal effect of road salt on soil conductivity.

Sites exposed to road salt application did have higher conductivity than sites protected from road salt, but the effect was not significant. It was predicted that the exposed sites would have higher soil conductivity than protected sites as there is a higher rate of road salt application. Road salt application does not have to be direct to observe increases in soil conductivity as ions can disperse through the soil (Snodgrass et al., 2017) and affect even protected sites.

4.4 Road Salt Alternatives

Road salt alternatives do exist and there is potential for their use to keep winter roads safe while minimizing ecological harm. In some parts of the HRM sand is used in combination with salt. Sand is preferred in areas where residents use well water or have gravel roads (Lake Simcoe Region Conservation Authority, 2018). Compared with salt, sand has limited effectiveness, has to be applied at higher rates, and costs more. Sand has to be manually removed from roads at the end of the season and cannot be reused due to contamination (Lake Simcoe Region conservation authority, 2018). Synthetic poly-vinyl alcohols (PVA) are a re-creation of antifreeze proteins found in animals such as the Antarctic toothfish (Wowk, 2005). The hydroxyl groups bind to water molecules to prevent ice formation and are nontoxic to humans and aquatic organisms (Wowk, 2005). PVA has the benefits of being possible to adapt into a spray, and not degrading too quickly (Wowk, 2005), but it is not commercially available.

Beet juice deicer is another natural alternative that is less harmful than road salt, as it contains only 12% NaCl. However, adverse effects have still been observed on freshwater organisms (Cuciureanu, 2018). Experiments looking at the ecological impacts have used mayflies, as they are particularly sensitive to water pollutants (Cuciureanu, 2018). The high levels of potassium in beets resulted in elevated blood salt levels and significantly higher fluid retention compared to a control group (Cuciureanu, 2018). This material is also anti-corrosive and biodegradable (Cuciureanu, 2018), but it is not widely available or cheaper than regular road salt. All of these alternatives have a lower level of NaCl than traditional deicers, and thus a lower environmental impact, but runoff and soil and water contamination is still a concern. There is a lack of experimental data on the long-term impacts of these alternatives that promote their use over road salt. Road salt alternatives are not likely to see much popularity with municipalities as the cheap cost of salt (Corsi et al., 2015; Toronto and Region Conservation Authority, 2019) reduces the economic burden of public safety.

4.5 Limitations, Future Directions and Summary

Road salt appears to be significantly impacting the environment in the HRM, although this study only examines changes in conductivity of water and soil. In some of the cases described above there is a lack of data available or limited data that was included within this study. Data on salinity, sodium and chloride ion concentrations in HRM lakes are available in other datasets not included in this study, which can more specifically examine the impact of road salt. Winter months in particular lack data points, which makes it difficult to establish seasonal trends. There are some challenges with lakes and soil freezing, but as this is the road salt application period it is important to measure the immediate impact of runoff. Better monitoring programs need to be implemented to learn more about the short- and long-term impacts of road salt on community composition and ecosystem functioning in the HRM.

The public has greatly increased their expectations for winter travel generally and during adverse weather conditions. Behavioural changes, such as reducing travel during a snowstorm and driving at a slower speed are also strategies to improve road safety (Environment Canada, 2001). While accessibility needs to be taken into consideration, and hazardous conditions avoided, I recommend the HRM continue to implement strategies for effective road salt application. Recent switches from straight salt application to a liquid saltwater brine (York pers. comm., 2020) reduce the amount of salt being used as well as allowing road salt to better adhere to pavement (Robinson and Thomson, 2015) to reduce runoff. Early intervention methods, such as shoveling, also limit the need for deicers (Hunt et al., 2012). Road salt alternatives are worth exploring but transitioning away from road salt use will not remedy the ecological impacts of salt already released into the environment.

5. Conclusion

There have been significant increases in conductivity, sodium, and chloride in lakes in the HRM over the past 40 years. Several sites have been noted for having sodium and/or chloride levels that exceeded recommended limits in 2000 (Figure 2). Seasonal water conductivity trends are inconsistent as a result of differing annual and monthly rates of precipitation. Proximity to road salt application did not have a significant effect on water conductivity, but exposed sites had significantly higher levels of water conductivity. In contrast, soil conductivity did not have a consistent trend. Ions move at different rates throughout the soil and groundwater, so the effects of road salt can be observed over a long period of time. While public safety remains the priority, current road salt application methods can be adapted to improve the efficiency of use allowing for lower quantities of road salt to be used to minimize ecological impacts.

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Appendix A

Complete Code for Data Analysis

This appendix consists of the complete code used for the data analysis for this study. Data files and code can be found at https://github.com/skanabar27/Road-salt.