Global and local ecological impacts of chloride-based road deicing salts

By

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ABSTRACT

Chloride-based road deicers are commonly used for winter road maintenance but can be detrimental in both terrestrial and aquatic environments. The objective of this thesis was to investigate the impacts of road salting both globally and locally in Halifax, Nova Scotia. A meta-analysis of the impacts of road salting across individual, community, and ecosystem levels found that road salt can have significant negative effects across ecological scales. Locally, fifteen wetlands across Halifax were tested to determine whether direct stormwater outflows impacted salinity and soil mineral concentrations more than runoff and identify whether these sites were salinized above recommended thresholds. Although all fifteen wetlands were above the threshold, direct stormwater outflows were not found to significantly impact wetland soil salinity, suggesting that other factors (such as urbanization) may be affecting the salinization of these wetlands. This thesis highlights the need for further research on road salting impacts in understudied ecosystems.

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CHAPTER 1. INTRODUCTION

Background

Anthropogenic activities have a pronounced influence on both freshwater and terrestrial ecosystems in urbanized regions, where development has contributed to habitat loss and the contamination of the environment, including the use of chemical deicers for winter road maintenance (Environment Canada and Health Canada, 2001). Chloride pollution from road salting through runoff or spray mechanisms is known to have significant and severe impacts on aquatic and terrestrial ecosystems in northern latitudes and high-elevation regions where road salts are commonly used (Tiwari and Rachlin, 2018). There is a direct relationship between the quantity of impervious surface coverage, such as roads and pavements, and the salinization of inland waters (Kaushal et al., 2005). The effects of salts normally diminish with distance from roads, with the maximum impacts being reported within 10 m of the road in regions where road salts can be linked to a single source point (i.e., a single road or highway) (Bäckström et al., 2004). However, soil chloride concentrations can vary greatly in metropolitan settings with higher densities of paved surfaces like roads and parking lots (Cunningham et al., 2008). After cold weather events, excessive use and levels of chloride salts can push watersheds past acute toxicity levels (Environment Canada and Health Canada, 2001).

Wetlands are defined as “areas where water covers the soil or is present either at or near the surface of the soil all year or for varying periods of time during the year” (USEPA, 2023). Wetlands are known to be significantly affected by road deicing salts, but the effects of road salts on these ecosystems have not been as widely studied as the effects on lakes, rivers, and other freshwater environments (Hill and Sadowski, 2016; Kinsman-Costello, 2023). Wetland ecosystems contribute to a wide range of ecosystem services, such as climate regulation, carbon sequestration, recreational usage, and pollutant filtration for ground and surface water (Millennium Ecosystem Assessment, 2005), and have been referred to as "kidneys of the landscape" because they function as the downstream receivers of water and waste from both natural and human sources (Mitsch & Gosselink, 2015). The chief drivers of wetland degradation and loss have been identified as infrastructure development and pollution (Millennium Ecosystem Assessment, 2005). Hill and Sadowski (2016) compared chloride concentrations in urban and rural land use settings and found that wetlands in urban areas had chloride levels that were at or above the thresholds for chronic water quality impacts on aquatic organisms, and that the main source of contamination in urban wetlands was road deicing salts. Although water quality impacts have been well studied, there is a lack of knowledge on how salt used for deicing roads affects soils in wetlands (Kinsman-Costello et al., 2023). Kim and Koretsky (2013) found that adding sodium chloride and calcium chloride to wetland sediment cores led to the growth of microbes, decreased pH, and increased concentrations of Mn^{2+}, Fe^{2+}, Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, indicating that the addition of road deicing salts may have an impact on the cycling of nutrients in wetland soils. Additionally, the capacity of wetland soils to protect downstream lakes and rivers from excess chloride is variable, and most likely limited to low concentrations of salt, which is significant because one of the main ecosystem services provided by wetlands is the retention and prevention of pollution (Millenium Ecosystem Assessment, 2005). Wetland soils have been reported to have lower denitrification rates when contaminated by acute chloride concentrations, even though nitrate is a crucial compound that wetlands buffer (Lancaster et al., 2016). Moreover, excess sodium from sodium chloride road salt contamination can collapse mineral soil structure, especially near the surface, potentially increasing soil moisture and decreasing the amount of filtration that wetlands provide (Walker et al., 2021).

Chloride negatively impacts soil fertility, soil structure, and water transport in soils. Excessive salt concentrations can mobilize heavy metals such as mercury and lead, which can then bioaccumulate in food webs and contaminate groundwater (Amrhein et al., 1992). The use of sodium chloride as a deicer has been highly correlated with increased concentrations of cadmium, copper, lead, and zinc detected in roadside soils (Bäckström et al., 2004). In addition, by deflocculating soil clay particles and obstructing pores, increased sodium concentrations from sodium chloride road salts can cause changes in soil structure (Shannon et al., 2020), which in turn may decrease hydraulic conductivity (Norrström and Bergstedt, 2001). As road salts dissolve in the ground, the electrical conductivity of soils rises after their application (Shannon et al., 2020). Increases in electrical conductivity have been reported to have a substantial inverse link with soil pH in studies (Bäckström et al., 2004). Road salt buildup can also cause a decrease in soil cation exchange capacity (Ke et al., 2013), and variations in cation concentrations and cation exchange capacities may interfere with many biogeochemical cycles.

The location where road salt is deposited is frequently where chloride concentrations are highest, with a further surge in the middle of summer when water evaporation occurs (Environment Canada and Health Canada, 2001). Splashing may also hasten the leaching of sodium chloride through the soil along roadside ditches, negatively impacting soil aggregation (structure) and resulting in lower soil infiltration rates, which could increase soil erosion and dispersion (Environment Canada and Health Canada, 2001). Chloride concentrations in many suburban and urban streams surpass the chronic toxicity level recommended for the protection of freshwater life, which is estimated to be 120 mg Cl^-/L for long-term or chronic exposures and 640 mg Cl^-/L for short-term (acute) exposures (CCME, 2011). While concentrations as low as 16 mg Na^+/kg and 30 mg Cl^-/kg dry weight can harm plants, the threshold for soil integrity is 60 mg

Na^+/L and 90 mg Cl^-/L (Environment and Climate Change Canada, 2004). Species living in roadside habitats may adapt to surroundings with greater chloride concentrations, making them more able to withstand acute toxicity level contamination (e.g., Lancaster et al., 2016; Craig and Zhu, 2018), but the effects of chronic chloride toxicity are still understudied.

A 2001 evaluation of road salt impacts in Canada determined that road salts containing inorganic chloride salts can be classified as "toxic" according to the requirements of the Canadian Environmental Protection Act (Environment Canada and Health Canada, 2001). Because there are no set legal limits for road salting, regulation is ultimately up to the province or municipality, although Environment and Climate Change Canada offers recommendations on best practices for salting roads (Environment and Climate Change Canada, 2004), including recommending the creation and publication of road salt management plans. In Halifax, Nova Scotia, chloride-based road salts have been used for regular winter maintenance since the 1950s (Ginn et al., 2015); however, there is a knowledge gap with respect to environmental impacts in the region, especially around wetlands and soil resources (Kanabar, 2021).

Research Objectives

The aim of this research was to gain a broader understanding of how road salt is impacting environmental quality, both globally as well as locally within Halifax, Nova Scotia. Firstly, in a meta-analysis, I focus on the effects of chloride-based road deicing salts on individuals, communities, and ecosystems globally in order to 1) examine how the magnitude and direction of impacts may vary across different ecological scales, and 2) to investigate how moderating effects in both the environment and the study methodology may influence the effects. Second, in my field study, I focus on the use of road salt on wetlands, and the subsequent influence on soil chemistry to 1) identify whether the dispersal of road salt through stormwater outfalls has a larger impact than indirect salt spray mechanisms, 2) investigate how the distance to the road salt source and soil depth impact soil salinity and mineral concentrations, and 3) examine the relationship between salinity and soil chemistry across a sub-sample of Halifax wetlands. As such, this thesis will contribute to better understanding the effects of road salting on roadside wetland soils, especially in Halifax where road salt has been understudied, and improve our understanding of the impacts of road salting across ecological scales. An improved understanding of the effects of road salting will benefit people by allowing managers to make decisions about how much salt to use to keep roads safe while minimizing environmental damage.

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CHAPTER 2. A META-ANALYSIS OF THE IMPACTS OF CHLORIDE-BASED ROAD SALT ON BIODIVERSITY AND ECOSYSTEMS

Abstract

Although chloride-based road salts deployed for winter road safety are effective and relatively low-cost, they can have extensive and long-term impacts on aquatic and terrestrial species and ecosystems. While qualitative reviews on these effects have previously been published, a quantitative meta-analysis allows a broader understanding of the intensity of effects across different environments. We conducted a random-effects meta-analysis to explore the ecological impacts of chloride-based road salts and to determine whether they are moderated by habitat type (aquatic vs. terrestrial), salt type ($NaCl$, $CaCl_2$, $MgCl_2$, or a mixture), and study characteristics. Hedge's d was calculated for a total of 491 cases across 21 variables of impact. Impacts were consistently negative across species, populations, and ecosystems, with significant reductions in animal and plant fitness, animal production, animal abundance, soil and water pH, and soil moisture. Overall, deicing salts have negative impacts on biodiversity and ecosystems; ideally, their use would be reduced to mitigate these impacts.

Introduction

Anthropogenic pollution, including road salts for winter road maintenance, is having major environmental impacts in both aquatic and terrestrial environments (Tiwari & Rachlin, 2018). The use of chloride-based deicing salts to clear roads has been widespread in countries in northern latitudes since the late 1930s and has been steadily increasing (Kelly et al., 2010). Road salting is conducted across North America, Europe, and Asia, with approximately 37% of the drainage area of the contiguous United States affected by road salts (Kaushal et al., 2018). In Canada, it is estimated that about 4 million tonnes of road deicing salt are used every winter (Environment Canada, 2018). It has been estimated that between 75 and 90% of added salts may enter roadside environments via runoff or splashing (Norrstrom & Bergstedt, 2001).

Sodium chloride ($NaCl$) is the most widely used road salt; however, many jurisdictions may use calcium chloride ($CaCl_2$) or magnesium chloride ($MgCl_2$) as alternatives (Environment and Climate Change Canada, 2018). While $NaCl$ is the most cost-effective deicer, it is most useful above –12 °C, after which it can no longer effectively lower the freezing point of water (Transportation Research Board, 1991). Below –21 °C, $CaCl_2$ is more effective, however it is cost-prohibitive, costing about 5 times more than $NaCl$ (Kelly et al., 2010). $MgCl_2$ is about twice as expensive as $NaCl$ and is thought to be more harmful to aquatic organisms, with significantly higher reductions in abundance, taxa richness, and community biomass (Kotalik et al., 2017). Although the use of chloride-based road salts is known to have a negative influence on freshwater and terrestrial environments, the magnitude of the problem is unclear (see Mazumder et al. 2021, Cunningham et al., 2008). Previous qualitative studies have highlighted the negative impacts of these chemicals on both aquatic and terrestrial species and communities (Hintz & Relyea, 2019; Tiwari & Rachlin, 2018). Despite the widespread use and known effects of chloride-based road salts across northern latitudes (Tiwari & Rachlin, 2018), there has yet to be a quantitative synthesis of their ecological impacts in both terrestrial and aquatic systems.

Chloride-based road salts impact ecological functions at multiple scales (Hintz and Relyea, 2019). At the individual level, road salts may alter physiology and reduce growth and locomotion in aquatic species (Hintz et al., 2017). They also contribute to the mortality of sensitive aquatic primary producers and macroinvertebrates (Hintz et al., 2017). Road salt has been found to cause needle necrosis and death in conifer species, as well as foliar injury to roadside plants (Tiwari and Rachlin, 2018). At the community level, road salt toxicity can have trophic cascade effects (Hintz et al., 2017) and result in changes in community structure (Astorg et al., 2022; Fournier et al., 2021) due to decreased abundance, density, and biomass of salt-intolerant species and increased abundance, density, and biomass of salt-tolerant species (Fournier et al., 2021; Wilcox, 1986). At the ecosystem level, salinity from road salting can influence water quality and natural mixing in lakes (Novotny & Stefan, 2012), as well as decreasing soil carbon mineralization and soil respiration (Craig & Zhu, 2018), and increasing trace and heavy metal mobility in soils and groundwater (Amrhein et al., 1992).

Although qualitative reviews have previously discussed the environmental implications of road salting (Hintz & Relyea, 2019; Tiwari & Rachlin, 2018), a quantitative review of the impacts on both aquatic and terrestrial species had yet to be completed. While primary studies are necessary to provide detailed information on a variety of species and ecosystems, different studies on the same organisms may lead to conflicting results. For example, Stoler et al. (2016) found that road salt led to increased *Physidae* (fresh-water snail) abundance, however Delaune et al. (2021) conversely measured a decrease in *Physidae* abundance when treated with road salts. Meta-analyses are important tools for examining and synthesizing research across large numbers of independent studies (Koricheva et al., 2013). We conducted a meta-analysis of the ecological impacts of chloride-based road salts to examine how the magnitude and direction of impacts may vary across different ecological scales and to investigate environmental moderators such as salt type and habitat type. In addition, we included study characteristics (study type and study length) as moderators because the direction and magnitude of the outcome may differ between controlled experiments and field observations. We hypothesized that: 1) impacts would be highest at the community level due to the wide range of changes in community composition from salts (as suggested in Astorg et al., 2022; Fournier et al., 2021), 2) salt type would be a significant moderator of effect size, with $MgCl_2$ having the greatest negative impact followed by $CaCl_2$, and NaCl, based on previous comparisons (Coldsnow & Relyea, 2021; Harless et al., 2011), 3) impacts would be greater in aquatic versus terrestrial ecosystems due to solubility and mobility through watersheds, 4) study type would be a significant moderator of effect sizes as experimental studies likely had less variation because of control/lack of environmental noise, and 5) shorter term studies would likely have a greater effect size as some research has suggested that species may be able to adapt to salinity over longer periods of time (Coldsnow et al., 2017). This research is the first to quantitatively synthesize the impacts of road salting across scales and environments and may assist in pinpointing areas for future research. Having an improved understanding of the ecological consequences of road salting allows managers and policymakers to determine how much and what type of salt to use to ensure road safety while reducing environmental harm.

Methods

A meta-analysis was conducted following the ROSES reporting standards (Appendix A; Haddaway et al., 2018). Three academic search engines were selected to search for relevant papers: ISI Web of Science, EBSCO Academic Search Premier, and PubMed.

Inclusion Criteria

We searched ISI Web of Science on 22 February 2022 using the topic (title, abstract, author keywords, and Keywords Plus) search term *(("road salt" OR deic*) AND (impact* OR effect)) NOT (airp* OR deictic OR concrete)*. This search produced 1164 records, which were screened for selection based on the following inclusion criteria: 1) studies which examined effects of road deicing salts on the natural environment, 2) records which reported impacts of road deicing salts, and 3) studies that quantitatively compared either impacted versus unimpacted treatments, or heavily versus lightly impacted treatments.

Exclusion Criteria

We excluded articles from our search based on the following: 1) studies that did not directly report ecological effects, including those that documented an increase in chloride, described spatial patterns only, described remediation efforts, or focused on artificial environments (including roads, drinking water wells, etc.), 2) studies that considered salinity impacts from mining, natural occurrences, and saltwater, 3) studies assessing the impacts of road salts on the cellular level, and 4) articles lacking appropriate controls or replication.

We screened the titles of articles from the search (n = 1164) and were left with 524 records. After screening abstracts for inclusion and exclusion criteria, 228 records remained. In addition to the Web of Science search, we searched PubMed on 22 February 2022. This search produced 974 records, but after removing duplicate records and abstract screening, only four records from this search were retained. We also searched Academic Search Premier on 24 February 2022. This search provided 847 results, and after screening and removing duplicates 5 results remained. Thus, in total, there were 237 records in the dataset after abstract screening. After screening the records for suitability, 163 records remained. Relevant literature found through these searches were then compared against Tiwari and Rachlin (2018) and Hintz and Relyea (2019), two recent qualitative reviews on road salt effects, and additional suitable papers from these reviews were added to the meta-analysis (Appendix A). Of the papers cited in the qualitative reviews, 125 were not already found by our search and 9 of those records met our inclusion criteria.

Data Extraction and Effect Sizes

We recorded means, variance (standard deviation, standard error, and 95% confidence intervals) and sample sizes for each record. When multiple ecosystem types, species or response variables were examined separately within the same article, they were treated as separate case studies. We included a random effect for case studies from the same article in the analysis to account for any lack of independence. If an article included studies conducted on the same species and ecosystem type that were located in two or more distinct regions, we also considered them as separate case studies. When more than two treatment levels were examined in a study, only the largest contrast was included, in order to use Hedge’s d. For example, if the degree of impact varied, we examined the least impacted versus the most impacted treatments; or, if the time of impact varied, we examined treatments that impacted the longest. If response variables were measured at multiple time points, we included only the longest time range. If data were presented graphically, we extracted values using the image analysis software WebPlotDigitizer (Rohatgi, 2022).

Case studies were classified based on whether impacts related to species, communities, or ecosystems. These impacts were further divided into 23 impact types (Table 1), following Cameron et al. (2016) and Vilà et al. (2011). We also identified the taxa examined in each study if applicable at the class level for animal species and by functional group (tree, shrub, graminoid, forb) for plant species, habitat type (aquatic vs. terrestrial), salt type, study type (experimental vs. observational), and experiment duration. Salt type was categorized as NaCl, $CaCl_2$, $MgCl_2$, or a mixture. Experiment duration was categorized as short-term, or less than a month ($\leq$31 days; n = 265), intermediate, or over the course of a season (> 31 days to < 70 days; n = 108), and long-term ($\geq$ 70 days; n = 118). These ranges were chosen as study lengths in the literature generally cluster into these groups.

Table 1. Variables used for each road salt impact type assessed at the individual, community, and ecosystem level, and number of records and cases which examined each road salt impact type. Note: some records examined multiple impact types and were thus counted twice.

Level	**Impact Type**	**Variables**	**Records**	**Cases**
Individuals	Plant fitness	Seedling establishment, fruit set, seed set, flowering, mortality (–)	6	24
Individuals	Plant growth	Increase in size of whole plants or plant parts	11	72
Individuals	Animal fitness	Fledging success, hatching success, juvenile recruitment, survival, mortality (–), reproduction	21	51
Individuals	Animal growth	Increase in size of whole animals at any life stage	16	38
Individuals	Animal performance	Grazing, predation, mobility, activity	18	33
Communities	Animal production	Biomass	3	5
Communities	Animal abundance	Density, number, volume, cover	13	73
Communities	Animal diversity	Richness, diversity	3	10
Communities	Plant production	Biomass	14	39
Communities	Plant abundance	Density, cover, number	2	8
Communities	Plant diversity	Richness, diversity	1	3
Ecosystems	Microbial activity	Respiration, enzyme activity	7	22
Ecosystems	pH	Soil pH, water pH	15	24
Ecosystems	C pools	Soil C, plant C	4	7
Ecosystems	C/N	Plant C/N, soil C/N	2	2
Ecosystems	N pools	Soil N/NO3/NH4, plant N	3	13
Ecosystems	N fluxes	N mineralization/nitrification rate	2	4
Ecosystems	Soil moisture	Soil moisture	2	8
Ecosystems	DO	Dissolved Oxygen	8	15
Ecosystems	SOM	Soil organic matter	2	3
Ecosystems	Temperature	Water temperature	3	6
Ecosystems	Chlorophyll	Water chlorophyll A concentration	13	31

Hedges' d, a measure of the standardized difference of means, was calculated for each case study (Equation 1; Koricheva et al., 2013),

Equation 1. $$d = \frac{\bar{X}_{treatment} - \bar{X}_{control}}{SD_{pooled}} J$$

where $\bar{X}_{treatment}$ and $\bar{X}_{control}$ are the sample means of the treatment and control (or heavily and lightly salted), SD_{pooled} is their pooled standard deviation, and J is a weighting factor based on the number of replicates per group. SD_{pooled} was calculated as:

Equation 2.
$$SD_{pooled} = \sqrt{\frac{SD_t^2(n_t-1)+SD_c^2(n_c-1)}{n_t+n_c-2}}$$

where n_t and n_c are the number of samples in the two groups, and SD_t^2 and SD_c^2 are their standard deviations.

J was calculated as:

Equation 3.
$$J = 1 - \frac{3}{4(n_t+n_c-2)-1}.$$

The variance of Hedge's d was calculated as:

Equation 4.
$$d = \frac{n_t+n_c}{n_t n_c} + \frac{d^2}{2(n_t+n_c)}$$

With Hedges' d, larger effect sizes indicate a greater difference between road salt treatments and controls, and a Hedges' d of zero means there is no difference between treatments. The metric ranges from −∞ to +∞, with a positive value indicating an increase in the variable of interest and a negative value indicating a decrease.

A grand mean effect size (d+) was calculated for each impact type by combining effect sizes of all relevant comparisons using a random effects model (Koricheva et al., 2013). We used a random effects model in the *metafor* package (Viechtbauer, 2010) to account for both within study variance and between study variance. The random effect for within study variance was included to account for potential lack of independence between cases from the same article (e.g., because of study location or methods). Mean effect sizes were considered significantly different from 0 if their confidence intervals did not include 0. The mean percentage of change in response variables between impacted and not impacted treatments was estimated as:

Equation 4. $$\% \text{ change} = (e^{R+})-1 \text{ x } 100$$

where R+ is the weighted mean response ratio (R) across studies. The natural logarithm of R was calculated as (Koricheva et al., 2013):

Equation 5. $$lnR = ln\left(\frac{X_{treatment}}{X_{control}}\right).$$

We calculated total heterogeneity (Qt) for each weighted mean effect size in order to test heterogeneity across case studies (Koricheva et al., 2013). A significant Qt value indicates that the individual effect sizes used to calculate the weighted mean effect size (d+) are heterogeneous, and that the variance among individual effect sizes is greater than would be expected due to sampling error alone, which would suggest that there may be unexamined moderators influencing effect sizes. We also calculated between-group heterogeneity (Qb) to investigate whether mean effect sizes differed among impact types, and within-group heterogeneity (Qw) to assess whether effect sizes differed within each impact type.

Publication bias can result from the publication (or non-publication) of relevant research depending on their results. For example, a study may be published if the results are significant, but less likely to be published if they are not significant. This could result in a bias towards only the inclusion of records with high effect sizes. To examine whether the results of our meta-analysis may be affected by publication bias, we examined the correlation between sample size and standardized effect sizes across studies (Koricheva et al., 2013; Figure 1). We also used multivariate linear mixed effects models in the '*metafor*' package (Viechtbauer, 2010) to examine the impacts of the moderators on effect size for impact types where n > 50 (plant growth, animal fitness, and animal abundance). All data analysis were conducted using R 4.0.2 (R Core Team 2022).

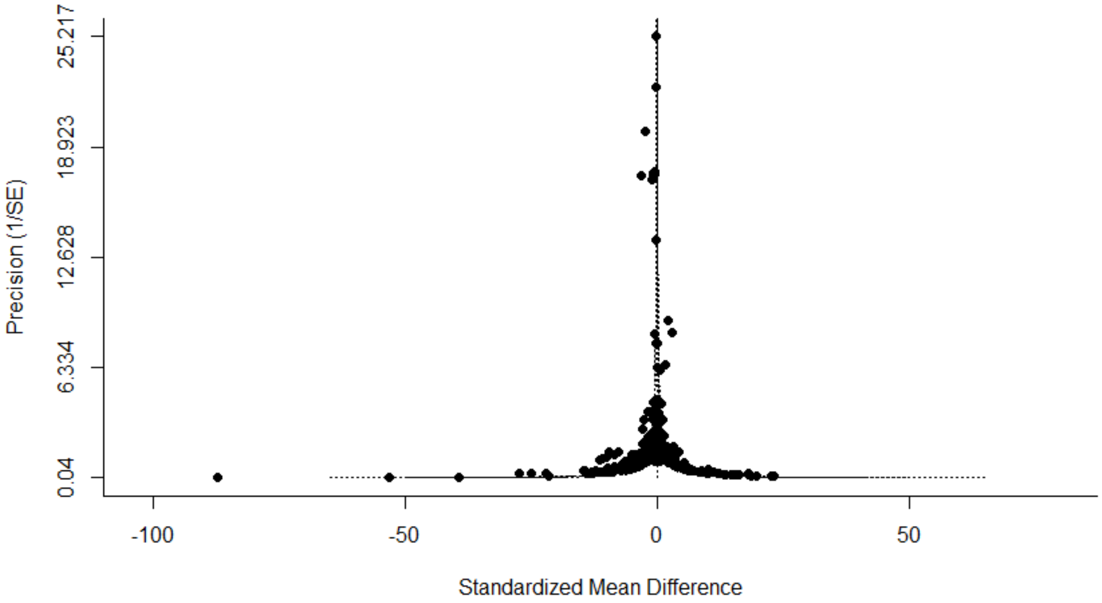

Figure 1. Plot of effect sizes against the inverse of the standard error. When no sampling bias is present, a funnel-shaped distribution is expected.

Results

Database Characteristics

In total, 491 cases from 74 papers were examined across 22 impact types. Three different chloride-based road salts were primarily used within the cases: NaCl (n = 359), $MgCl_2$ (n = 43), and $CaCl_2$ (n = 47), with 42 cases examining a mixture of chloride-based road salts. Cases were located primarily in North America (61.7%) and Europe (32.4)%, with only 5.9% of cases from Asia. We did not find any cases from Africa, South America, Australia and Oceania, or Antarctica. 64.2% of cases were aquatic environments and 35.8% were terrestrial environments. Cases included in our analysis were primarily experimental (n = 456), with only 35 observational cases meeting selection criteria. Experimental studies were conducted in both the field and the laboratory; however, all observational studies were conducted in the field. Animals were examined in 208 cases, with 161 cases examining impacts on plants and 4 on bacteria. Forty-eight percent (48%) of cases examined road salt impacts on species, 28% examined impacts on communities, and 24% examined impacts on ecosystems. Eighty-nine (89) animal, plant, and bacteria species were represented across the studies, with the most examined species being wood frog (*Lithobates sylvaticus*; n = 30, records = 12; Table S1) and perennial ryegrass (*Lolium perenne*; n = 19, records = 3; Table S2).

Effect Sizes

Heterogeneity in effect sizes across all studies was very large (Q_T(df = 486) = 8898.0071, $p < 0.0001$). There was a substantial amount of variance among impact types (Q_M(df = 20) = 58.9846, $p < 0.0001$) as well as within impacts types (Q_E(df = 464) = 8617.5233, $p < 0.0001$). There was a significant decrease in plant fitness (28.7%), animal fitness (39.1%), animal production (biomass) (5.2%), and animal abundance (34.4%) at the local and community levels. At the ecosystem level, combined soil and water pH (8.6%), and soil moisture (5.3%) significantly decreased in treatments containing chloride-based road salts (Figure 2). All other impact types had non-significant effect sizes as their 95% confidence intervals overlapped with zero.

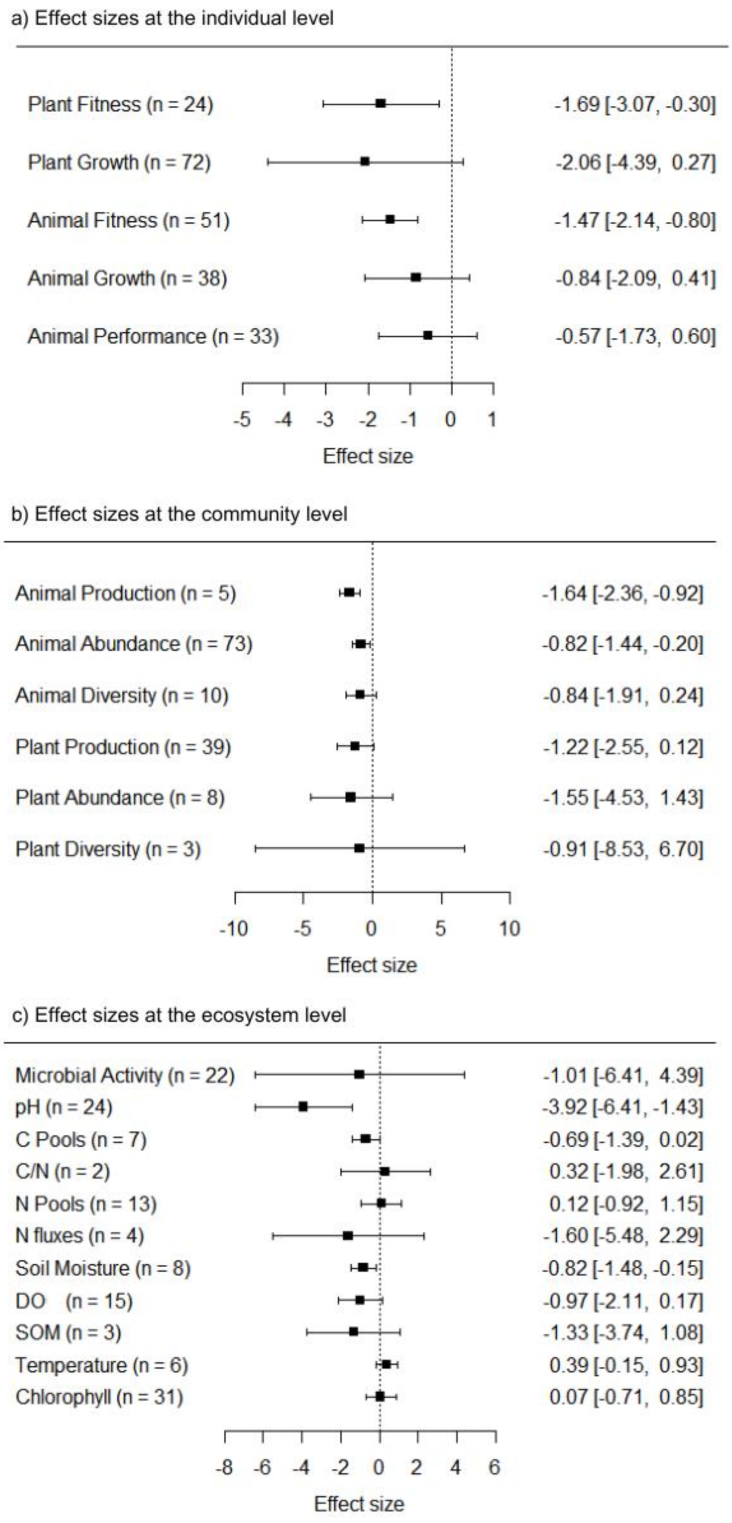

Figure 2. Mean effect size (Hedge's d) of impacts of chloride-based road salt on a) individuals, b) communities, and c) ecosystems. Lines indicate 95% confidence intervals and sample sizes are indicated in parentheses beside the impact type. The values of the effect sizes and confidence intervals are located to the right of the figure.

The three impact types with sample sizes n > 50 (animal fitness, plant growth, and animal abundance) were tested against the moderators. All animal abundance and animal fitness cases were aquatic and experimental, and all plant growth cases were terrestrial, therefore only salt type and study length were tested for moderating effects against all three impact types, with study type tested only against plant growth cases. Study type was a significant moderator of plant growth impacts (p = 0.0019), with negative effects shown in experimental but not observational studies. Salt type and study length did not significantly moderate the three tested impact types.

Effect sizes were examined at the Class level for animals and by functional group for plants, to see which types of species were being most affected by road salting. For animals, branchiopods, copepods, insects, and ostracods were significantly impacted by road salt across all impact types (Figure 3). For plants, most functional groups saw negative impacts, with species in the algae, forb, graminoid, hydrophyte, shrub, and tree functional groups significantly impacted by road salt across all impact types, but not herbs, which was not significant likely due to small sample size (n = 2; Figure 4).

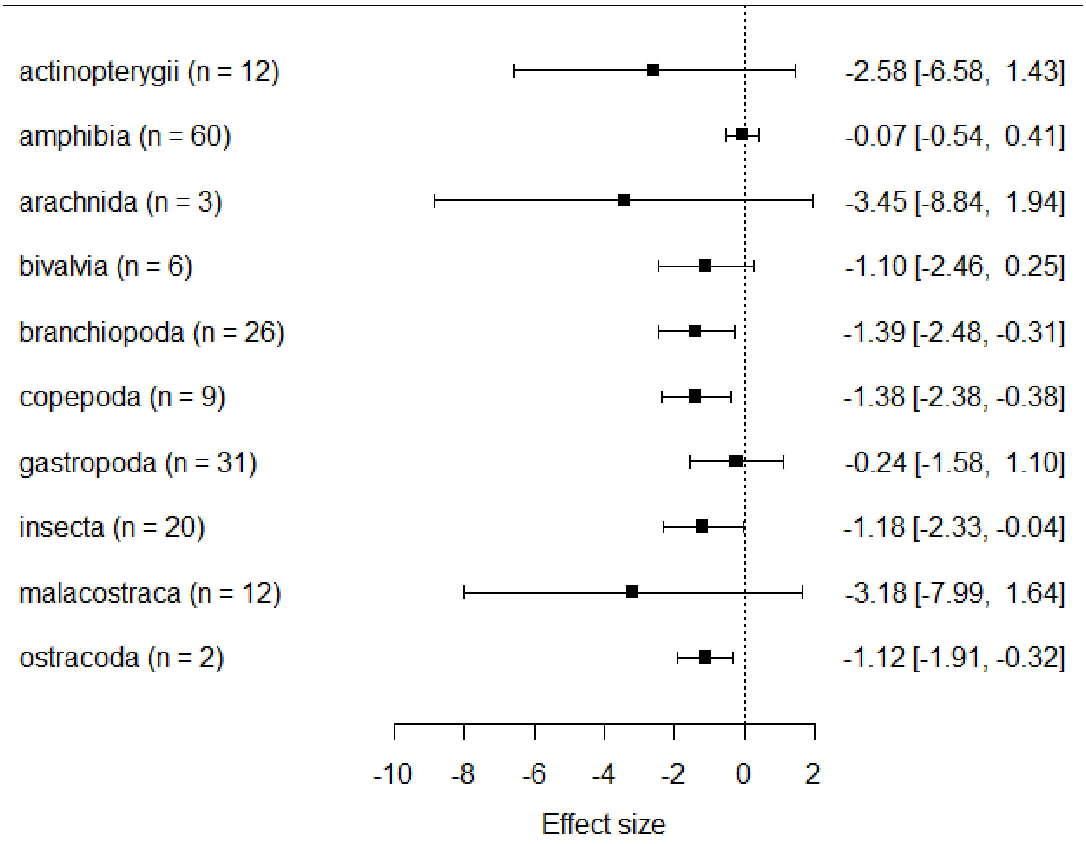

Figure 3. Effect sizes and confidence intervals across all impact types for which there was data for different animal classes. Lines indicate 95% confidence intervals and sample sizes are indicated in parentheses beside the impact type. The values of the effect sizes and confidence intervals are located to the right of the figure.

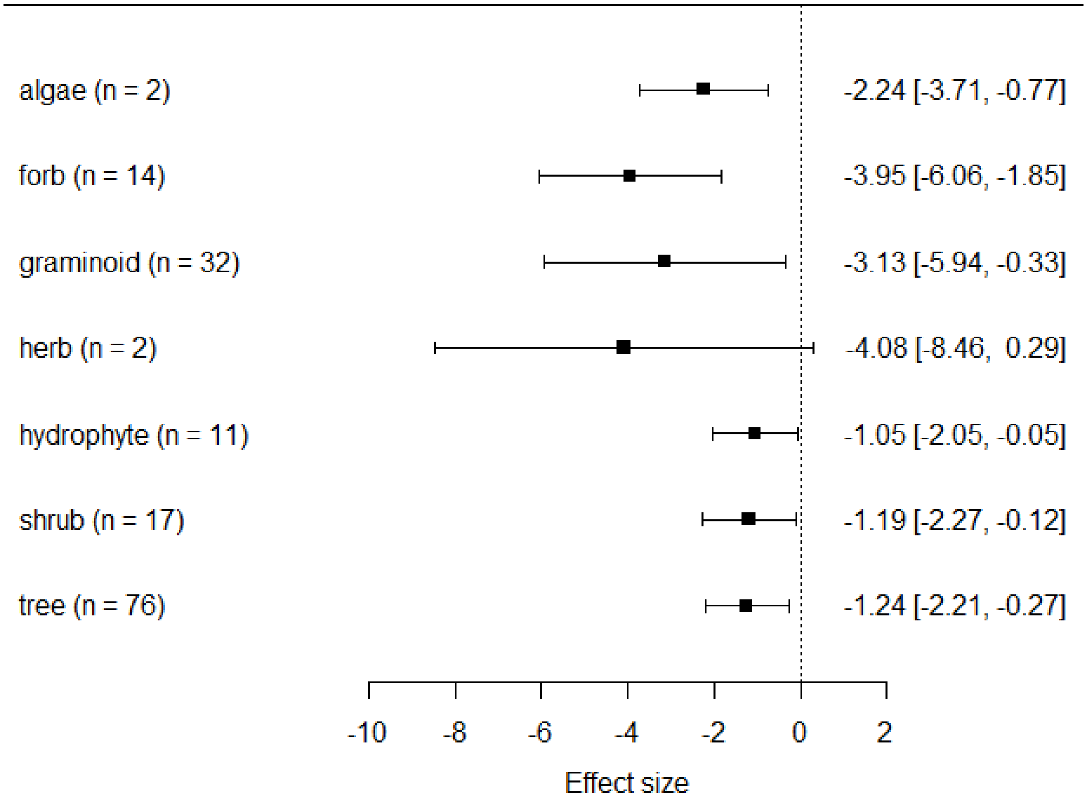

Figure 4. Effect sizes and confidence intervals across all impact types for which there was data for different plant functional groups. Lines indicate 95% confidence intervals and sample sizes are indicated in parentheses beside the impact type. The values of the effect sizes and confidence intervals are located to the right of the figure.

Discussion

Impacts across Ecological Scales

Effects of road salt can vary across ecological scales. It has previously been unclear which ecosystems and organisms tend to be most strongly impacted. Our meta-analysis allowed us to address these knowledge gaps. We found ample evidence in the literature that road salting has negative impacts on individuals, communities, and ecosystems. Overall impacts on plants and animals included a 28.7% decrease in plant fitness, a 39.1% decrease in animal fitness, a 5.2% decrease in animal production, and a 34.4% decrease in animal abundance (Figure 2). At the ecosystem level, combined soil and water pH decreased by 8.6% and soil moisture decreased by 5.3% in the presence of chloride-based road salts. Our analysis found that the effect of chloride-based road salts on ecosystems was overall less negative than those on individuals and communities. Contrary to our hypothesis that communities would be impacted the most by road salting, the greatest impacts were found at the individual level. This suggests that many of our findings are in line with what has been suggested in previous primary studies and qualitative reviews, including significant negative impacts on plant and animal fitness and animal abundance (Tiwari and Rachlin, 2018; Hintz and Relyea, 2019). However, wide variation found within other impact types, especially those that contain larger numbers of cases, suggest that findings may not be consistent across primary literature, possibly due to differences in study methodology.

Water and soil pH decreased in road salt treatments compared to controls. Most records of pH included in the analysis were included as background data rather than trying to investigate pH specifically, so previous conclusions were mostly indirect. The few studies discussing impacts on pH previously suggested an increase in both soil and water pH due to road salting (Young et al., 2012; Kaushal et al., 2018). Although the pH of many aquatic ecosystems appears to be trending upwards in recent years (Bunbury et al., 2020; Webster et al., 2021), our analysis suggests that road salts could be associated with the acidification of urban soils and watersheds, although in field studies, acidity could also be affected by long term acid rain deposition.

We examined effect sizes at the class level for animals and by functional group for plants. Road salt significantly impacted branchiopods, copepods, insects, and ostracods across all impact types (Figure 3). For plants, species in the algae, forb, graminoid, hydrophyte, shrub, and tree functional groups were significantly negatively impacted by road salt across all impact types

(Figure 4), with only herb species not being significantly impacted, although that is likely due to only having two samples rather than it not being impacted. This suggests that herbs, which we have few studies researching, should be the focus of further study and management. Our systematic review of the primary literature found that there is a lack of research on the impacts of road salts on terrestrial animals. Forty-seven (47) animal and 41 plant species were studied in the literature. Of the animal phylums, 20 Arthropoda, 14 Chordata, 11 Mollusca, and 1 Platyhelminthes species were studied in the primary literature. The most studied animal classes were amphibians (11 species with 60 cases across 25 records), insects (11 species, 20 cases, 12 records), and gastropods (7 species, 30 cases, 10 records). Of the plant orders, Alismatales (water plantains; 7 species, 9 cases, 7 records), Poales (including grasses, bromeliads, and sedges; 8 species, 32 cases, 10 records), and Sapindales (including maples; 5 species, 16 cases, 6 records) were most recorded. The species that were the most represented in primary literature were *Lithobates sylvaticus* (n = 30, records = 12) and *Lolium perenne* (n = 19, records = 3; Table 4). Soil biota, mammals, and birds were all underrepresented in the literature. The lack of studies on soil biota was not surprising, given that soil biodiversity and ecological impacts are understudied globally (Cameron et al., 2018), however the lack of research on mammals and birds was particularly interesting, as Titley et al (2017) found that mammals were overrepresented in biodiversity literature, making up around 0.4% of known animal species but being studied in approximately 12% of biodiversity papers. Similar numbers were found for birds, making up around 0.7% of known animal species but encompassing 13% of biodiversity literature (Titley et al., 2017). Although road salt impacts may be of less concern for mammal and bird species as many do not live in salinized water or soils, they may be affected through trophic cascades and should still be studied in further detail.

Effects of Moderators

The lack of moderating impacts of salt type suggests that despite previous studies indicating that $MgCl_2$ and $CaCl_2$ may be more harmful for the environment than NaCl (Coldsnow & Relyea, 2021; Harless et al., 2011), they may be having similar effects when accounting for other possible moderating effects. Study type was a significant moderator of plant growth, suggesting that plants grown in experimental studies showed higher impacts of road salting than those naturally impacted in the environment, which could be due to potentially higher rates of application of road salt in experimental studies. However, further research is required due to the low sample size of observational studies obtained. The variation in observational studies could also be a result of increased environmental noise which was possibly controlled within experimental studies, or due to the attenuation of impacts across more ecosystem components.

Conclusions

Our analysis has highlighted the consistent negative impacts of chloride-based road salts across ecological scales, with individual level effects being the most negative. Branchiopods, copepods, insects, and ostracods were the animal classes significantly affected, and only herb plants were not affected of the plant functional groups, although again this is likely more due to sample size than not being affected. Despite previous studies showing differences between salt types, our analysis showed no such differences with NaCl, $CaCl_2$, $MgCl_2$, and mixtures all having similar negative effects. We also found that the current primary literature focuses only on a small range of impacted species, and further research should be completed to more fully understand the complex effects of road salt on individuals, communities, and ecosystems. This research is useful for the continued monitoring and mitigation of road salting in northern countries and highlights the need for a reduction in the use of chloride-based road salts.

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Supplementary Tables

Supplementary Table 1. List of animal species included in the meta-analysis, their phylum and class, and the number of records and cases examining each species. Some records examined multiple species and thus were included more than once.

Record Count	Case Count	Species (or listed classification)	Phylum	Class
1	3	*Amblyomma maculatum*	Arthropoda	Arachnida
1	1	*Amphipod*	Arthropoda	Malacostraca
2	3	*Anadonta anatina*	Mollusca	Bivalvia
1	1	*Anax junius dragonfly larvae*	Arthropoda	Insecta
1	2	*Anaxyrus americanus*	Chordata	Amphibia
1	1	*Arthropod*	Arthropoda	
1	1	*Bufo melanostictus*	Chordata	Amphibia
1	1	*Capnia sp.*	Arthropoda	Insecta
1	2	*Ceriodaphnia dubia*	Arthropoda	Branchiopoda
1	1	*Chironomidae*	Arthropoda	Insecta
1	6	*Chironomus dilutus*	Arthropoda	Insecta
2	5	*Chironomus riparius*	Arthropoda	Insecta
1	1	*Cladoceran*	Arthropoda	Branchiopoda
1	1	*Copepod*	Arthropoda	Copepoda
1	1	*Culex restuans*	Arthropoda	Insecta
1	11	*Daphnia dentifera*	Arthropoda	Branchiopoda
1	1	*Diamesinae*	Arthropoda	Insecta
1	1	*Ephemeroptera*	Arthropoda	Insecta
1	1	*Fejervarya limnocharis*	Chordata	Amphibia
1	6	*Helisoma trivolvis*	Mollusca	Gastropoda
1	1	*Hyla versicolor*	Chordata	Amphibia
1	1	*Kaloula pulchra*	Chordata	Amphibia
12	30	*Lithobates sylvaticus*	Chordata	Amphibia
2	6	*Lymnaeidae*	Mollusca	Gastropoda
1	1	*Microhyla ornata*	Chordata	Amphibia
1	5	*Moina macrocopa*	Arthropoda	Branchiopoda
1	2	*Musculium transversum*	Mollusca	Bivalvia
1	1	*Notropis bifrenatus*	Chordata	Actinopterygii
2	8	*Oncorhynchus mykiss*	Chordata	Actinopterygii
1	1	*Ostracod*	Arthropoda	Octracoda
1	1	*Physa acuta*	Mollusca	Gastropoda
1	6	*Physa pomillia*	Mollusca	Gastropoda
2	4	*Physidae*	Mollusca	Gastropoda
1	5	*Planorbidae*	Mollusca	Gastropoda
1	1	*Plecoptera*	Arthropoda	Insecta
1	1	*Polypedates megacephalus*	Chordata	Amphibia

2	5	*Rana clamitans*	Chordata	Amphibia
2	7	*Rana temporaria*	Chordata	Amphibia
1	1	*Rhithrogena sp.*	Arthropoda	Insecta
1	3	*Salmo salar*	Chordata	Actinopterygii
1	1	*Sphaeriidae*	Mollusca	Bivalvia
2	10	*Taricha granulosa*	Chordata	Amphibia
2	3	*Trematode*	Platyhelminthes	Trematoda
1	1	*Trichoptera*	Arthropoda	Insecta
2	2	*Viviparus georgianus*	Mollusca	Gastropoda

Supplementary Table 2. List of plant species included in the meta-analysis, their functional grouping, and the number of records and cases examining each species. Some case studies examined multiple species and thus were included more than once.

Record Count	Case Count	Species	Functional group
1	35	*Abies alba*	Tree
1	1	*Acer campestre*	Tree
2	3	*Acer platanoides*	Tree
1	2	*Acer pseudoplatanus*	Tree
1	8	*Acer saccharinum*	Tree
1	2	*Aesculus hippocastanum*	Tree
2	11	*Arctostaphylos uva-ursi*	Shrub
1	8	*Aster sphathulifolius*	Forb
1	2	*Canna x generalis*	Forb
1	1	*Ceratophyllum demersum*	Hydrophyte
1	1	*Commelina communis*	Herb
1	1	*Cyperaceae sp.*	Graminoid
1	1	*Digitaria sanguinalis*	Graminoid
1	3	*Elodea*	Hydrophyte
1	1	*Elodea canadensis*	Hydrophyte
1	1	*Elodea nuttallii*	Hydrophyte
1	2	*Euonymus fortunei*	Shrub
1	2	*Fagus sylvatica*	Tree
1	2	*Festuca pratensis Huds*	Graminoid
1	6	*Festuca rubra*	Graminoid
1	2	*Gelsemium sempervirens*	Forb
1	1	*Glyceria grandis*	Graminoid
1	5	*Larix decidua*	Tree
3	19	*Lolium perenne*	Graminoid
1	1	*Myriophyllum spicatum*	Hydrophyte
1	1	*Najas flexilis*	Hydrophyte
1	2	*Nitella sp.*	Macroalgae
1	1	*Persicaria nodosa*	Herb
1	1	*Pinus densiflora*	Tree
1	4	*Pinus sylvestris*	Tree

1	1	*Potamogeton robbinsii*	Hydrophyte
1	11	*Quercus robur L.*	Tree
1	2	*Rosa rugosa*	Shrub
1	1	*Scirpus Validus*	Graminoid
1	1	*Sium suave*	Forb
1	1	*Stuckenia pectinata*	Hydrophyte
1	2	*Tilia cordata*	Tree
1	2	*Trachelospermum asiaticum*	Shrub
1	1	*Typha augustifolia*	Graminoid
1	1	*Vaccinium myrtillus L.*	Shrub

CHAPTER 3. THE INFLUENCE OF ROAD SALT ON SOIL MINERAL CONTENT OF WETLANDS, HALIFAX, NOVA SCOTIA, CANADA.

Abstract

The use of chloride-based deicing salts to clear roads of ice has been widespread in countries in northern latitudes since the late 1930s. Although advantageous for road safety, these salts can have extensive and long-term impacts on the environment. Increases in chloride and salinity in lakes in Halifax, Nova Scotia have been well documented from the 1950s onwards, but impacts on wetlands and soil have yet to be examined in the region. In Halifax, snow meltwater from sidewalks and roadways is drained through pipes and in some areas outfall directly into the city's freshwater resources, including wetlands. The aim of this study was to investigate the impacts of road deicing salts on soil chemistry within urban wetlands in Halifax. Wetland sites (n = 15) across the region were selected, five with direct outfall drainage, five roadside, and five control sites. At each plot, soil samples were collected at 1 m, 5 m, and 15 m from the input source (stormwater drain, roadside wetland edge, or water inflow) at 0-10 cm and 10-20 cm depths, and each location and depth was sampled in triplicate (n = 270). Using mixed-effects models and principal component/redundancy analysis, I examined whether the direct input of road salts through stormwater drainage outfalls had a greater influence on the salinity and element (Na^+, Ca^{2+}, Cu^{2+}, Zn^{2+}, Al^{3+}) content of wetland soils than indirect inputs from roadways. I found no significant differences in salinity between input types, including control types, suggesting that there are other factors influencing salinity at these sites. Mean levels of chloride related to salinization were above toxicity guidelines for all 15 wetlands sampled in the region, including

control sites, suggesting that road salt needs to be better mitigated to protect Halifax's wetland ecosystems.

Introduction

Freshwater wetlands are being degraded at a higher rate than other ecosystems, with urbanization strongly influencing salinization due to the use of road deicing salts (Millenium Ecosystem Assessment, 2005; Kaushal et al., 2018). The use of chloride-based deicing salts to clear roads of ice has been widespread in countries in northern latitudes since the late 1930s (Kelly et al., 2010). Although beneficial for road safety and cost-effective, deicing salts have been found to have extensive and long-term impacts on aquatic and terrestrial species and ecosystems (Environment and Climate Change Canada, 2001). In Canada, it is estimated that about 4 million tonnes of road deicing salt are used every winter, leading to the release of 3 million tonnes of chloride into the environment (Environment Canada, 2018). Of this, between 75-90% of added salts may enter roadside environments via runoff or splashing (Norrstrom & Bergstedt, 2001). Ontario, Quebec, and the Maritime provinces (Nova Scotia, New Brunswick, and Prince Edward Island) have the highest usage of sodium chloride, and Nova Scotia has the highest chloride loadings per unit area of land (Environment Canada and Health Canada, 2001).

Halifax is the capital city of the province of Nova Scotia, and the largest municipality in Atlantic Canada, with an estimated population of 480,582 in 2022 (Statistics Canada, 2023). In Halifax, sodium chloride ($NaCl$) is primarily used for winter deicing due to its effectiveness, ease of use, and low cost. It is used as rock salt, as brine composed of a 23% salt solution, or is mixed with sand (Halifax Regional Municipality, 2022). In other jurisdictions, deicing solutions may also be comprised of magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), or potassium chloride (KCl) (Environment Canada and Health Canada, 2001). Between 1997 and 1998, around 370,000 tonnes of sodium chloride were applied to roads in Nova Scotia (Environment Canada and Health Canada, 2001), with around 41,000 tonnes used in the city of Halifax. The increase in chloride and salinity in lakes has been well documented in the region from the 1950s onwards (e.g., Gorham, 1957; Watt et al., 1979; Clement et al., 2007; and Clement et al., 2019). In 1955, twenty-three lakes in the Halifax area were surveyed (Gorham, 1957), which provided information on the natural background levels of chloride as road salt was not used in Nova Scotia before 1958 (Ginn et al., 2015). When the same lakes were resurveyed in 1977, they had an average increase in chloride concentrations of 172% (or 9.3 mg/L), presumably due to road deicing salts (Watt et al., 1979). Synoptic water quality surveys took place in 1980, 1991, 2000, and 2011, which showed a mean chloride increase of almost 200% between 1980 and 1991 and further significant increases from 1991 to 2011, particularly for lakes in developed watersheds (Clement et al., 2019). At a provincial level, the Nova Scotia Lake Survey Program by the Nova Scotia Department of Environment and Climate Change in partnership with the Nova Scotia Department of Fisheries and Aquaculture conducts water quality monitoring at lakes across the province. In 2022, a lake water quality program called LakeWatchers was announced by the municipality of Halifax for the biannual monitoring of 76 lakes in the region (Halifax, 2022).

Although the water quality of lakes in the region is monitored at both the federal and provincial levels, with municipal monitoring in the future, there are still limitations to monitoring road salting in the municipality. In 2020, the municipality retained AECOM Canada Ltd. to aid in the development of a water quality monitoring policy and program (AECOM Canada Ltd., 2020). The report found that the municipality conducted water quality monitoring on an as-needed reactionary basis, which has considerable downsides, including inconsistent sampling protocols and quality controls, and a lack of background data (AECOM Canada Ltd., 2020). The water quality monitoring undertaken to date provides a comprehensive overview of changes to lake chloride levels which can be compared to CCME guidelines for toxicity, but this is not necessarily linked to road salt locations. Wetlands, rivers, and soils are also ecosystems which are being significantly impacted by road salting, however, environmental quality is not being monitored in non-lake environments. Although water quality surveys can provide insight into chloride pollution in Halifax, only one study has been published to date on road salt impacts. That study found that amphibian community structure and species richness were altered in road salt-affected wetlands within Nova Scotia (Collins and Russell, 2009).

As of 2022, the municipality of Halifax does not publish a road salt management plan for the management of road salt deposition and runoff. There is little snow removal within the municipality, with roadway meltwater being channeled to storm sewers (Environment Canada and Health Canada, 2001). While storm drain locations vary across the city, stormwater contaminated with road salts and other anthropogenic pollution is known to be drained directly into wetlands and lakes within the region (Halifax Water, 2021). There are approximately 344 stormwater outfalls across the city, with at least 206 located within 10 m of a watercourse (Halifax Water, 2021). In Halifax, the spraying of liquid brine (consisting of 23% sodium chloride solution) may reduce salt usage by ~80% (Halifax, 2022). Pre-wetting is also used in the municipality, which covers dry salt in 23% brine solution before leaving application trucks, causing the salt to adhere better to the road surfaces, which may result in less direct salt spray onto roadsides (Halifax, 2022). Prewetting is a mitigative strategy that helps to lower the amounts of salts needed by adding liquid chemicals to solid salts, helping them adhere to the road and preventing salt spray, thereby increasing the amount of salt that stays on the road. The

Michigan Department of Transportation found a 27% reduction in salt loss on roads with prewet salts compared to dry salts (MDOT, 2012).

Wetland ecosystems contribute to a myriad of ecosystem services, including but not limited to climate regulation, carbon sequestration, recreational uses, and buffering of contaminants for ground and surface water (Millennium Ecosystem Assessment, 2005). Although the impacts of road de-icing salts on wetlands are not as well documented as their impacts on lakes, rivers, and other freshwater environments, wetlands in urban areas are known to be particularly affected by road de-icing salts. Hill and Sadowski (2016) found that in Ontario, Canada, wetlands in urban areas met or surpassed chronic water quality thresholds of chloride concentration for negative impacts on aquatic organisms, and that road deicing salts were the primary cause of contamination in urban wetlands. A major knowledge gap in the study of road salting impacts is the effects on wetland soils, and research on the mechanisms of the effects of road salts on urban wetland biogeochemistry is particularly lacking (Kinsman-Costello et al. 2023). The addition of road de-icing salts may affect both metals and nutrients cycling in wetland soils; NaCl decreased pH and increased Mn^{2+}, Fe^{2+}, Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} concentrations in laboratory tests (Kim and Korestky, 2013). The ability of wetland soils to buffer downstream lakes and rivers against chloride is variable, and most likely limited to low concentrations of salt, which is important since a major ecosystem service of wetlands is to retain pollutants and prevent the transport of those pollutants downstream (McGuire & Judd, 2020). Nitrate nitrogen (NO_3-N) is a key nutrient that is buffered by wetlands; however, wetland soils contaminated with acute chloride concentrations have been found to have reduced denitrification rates (Lancaster et al., 2016). Road salt contamination can also alter wetland soil structure, particularly at the surface level, increasing soil moisture and reducing the amount of filtration wetlands provide (Walker et al., 2021).

The salinization of inland waters has been strongly correlated to the amount of impervious surface coverage such as roads and sidewalks (Kaushal et al., 2018). In areas where road salts can be attributed to one source point (i.e., a single road or highway), impacts of salts have been found to decrease with distance from roads, with the highest impacts being seen within 10 m of the road (Bäckström et al., 2004). In urban areas however, where the density of paved areas such as roads and sidewalks are higher, soil chloride concentrations can be highly variable (Cunningham et al., 2008). How road salts enter an ecosystem can also change its effects, with Helmueller et al. (2020) finding that storm outfalls played a significant role in chloride levels compared to road runoff, and that chloride levels were higher near outfalls.

In roadside soils, chloride adversely affects soil fertility, soil structure and water transport. High concentrations of salts can mobilize heavy metals including mercury and lead, which may contaminate groundwater (Amrhein et al., 1992) and bioaccumulate in food webs (Bäckström et al., 2004). Concentrations of Cd^{2+}, Cu^{2+}, Pb^{2+}, and Zn^{2+} found in roadside soils have been strongly linked to the use of NaCl as a deicer (Bäckström et al., 2004). Increases in soil salinity can lead to alterations in soil structure by deflocculating clay particles within soil and blocking pores (Shannon et al., 2020), which in turn may reduce hydraulic conductivity (Norrström and Bergstedt, 2001). The application of road salts increases the electrical conductivity of soils as the salts dissolve in the ground (Shannon et al., 2020). A strong negative correlation exists between increases in electrical conductivity and soil pH (Bäckström et al., 2004). Soil cation exchange capacity has also been found to decrease with accumulating road salt (Ke et al., 2013), and changes in cation concentrations and cation exchange capacities may disrupt various biogeochemical cycles (Norrström and Bergstedt, 2001). Chloride concentrations have been found to be highest at the point of road salt deposition, with a secondary spike in mid-summer when water evaporates (Environment Canada and Health Canada, 2001). Along roadsides, splashing may accelerate the leaching of NaCl through the soil, which could have deleterious effects on soil aggregation (such as soil clay and silt dispersion) and lead to reduced soil infiltration rates, causing enhanced soil erosion and dispersion (Environment Canada and Health Canada, 2001).

Here, I investigate the impacts of NaCl road salt on the chemical attributes of surface organic soils within select urban wetlands in Halifax to understand the influence of: 1) input type (i.e. proximity to a road vs outfall); 2) distance to source; and 3) relationship between salinity and soil chemistry. Al^{3+} was identified for study as it has been found to be toxic to plants in acidic soils (Panda et al., 2009). Cu^{2+}, Zn^{2+}, and Na^{+} are all essential nutrients for plant growth, but over certain levels are also toxic for soil biota and plant health (see Shabbir et al., 2020; Kaur and Garg, 2021; CCME, 2011). Ca^{2+} was chosen because it is an essential nutrient for plant health and can potentially alleviate mineral toxicity (Kinraide, 1998).

We hypothesize that salinity will be highest in soils at outfall sites as Helmueller et al. (2020) found that storm outfalls played a significant role in chloride levels compared to road runoff. The proximity to point-sources of deicing salts, i.e. stormwater outfalls, will also likely affect the upper layers of soils more than deeper layers (Ke et al., 2013). A meta-analysis (see Chapter 2) found a 5.9% reduction in pH in sites treated with road salt versus control sites, therefore we hypothesized that sites with higher salinities would also have a lower pH. We also hypothesized that wetlands with more road salt influence would have a greater concentration of Al^{3+}, Cu^{2+}, Zn^{2+}, and Na^{+}, as Kim & Koretsky (2013) found that road salts can contribute to metal contamination in wetland soils, and Granato et al. (1995) found higher concentrations of Al^{3+}, Cu^{2+}, Zn^{2+}, Ca^{2+}, and Na^{+} in high-chloride groundwater. Knowledge of how road salt influences wetlands is important for urban planning in Halifax, as it allows managers and policymakers to make informed decisions on road salt amounts and salting areas to balance environmental protection and road safety. This analysis may also help to identify vulnerable wetland ecosystems within the region which may benefit from reduced salting or even temporary sanding measures.

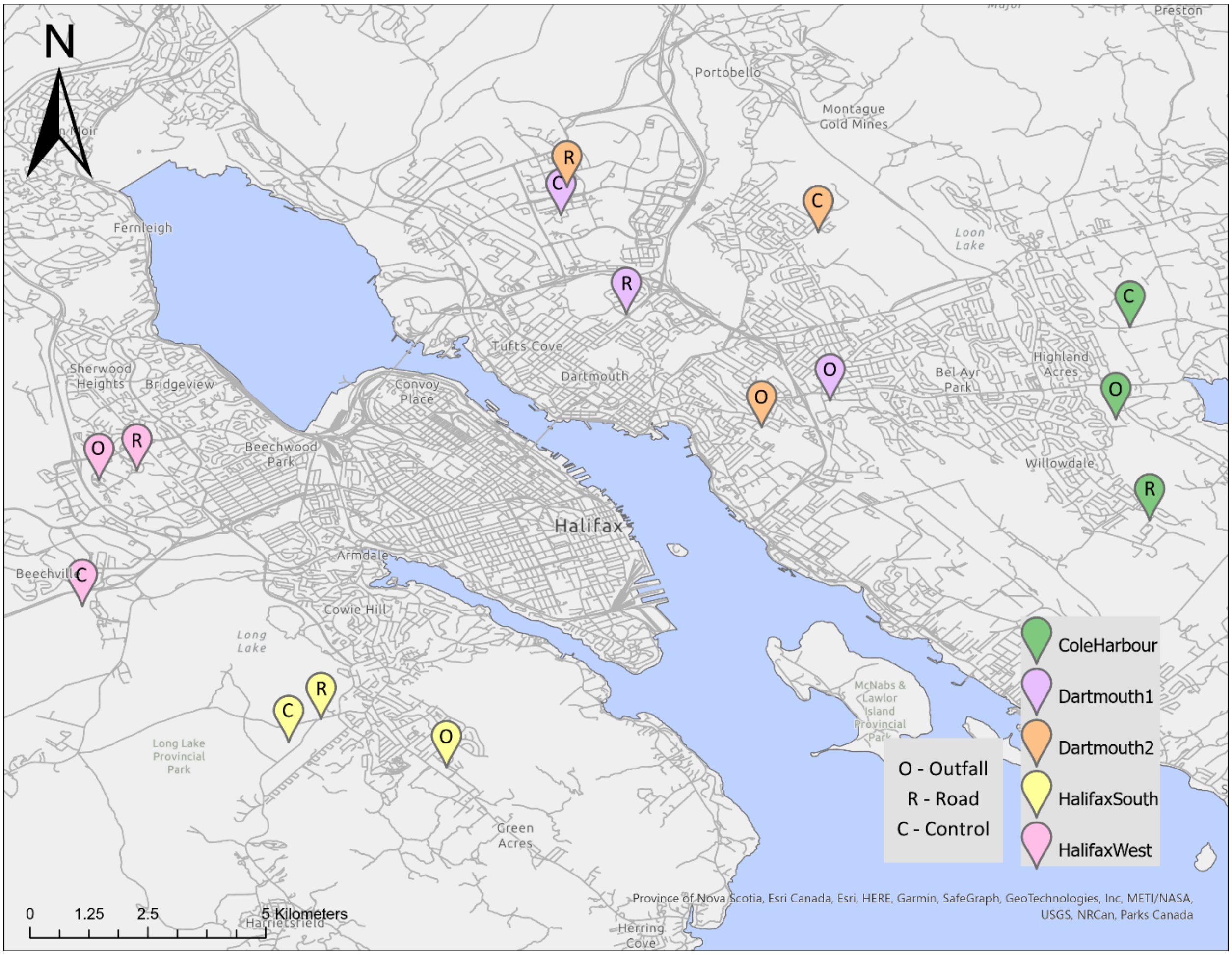
Methods

Site Selection

Sites were selected in Halifax, Nova Scotia using ArcGIS Pro 2.9.x (ESRI, 2021). Road data was extracted from the Nova Scotia Roads, Rails, and Trails database (NS Open Data, 2022). The Nova Scotia Wetland Inventory (NS Provincial Landscape Viewer, 2022) was used to identify wetlands, and a dataset was provided by Halifax Water containing locations of stormwater outfalls (Halifax Water, pers. comm). Control sites were chosen by selecting wetlands which were at least 50 m from a roadway. Wetlands were chosen across the city, with control, roadside, and outfall sites being selected in the Halifax (west and south), Cole Harbour, and Dartmouth regions (Figure 2). To select outfall sites, wetland polygons and road lines were both buffered to 30 m and outfall points were buffered to 5 m. The buffered outfall points, wetland polygons, and road lines were then intersected. Locations of sites which intersected (n = 9) were exported and assessed further for suitability. An initial search was completed in Google Earth Pro to ensure sites had not undergone development since the inventory was updated, and field site checks were completed between January and April 2022 to ensure suitability. Of the nine intersected sites, five were suitable for analysis.

Field Sampling

Fifteen wetlands were sampled between May 24 and June 2, 2022 (Figure 1). At each wetland, a 15 m transect was set up running into the wetland from a) the stormwater drainage outflow pipe, b) the wetland roadside edge, or c) the wetland inflow (for control sites). A control, road, and outfall site were chosen across different regions of the city to identify differences in different areas: Cole Harbour (CH), Dartmouth1 = D1, Dartmouth2 = D2, HalifaxSouth = HS, and HalifaxWest = HW. Organic soil samples were collected at 1 m, 5 m, and 15 m from the inflow using a 20 cm auger to 20 cm depth. Only organic soils were sampled to maintain the same soil type across all sites. These soil samples were cut in the field using a serrated knife to separate into 0-10 cm and 10-20 cm depths. At each plot, three replicate samples spaced 1 m apart were collected (Figure 3). Soil samples were sent to the Nova Scotia Department of Agriculture Animal and Plant Laboratory for chemical analysis of exchange ion concentrations for Ca^{2+} (kg/ha), Na^{+} (kg/ha), Cu^{2+} (ppm), Zn^{2+} (ppm), and Al^{3+} (kg/ha) and tested at Saint Mary's University for electrical conductivity and pH.



Province of Nova Scotia, Esri Canada, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, NRCan, Parks Canada

Figure 1. Map of wetland sampling sites (n = 15) in Halifax, Nova Scotia, Canada. Sites are differentiated by region (in colour) and by road salt dispersal method, including 5 sites with stormwater drainage outfalls (O), 5 with indirect road salt spray (R), and 5 sites over 50m from a road as controls (C). ColeHarbour = CH, Dartmouth1 = D1, Dartmouth2 = D2, HalifaxSouth = HS, and HalifaxWest = HW.

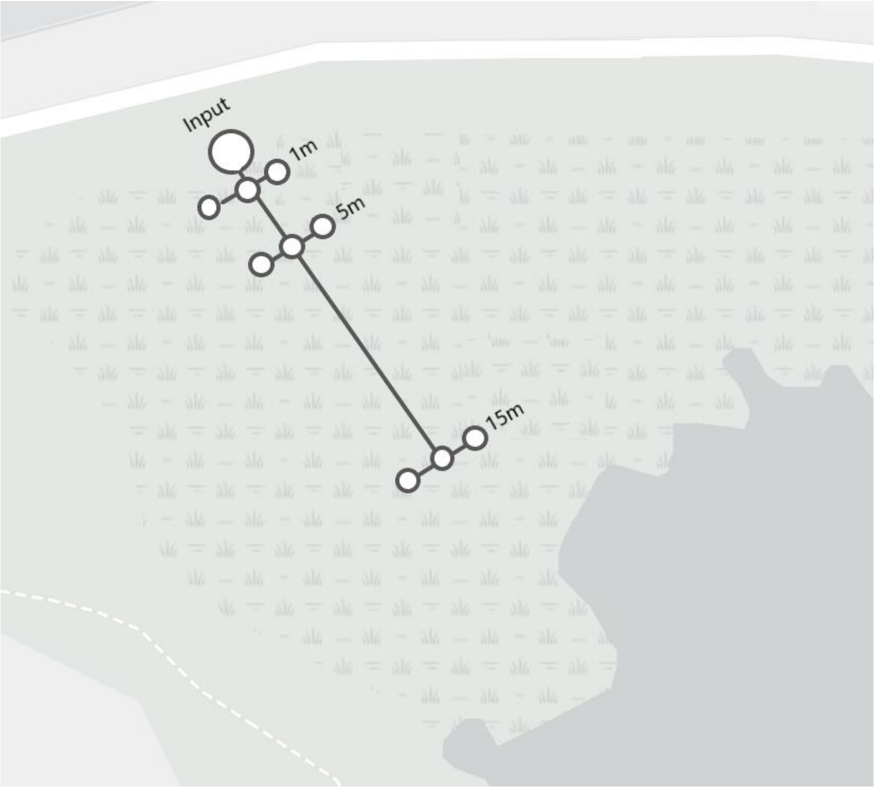


Figure 3. Diagram of wetland sampling methods. At each of the 15 sites, a 15 m transect was set up from the road salt input (storm drain for outfall sites, closest road edge for road sites, or stream input for control sites). Samples were collected at distances of 1 m, 5 m, and 15 m from the inflow at a depth of 0-20 cm and split between 0-10 cm and 10-20 cm. Three replicates spaced 1 m apart were collected at each distance for a total of 18 samples per site.

Laboratory Analysis

Samples were thoroughly mixed and air dried for 48 hours, and then crushed and sieved using a 2 mm sieve. At the Nova Scotia Department of Agriculture Animal and Plant Laboratory, sampled were analysed using the Mehlich III Extractable Major and Trace Metal Ions method through Inductively Coupled Plasma Optical Emission spectroscopy (ICP-OES). To measure pH and electrical conductivity at Saint Mary’s University, we added 2.0 (± 0.05) grams of soil to a labelled tube. Eight (8) mL of deionized water was added to each sample based on a protocol by Kalra and Maynard (1991), and the samples were shaken for 30 seconds every 5 minutes for 30 minutes, and then left to settle for an hour. Samples were then tested for pH and electrical conductivity using a ThermoScientific Orion Star A215 pH/Conductivity meter.

Statistical Analysis

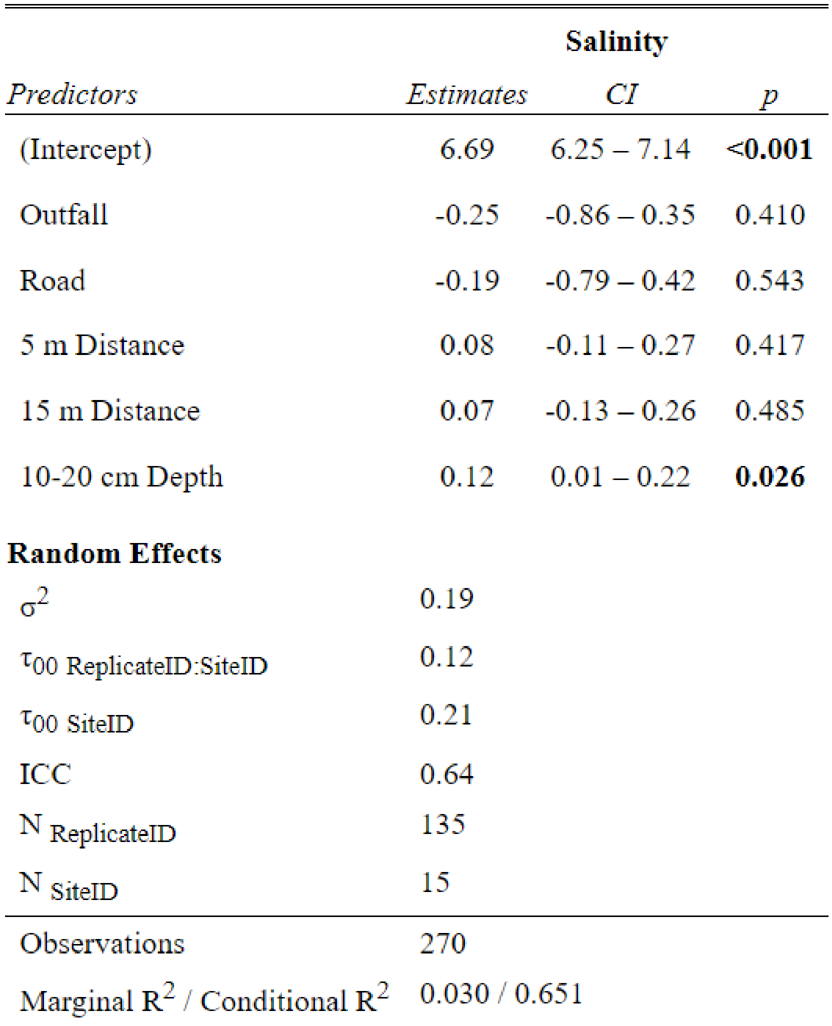
Soil salinity was calculated by using the following equation: salinity (mg/L or ppm) = EC (dS/m) x 640 (EC from 0.1 to 5 dS/m) (University of California, 2023). As 9 % (n = 26 out of 270) of the Cu^{2+} data was under the limit of detection (LOD), we used LOD/$\sqrt{2}$ to substitute (see Croghan and Egeghy, 2003). Samples measured in kg/ha were divided by 2 to convert to ppm (NSDA Laboratory Services, pers. comm). To meet normality assumptions, salinity, Na^{+}, Al^{3+}, Ca^{2+}, Cu^{2+}, and Zn^{2+} concentration measurements were ln-transformed + 1. To understand how road salt dispersal mechanisms, distance from the road salt input, and soil depth affect wetland soil salinity, a mixed effects model was run with the natural log +1 transformed salinity as the response variable and input type (outfall, road, or control), distance, and depth as predictor variables. Random effect variables were included to account for variation within replicates and sites, with a nested design as all replicates are within a site. To explore how salinity is related to the chemical composition of soils in these wetlands, we used redundancy analysis (RDA) to find trends in soil chemistry. Redundancy analysis is useful for finding the best explanatory variables and for examining the groups against a single explanatory variable (salinity). We then conducted an analysis of variance (ANOVA) of the redundancy analysis by axis to compare trends to salinity. We also used an analysis of similarities (ANOSIM) test to examine other possible factors affecting soil chemistry (input type, region, distance, and depth). ANOSIM uses dissimilarity matrices to compare groups based on similarities. All statistical analysis was undertaken in R 4.3.0 using the *vegan*, *car*, *lme4*, *dplyr*, and *tidyverse* packages (R Core Team 2021).

Results

Impacts of Salt Inflow Type

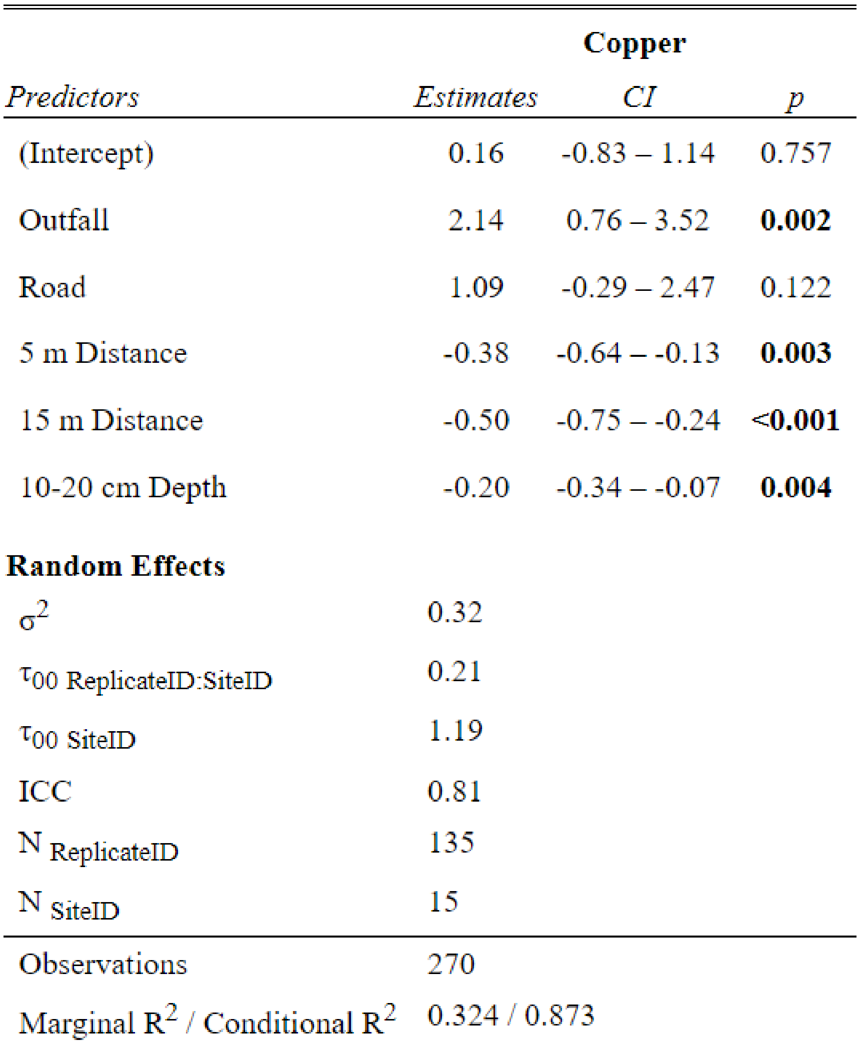
Input type was not a significant predictor of salinity (Table 1), Na^+, pH, Al^{3+}, Ca^{2+}, or Zn^{2+} at any of the wetland sites, but Cu^{2+} was significantly higher at the outfall sites ($t = 3.06$, $p = 0.01$, SE = 0.07; Table 2) compared to control sites.

Table 1. Results of the linear mixed effects model for the effects of road salt input type, distance, and depth on salinity in Halifax wetlands. The intercept is the estimate corresponding to the levels of 'control', '1 m distance', and '0-10 cm depth'. All other estimates are relative to the intercept. σ^2 represents the within-subject variance, and τ_{00} represents the between-subject variance. ICC is the intraclass correlation coefficient which represents the proportion of variance explained by the grouping structure in the population. Marginal R^2 is the variance explained by fixed factors, whereas conditional R^2 is the variance explained by both fixed and random factors.



	Salinity		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	6.69	6.25 – 7.14	**<0.001**
Outfall	-0.25	-0.86 – 0.35	0.410
Road	-0.19	-0.79 – 0.42	0.543
5 m Distance	0.08	-0.11 – 0.27	0.417
15 m Distance	0.07	-0.13 – 0.26	0.485
10-20 cm Depth	0.12	0.01 – 0.22	**0.026**
Random Effects			
σ^2	0.19		
τ_{00} ReplicateID:SiteID	0.12		
τ_{00} SiteID	0.21		
ICC	0.64		
$N_{ReplicateID}$	135		
N_{SiteID}	15		
Observations	270		
Marginal R^2 / Conditional R^2	0.030 / 0.651		

Table 2. Results of the linear mixed effects model for the effects of road salt input type, distance, and depth on Cu^{2+} concentrations in Halifax wetlands. The intercept is the estimate corresponding to the levels of ‘control’, ‘1 m distance’, and ‘0-10 cm depth’. All other estimates are relative to the intercept. σ^2 represents the within-subject variance, and τ_{00} represents the between-subject variance. ICC is the intraclass correlation coefficient which represents the proportion of variance explained by the grouping structure in the population. Marginal R^2 is the variance explained by fixed factors, whereas conditional R^2 is the variance explained by both fixed and random factors.

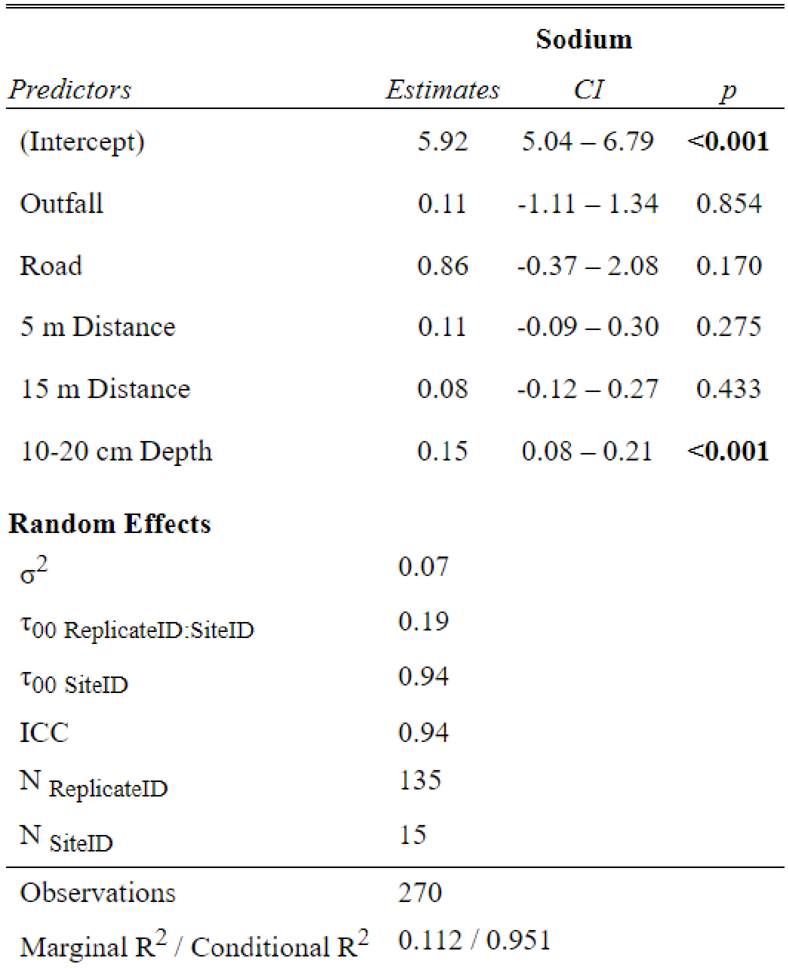


	Copper		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.16	-0.83 – 1.14	0.757
Outfall	2.14	0.76 – 3.52	**0.002**
Road	1.09	-0.29 – 2.47	0.122
5 m Distance	-0.38	-0.64 – -0.13	**0.003**
15 m Distance	-0.50	-0.75 – -0.24	**<0.001**
10-20 cm Depth	-0.20	-0.34 – -0.07	**0.004**
Random Effects			
σ^2	0.32		
τ_{00} ReplicateID:SiteID	0.21		
τ_{00} SiteID	1.19		
ICC	0.81		
$N_{ReplicateID}$	135		
N_{SiteID}	15		
Observations	270		
Marginal R^2 / Conditional R^2	0.324 / 0.873		

Impacts of Distance and Depth

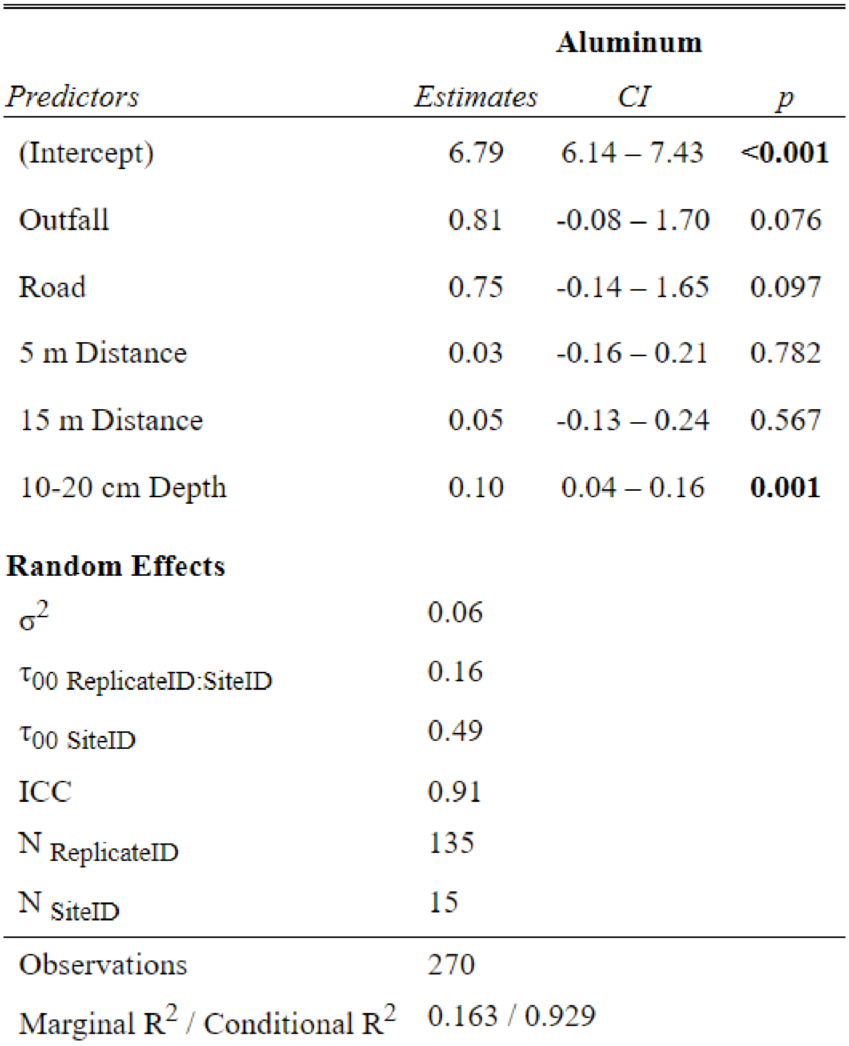
Salinity (t = 2.24, p = 0.03, SE = 0.05), Na^+ (t = 4.63, p = 8.71e-06, SE = 0.03; Table 3), and Al^{3+} (t = 3.41, p = 8.47e-04, SE = 0.03; Table 4) were significantly higher at 10-20 cm than 0-10 cm. Zn^{2+} (t = -5.13, p = 9.98e-07, SE = 0.05; Table 5) and Cu^{2+} (t = -2.95, p = 3.81e-03, SE = 0.07) were significantly lower at 10-20 cm than 0-10 cm. Soil pH (t = -3.43, p = 8.47e-04, SE = 0.09; Table 6) was significantly lower at 15 m from the outfall than 1 m, and Cu2+ was significantly lower at both 5 m (t = -2.98, p = 3.48e-03, SE = 0.13) and 15 m (t = -3.855, p = 1.89e-04, SE = 0.13) from the outfall than 1 m. Salinity, Na^+, Al^{3+}, and Zn^{2+} were not significantly affected by distance from the outfall.

Table 3. Results of the linear mixed effects model for the effects of road salt input type, distance, and depth on Na^+ concentrations in Halifax wetlands. The intercept is the estimate corresponding to the levels of ‘control’, ‘1 m distance’, and ‘0-10 cm depth’. All other estimates are relative to the intercept. σ^2 represents the within-subject variance, and τ_{00} represents the between-subject variance. ICC is the intraclass correlation coefficient which represents the proportion of variance explained by the grouping structure in the population. Marginal R^2 is the variance explained by fixed factors, whereas conditional R^2 is the variance explained by both fixed and random factors.



	Sodium		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	5.92	5.04 – 6.79	**<0.001**
Outfall	0.11	-1.11 – 1.34	0.854
Road	0.86	-0.37 – 2.08	0.170
5 m Distance	0.11	-0.09 – 0.30	0.275
15 m Distance	0.08	-0.12 – 0.27	0.433
10-20 cm Depth	0.15	0.08 – 0.21	**<0.001**
Random Effects			
σ^2	0.07		
τ_{00} ReplicateID:SiteID	0.19		
τ_{00} SiteID	0.94		
ICC	0.94		
$N_{\text{ReplicateID}}$	135		
N_{SiteID}	15		
Observations	270		
Marginal R^2 / Conditional R^2	0.112 / 0.951		

Table 4. Results of the linear mixed effects model for the effects of road salt input type, distance, and depth on Al^{3+} concentrations in Halifax wetlands. The intercept is the estimate corresponding to the levels of ‘control’, ‘1 m distance’, and ‘0-10 cm depth’. All other estimates are relative to the intercept. σ^2 represents the within-subject variance, and τ_{00} represents the between-subject variance. ICC is the intraclass correlation coefficient which represents the proportion of variance explained by the grouping structure in the population. Marginal R^2 is the variance explained by fixed factors, whereas conditional R^2 is the variance explained by both fixed and random factors.



	Aluminum		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	6.79	6.14 – 7.43	**<0.001**
Outfall	0.81	-0.08 – 1.70	0.076
Road	0.75	-0.14 – 1.65	0.097
5 m Distance	0.03	-0.16 – 0.21	0.782
15 m Distance	0.05	-0.13 – 0.24	0.567
10-20 cm Depth	0.10	0.04 – 0.16	**0.001**
Random Effects			
σ^2	0.06		
τ_{00} ReplicateID:SiteID	0.16		
τ_{00} SiteID	0.49		
ICC	0.91		
$N_{\text{ReplicateID}}$	135		
N_{SiteID}	15		
Observations	270		
Marginal R^2 / Conditional R^2	0.163 / 0.929		

Table 5. Results of the linear mixed effects model for the effects of road salt input type, distance, and depth on Zn^{2+} concentrations in Halifax wetlands. The intercept is the estimate corresponding to the levels of ‘control’, ‘1 m distance’, and ‘0-10 cm depth’. All other estimates are relative to the intercept. σ^2 represents the within-subject variance, and τ_{00} represents the between-subject variance. ICC is the intraclass correlation coefficient which represents the proportion of variance explained by the grouping structure in the population. Marginal R^2 is the variance explained by fixed factors, whereas conditional R^2 is the variance explained by both fixed and random factors.

		Zinc	
Predictors	*Estimates*	*CI*	*p*
(Intercept)	1.94	0.91 – 2.98	**<0.001**
Outfall	1.41	-0.04 – 2.86	0.057
Road	1.03	-0.42 – 2.48	0.164
5 m Distance	-0.07	-0.27 – 0.14	0.533
15 m Distance	-0.06	-0.27 – 0.15	0.578
10-20 cm Depth	-0.24	-0.33 – -0.15	**<0.001**
Random Effects			
σ^2	0.15		
τ_{00} ReplicateID:SiteID	0.17		
τ_{00} SiteID	1.33		
ICC	0.91		
N ReplicateID	135		
N SiteID	15		
Observations	270		
Marginal R^2 / Conditional R^2	0.183 / 0.926		

Table 6. Results of the linear mixed effects model for the effects of road salt input type, distance, and depth on pH in Halifax wetlands. The intercept is the estimate corresponding to the levels of ‘control’, ‘1 m distance’, and ‘0-10 cm depth’. All other estimates are relative to the intercept. σ^2 represents the within-subject variance, and τ_{00} represents the between-subject variance. ICC is the intraclass correlation coefficient which represents the proportion of variance explained by the grouping structure in the population. Marginal R^2 is the variance explained by fixed factors, whereas conditional R^2 is the variance explained by both fixed and random factors.

	pH		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	5.01	4.40 – 5.61	**<0.001**
Outfall	-0.36	-1.20 – 0.49	0.407
Road	0.33	-0.51 – 1.17	0.442
5 m Distance	-0.16	-0.34 – 0.01	0.062
15 m Distance	-0.30	-0.47 – -0.13	**0.001**
10-20 cm Depth	-0.01	-0.07 – 0.06	0.799
Random Effects			
σ^2	0.08		
τ_{00} ReplicateID:SiteID	0.14		
τ_{00} SiteID	0.44		
ICC	0.88		
N ReplicateID	135		
N SiteID	15		
Observations	270		
Marginal R^2 / Conditional R^2	0.126 / 0.899		

Impacts of Salinity on Soil Chemistry

The Analysis of Variance (ANOVA) of the redundancy analysis by axis found that salinity was a significant factor in soil chemistry ($p = 0.0109$, $F = 5.1302$). Our ANOSIM test found significant differences between groups for input type ($p < 0.0001$ and $R = 0.1179$) and regions ($p > 0.0001$

and R = 0.3898; Table 7), but there was no significant difference between groups for distance from the input (p = 0.9903 and R = -0.02188) or soil depth (p = 0.9861 and R = -0.01714).

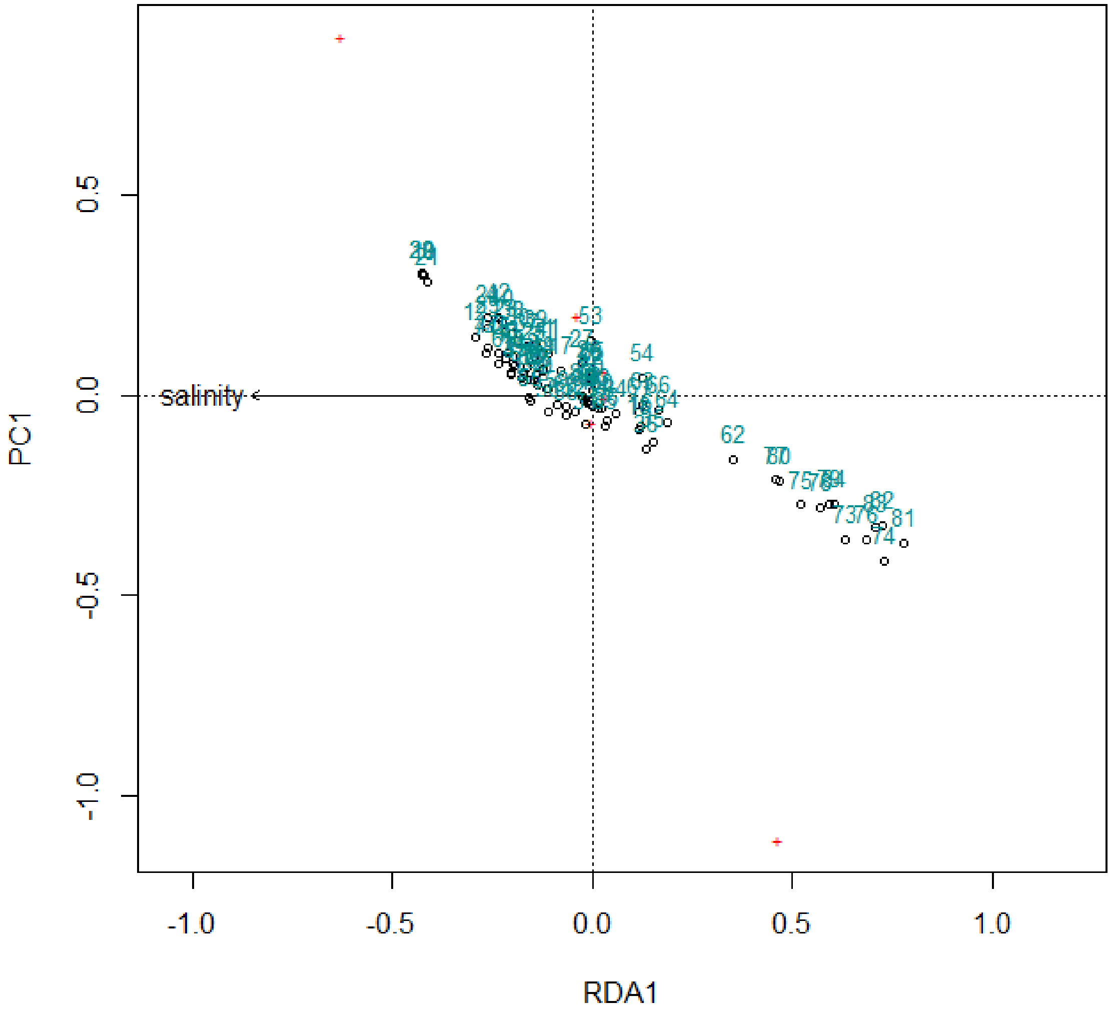


Figure 4. Biplot of principal component and redundancy analysis showing the impact of salinity on soil pH and concentrations of sodium, aluminum, calcium, copper, and zinc across samples. 94.7% of variance was explained between the first two axes.

Table 7. ANOSIM (Analysis of similarities) results for factors impacting variability in soil chemical concentrations of pH, sodium, aluminum, calcium, copper, and zinc.

Factor	**ANOSIM statistic R**	**P-value**
Input Type	0.1179	<0.0001*
Region	0.3898	<0.0001*
Distance	-0.02188	0.9903
Depth	-0.01714	0.9861

Salinization of Wetlands in Halifax

We calculated the mean salinity of the 15 wetland sites. CCME guidelines for chronic chloride toxicity is 120 mg/L, which is equivalent to ~198 mg/L NaCl (calculated by multiplying Cl^- by NaCl molar mass divided by Cl^- molar mass). Across all wetland sites except for one, mean salinity values were above the 198 mg/L NaCl toxicity guideline (Figure 5). CCME also puts a 60 mg/L sodium threshold guideline for soil health, of which the sodium (mg/L) levels were surpassed by 184 samples.

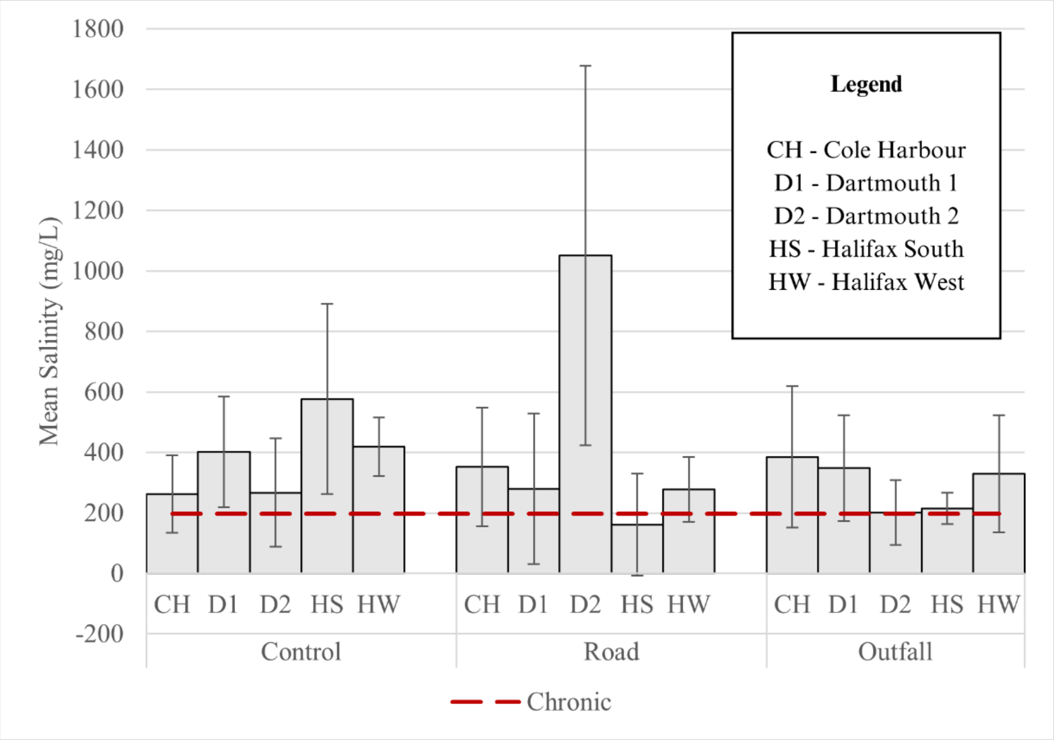


Figure 5. Bar chart with mean salinity ± SD in mg/L across sampling sites in Halifax. Sites are grouped by treatment (control, road, or outfall). The red dashed line shows the CCME guideline for chronic NaCl toxicity. Note that for the HS-Road site, the standard deviation was greater than the mean, hence the axis falling below 0.

Discussion

Impacts of Salt Inflow Type

I expected inflow type to affect the salinity of wetlands because of the direct input of salinity into waters and soils compared to the indirect input from salt spray or road runoff through groundwater; however, stormwater outfall pipes did not significantly influence salinity levels in the study wetlands. These results are in contrast to Helmueller et al. (2020), who found that storm outfalls played a significant role in chloride levels compared to road runoff, such that chloride levels were higher near outfalls than near roadside wetland edges.

Interestingly, there was little difference between the roadside, stormwater, and control sites, suggesting that factors other than proximity to roads/outfalls, such as surrounding land use or road density, are causing control sites to be similarly salinized. The control sites were over 50 m from a roadway, and should not have been influenced by road runoff, so the fact that they were so highly salinized, especially in May, suggests that these wetlands are not solely being salinized by spray or direct inputs. The salinity of soils in urban environments can be variable due to the amount of urban impact (Cunningham et al. 2007), however the salinity of the soils even in wetlands over 50 m from a road suggests that other factors are at play, including the possibility of groundwater contamination. Atmospheric salt deposition or different hydrology sources are also possible causes of increased salinity at these control sites. The range of salinity at control sites was smaller than road or outfall sites, suggesting that input type may still be a factor but that the small number of sample sites and a regional influence may be masking this influence. This also severely limited our analysis, as a comparison between salinized (outfall and road) and unsalinized (controls) wetlands could not be made.

Impacts of Distance and Depth

I anticipated that salinity would decrease at further distances from the input and greater depths from the surface due to the higher expected concentrations of salt near the input; however, we found that salinity, pH, and soil element concentrations over distance and across depths varied across the wetland sites. Salinity was significantly higher at depths of 10-20 cm than at surface level (0-10 cm). This differs from previous experimental research by Ke et al. (2013), who found that upper layers of soils (0-15 cm) had higher salt content than 15-30 cm; however, this could mean that the salt had already been translocated into lower layers of the soil by the time of sampling. Depth was also a significant predictor of Na^+, Al^{3+}, and Cu^{2+} concentrations with all values found to be greater in the 10-20 cm depth range. This suggests that leaching of these ions may be occurring in these soils. Similarly, Cunningham et al. (2007) found that the addition of road salt led to the leaching of elements through soil to lower depths.

Faster movement of sodium through soils may make sodium less available to wetland plants (Cunningham et al., 2007). Amrhein et al. (1992) and Bäckström et al. (2004) found that cations from deicing salts accelerate the leaching of metals from soils to groundwater, which is of concern in Halifax wetlands as the Al^{3+}, Zn^{2+}, and Cu^{2+} may be leached through groundwater and wetland soils. Organic soil pH was significantly lower at 15 m from the input compared to 1 m, and Cu^{2+} concentrations significantly decreased at 5 and 15 m from the input compared to 1 m. This suggests that soil depth and distance from roadways or road salt inputs may be having a significant impact on chemical makeup across Halifax wetlands. Bäckström et al. (2004) found that the greatest salinity was found within 10 m of a road for single point systems, however many of the wetlands sampled in this study had multiple road influences which likely resulted in salt entering the wetland system from multiple directions and sources rather than a single road.

Impacts of Salinity on Soil Chemistry

We expected that salinized sites would contain greater concentrations of aluminum, copper, zinc and sodium due to soil cation exchange. A redundancy analysis was conducted to examine whether salinity was a factor in soil chemistry trends across the sites (Figure 4). Salinity was a significant factor in soil chemistry ($p = 0.0109$, $F = 5.1302$). This is in line with previous studies which found that road salt runoff changed the chemical makeup of roadside soils due to cation exchange (see Amrhein et al., 1992; Amrhein et al., 1993; Bäckström et al., 2004), and suggests that this is also occurring in wetland ecosystems in Halifax. Bäckström et al. (2004) observed increased Cd^{2+}, Zn^{2+} and Ca^{2+} levels, and decreased pH in soils near a road treated with NaCl. Kaushal et al. (2018) found that increased sodium in aquatic ecosystems increased magnesium and calcium concentrations, and that variability in the rate of change of pH declined as the salinity of stream and river water increased. This is likely due to the Na^+ from NaCl being exchanged for Ca^{2+} and other cations in the soil, increasing their mobility and detection rate (Kelting and Laxson, 2010).

Salinization of Wetlands in Halifax

Our ANOSIM test found significant differences between groups for input type and region (Table 2), but there was no significant difference between groups for distance from the input or soil depth. This suggests that the chemical makeup of the soil may be influenced by not only the dispersal method, but also the region in which the dispersal is taking place. In North America, freshwater wetlands are generally characterized by chloride concentrations less than 100 mg/L (Herbert et al. 2015), but salinized urban wetlands commonly have concentrations in the thousands of mg/L (Kinsman-Costello, 2023). Canadian water quality guidelines for NaCl ions for freshwater aquatic life are estimated at 120 mg Cl^-/L for long-term or chronic exposures, and 640 mg Cl^-/L for short-term (acute) exposures (CCME, 2011), and the threshold for soil integrity is 60 mg Na/L and 90 mg Cl/L (Environment and Climate Change Canada, 2004). Across all wetlands sampled (including controls), the average salinity was above the 198 mg/L CCME guideline for chronic NaCl toxicity (Figure 4). Of the 270 samples taken, 184 were above the 60 mg/L sodium threshold for soil health. This suggests that despite there not being a significant difference between dispersal methods, these wetlands are being heavily salinized which is likely to negatively affect the ecosystem, as studies have found salinization to impact animal and plant reproduction and mortality, animal abundance and biomass production, and soil and water pH (see Chapter 2). Walker et al. (2021) also found that increased salinity significantly affected vegetation responses, including species richness, maximum seedling density, and aboveground biomass in wetlands.

Timing may also play a role in the impacts found at the sites. Water and soil chloride may be at peak levels between November and April (Corsi et al., 2010), so more research is needed to account for any temporal variations in soil measures, as this study took place in late May (to allow for ground thaw). As all wetlands, including those over 50 m from roads, had salinity levels above chronic threshold guidelines, more wetlands in the region should be tested to understand whether these wetlands are salinized year-round. Future research should also include data collection during periods of flow to better understand differences between stormwater runoff and road spray.

Management Implications

This research is of use to managers and policy makers in the Halifax region and beyond, as it improves our understanding of the impacts that road salting has on wetlands and soils in urban areas. Although research and monitoring has previously only occurred in lakes in the region (see Ginn et al., 2015; Clement and Gordon, 2019), this analysis shows that wetlands in the city are likely also being affected by the input of road salt, both through stormwater inputs, road runoff, and other mechanisms, and the city should ensure that proper management and mitigation techniques are undertaken to protect these important ecosystems. The fact that control sites were also highly salinized suggests that road salt management in the region needs to be even more controlled.

Conclusions

Salinity, input type, and the specific region of Halifax are factors that influence the chemistry of soils in urban wetlands. The input of road salt through stormwater outfalls and road runoff compared to control sites was not significantly different, suggesting that there are factors other than roadways influencing wetland salinity. As all wetlands had high salinity, including wetlands over 50 m from roadways, our ability to interpret the results was affected as our initial comparisons were unable to be met. Soil depth and distance from the road salt input impacted salinity and soil chemistry in a variety of ways, with salinity, Na^+, Al^{3+}, Zn^{2+}, and Cu^{2+} concentrations being significantly greater at 10-20 cm depths than at surface levels, and higher pH and Cu^{2+} concentrations further away from road salt inputs. We also found that soil depth and distance from inputs did not have a significant impact on the variability of soil chemical concentrations, but that salinity did have a significant impact on the variability of soil chemical concentrations. In our study, salinity was above the national guidelines for chronic chloride toxicity in all wetlands sampled and thus more effort is needed to reduce and mitigate the salinization of these important ecosystems.

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CHAPTER 4. CONCLUSION

This research demonstrates the ecological changes that are occurring due to road salting, both in Halifax and globally. A greater understanding of the effects of road salting across ecological scales benefits managers and policymakers, allowing them to make decisions to maximize winter road safety while minimizing environmental damage. Through my meta-analysis, I identified that animal and plant fitness, animal abundance and production, soil and water pH, and soil moisture are all being negatively impacted by road salting. I also identified that soil biota and terrestrial mammals were particularly underrepresented in road salt research. Future work should attempt to fill these gaps to better understand the impacts on these organisms. I also found that there is a major knowledge gap in the use of field studies and observational studies for investigating road salt impacts and that many of the studies that do exist may not be appropriately measuring salinity or salt content in order to be able to make meaningful implications for ecological impacts. Future work should also focus on conducting field studies that measure salinity, instead of using distance from roads as a proxy.

In our third chapter, we examined whether the direct input of road salts into urban wetlands in Halifax, Nova Scotia, had an impact on salinity and soil element concentrations in the study area. We found no significant differences in salinity across input types, suggesting that urban wetlands with direct stormwater drainage were not more likely to undergo salinization than those with indirect inputs. We also found that salinity may be significantly affecting soil element concentrations within Halifax wetlands, and that many wetlands are experiencing significant chronic salinization, which is likely having negative ecological impacts. Future work should undertake longer-term sampling to identify changes over time, as well as further study the impacts that the use of road salt on roads in Halifax may be having on these ecosystems.

This research also suggests the need for increased research on road salt impacts within the Halifax region. In Chapter 1, we summarized the effects of road salting on both terrestrial and aquatic ecosystems. A peer-reviewed meta-analysis had not previously been completed on the ecological impacts of chloride-based road salting, and as such this analysis is essential for managers and planners looking to identify and quantify risks in winter management planning. Kinsman-Costello (2023) found that there is a lack of knowledge about the impacts of road salt on wetland soil biogeochemistry, and our third chapter helped to fill that gap by analyzing both the impacts of salinity on sample urban wetlands in Halifax, Nova Scotia, as well as finding that background salinity levels were high in all wetlands studied (including controls), perhaps masking to some extent the expected impacts of dispersal methods on wetland chemistry. This work is important for future road and winter planning in Halifax and may help to identify vulnerable wetland ecosystems within the region. This work adds to the small amount of data available for examining the impacts of road salting on the environment in Halifax and complements the larger global research available through quantitatively synthesizing previous primary studies and partially addressing a known knowledge gap on wetland soil chemistry impacts.

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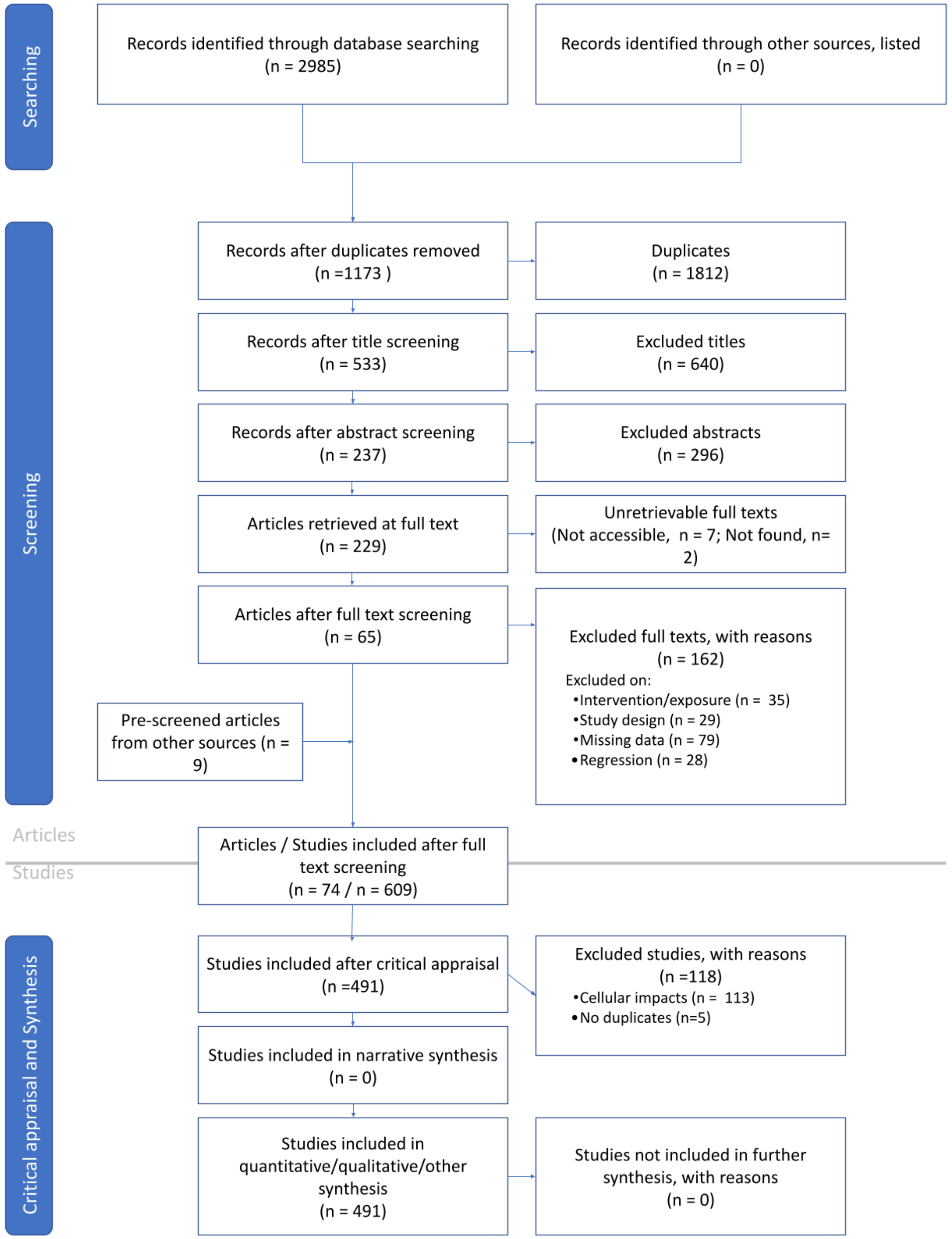
APPENDICES

Appendix A – Roses Diagram


ROSES flow diagram

Appendix B: Raw data for Chapter 3.

*Concentrations below limit of detection (LOD) were substituted using LOD/√2

SampleID	Region	Site Type	Replicate	Depth_cm	Distance_m	Ca_kg/ha	Ca_ppm	Mg_kg/ha	Mg_ppm	Na_kg/ha	Na_mg/L	Al_ppm	Cu_ppm	Zn_ppm	pH	EC_uS/cm	Salinity_mg/L
CH-C-1-1-10	Cole Harbour	Control	1	10	1	1621	810.5	173	86.5	115	57.5	997	1.23	2.28	5.81	211	135.04
CH-C-1-1-20	Cole Harbour	Control	1	20	1	1115	557.5	132	66	83	41.5	658	0.81	1.71	5.8	572.2	366.208
CH-C-1-2-10	Cole Harbour	Control	2	10	1	890	445	119	59.5	88	44	726	1	1.41	5.05	562.5	360
CH-C-1-2-20	Cole Harbour	Control	2	20	1	2149	1074.5	229	114.5	138	69	699	0.67	1.72	5.2	279.6	178.944
CH-C-1-3-10	Cole Harbour	Control	3	10	1	1249	624.5	154	77	107	53.5	461	0.23	1.59	3.94	429.5	274.88
CH-C-1-3-20	Cole Harbour	Control	3	20	1	1265	632.5	158	79	104	52	366	0.19	1.32	4.97	339.5	217.28
CH-C-5-1-10	Cole Harbour	Control	1	10	5	2130	1065	263	131.5	191	95.5	939	0.66	2.69	5.75	271	173.44
CH-C-5-1-20	Cole Harbour	Control	1	20	5	2360	1180	296	148	212	106	831	0.33	1.96	5.52	233.8	149.632
CH-C-5-2-10	Cole Harbour	Control	2	10	5	1880	940	196	98	153	76.5	563	0.37	1.83	5.62	258.5	165.44
CH-C-5-2-20	Cole Harbour	Control	2	20	5	2924	1462	297	148.5	199	99.5	722	0.3	2.08	5.78	319	204.16
CH-C-5-3-10	Cole Harbour	Control	3	10	5	3226	1613	320	160	220	110	407	0.13	0.99	5.25	327.9	209.856
CH-C-5-3-20	Cole Harbour	Control	3	20	5	2588	1294	249	124.5	144	72	543	0.32	1.65	5.36	246.4	157.696
CH-C-15-1-10	Cole Harbour	Control	1	10	15	1678	839	191	95.5	159	79.5	528	0.24	2.42	4.95	322.6	206.464
CH-C-15-1-20	Cole Harbour	Control	1	20	15	2356	1178	250	125	176	88	583	0.07*	1.43	5.57	299.6	191.744
CH-C-15-2-10	Cole Harbour	Control	2	10	15	2031	1015.5	224	112	174	87	635	0.37	3.19	5.2	789.6	505.344
CH-C-15-2-20	Cole Harbour	Control	2	20	15	1853	926.5	185	92.5	136	68	411	0.07*	1.19	5.24	932.6	596.864
CH-C-15-3-10	Cole Harbour	Control	3	10	15	1287	643.5	144	72	134	67	338	0.16	1.59	5.5	447.1	286.144
CH-C-15-3-20	Cole Harbour	Control	3	20	15	2133	1066.5	245	122.5	175	87.5	454	0.07*	1.15	5.49	528.2	338.048
CH-0-1-1-10	Cole Harbour	Outfall	1	10	1	1677	838.5	217	108.5	63	31.5	834	0.63	7.02	5.06	627.9	401.856

CH-0-1-1-20	Cole Harbour	Outfall	1	20	1	1940	970	194	97	66	33	904	1.04	6.47	4.78	499.2	319.488
CH-0-1-2-10	Cole Harbour	Outfall	2	10	1	3986	1993	188	94	120	60	680	0.3	2.9	4.81	850.4	544.256
CH-0-1-2-20	Cole Harbour	Outfall	2	20	1	4267	2133.5	188	94	113	56.5	816	0.8	2.77	4.59	556.9	356.416
CH-0-1-3-10	Cole Harbour	Outfall	3	10	1	2783	1391.5	215	107.5	51	25.5	603	1.67	9.51	4.83	1419	908.16
CH-0-1-3-20	Cole Harbour	Outfall	3	20	1	2932	1466	187	93.5	52	26	754	3.01	14.33	4.63	1021	653.44
CH-0-5-1-10	Cole Harbour	Outfall	1	10	5	2179	1089.5	238	119	80	40	794	0.34	8.21	4.82	1209	773.76
CH-0-5-1-20	Cole Harbour	Outfall	1	20	5	2883	1441.5	279	139.5	76	38	832	0.37	6.45	4.78	570.7	365.248
CH-0-5-2-10	Cole Harbour	Outfall	2	10	5	2624	1312	143	71.5	91	45.5	817	0.22	9	5.2	388.9	248.896
CH-0-5-2-20	Cole Harbour	Outfall	2	20	5	2901	1450.5	159	79.5	104	52	859	0.07*	4.66	5.12	319.1	204.224
CH-0-5-3-10	Cole Harbour	Outfall	3	10	5	1112	556	181	90.5	102	51	699	0.45	4.91	5.6	283.7	181.568
CH-0-5-3-20	Cole Harbour	Outfall	3	20	5	1972	986	269	134.5	149	74.5	400	0.17	1.67	5.24	1091	698.24
CH-0-15-1-10	Cole Harbour	Outfall	1	10	15	1516	758	178	89	76	38	983	0.45	1.79	5.11	412.1	263.744
CH-0-15-1-20	Cole Harbour	Outfall	1	20	15	1108	554	105	52.5	69	34.5	491	0.2	1.5	4.93	402.4	257.536
CH-0-15-2-10	Cole Harbour	Outfall	2	10	15	2139	1069.5	157	78.5	81	40.5	343	0.36	2.06	5.04	246.6	157.824
CH-0-15-2-20	Cole Harbour	Outfall	2	20	15	2332	1166	167	83.5	67	33.5	327	0.36	1.98	4.77	246.3	157.632
CH-0-15-3-10	Cole Harbour	Outfall	3	10	15	2893	1446.5	275	137.5	136	68	478	1.12	6.79	5.05	198.3	126.912
CH-0-15-3-20	Cole Harbour	Outfall	3	20	15	2436	1218	337	168.5	177	88.5	192	0.2	1.17	4.9	473.3	302.912
CH-R-1-1-10	Cole Harbour	Road	1	10	1	1247	623.5	322	161	66	33	780	1.03	5.24	4.55	224.6	143.744
CH-R-1-1-20	Cole Harbour	Road	1	20	1	852	426	191	95.5	80	40	917	0.48	3.06	4.83	227.3	145.472
CH-R-1-2-10	Cole Harbour	Road	2	10	1	2080	1040	175	87.5	151	75.5	800	0.48	4.47	5.26	331.3	212.032
CH-R-1-2-20	Cole Harbour	Road	2	20	1	1907	953.5	136	68	127	63.5	929	2.24	6.17	5.21	936.6	599.424
CH-R-1-3-10	Cole Harbour	Road	3	10	1	1238	619	138	69	115	57.5	964	0.54	6.57	4.84	376.6	241.024

CH-R-1-3-20	Cole Harbour	Road	3	20	1	1776	888	137	68.5	109	54.5	891	2.25	11.55	4.76	936.6	599.424
CH-R-5-1-10	Cole Harbour	Road	1	10	5	1289	644.5	167	83.5	134	67	1032	0.88	3.37	5.07	420.6	269.184
CH-R-5-1-20	Cole Harbour	Road	1	20	5	856	428	99	49.5	108	54	1033	0.65	4.6	4.68	603.6	386.304
CH-R-5-2-10	Cole Harbour	Road	2	10	5	1989	994.5	182	91	146	73	894	1.99	8.26	4.91	244.7	156.608
CH-R-5-2-20	Cole Harbour	Road	2	20	5	1197	598.5	118	59	120	60	961	1.52	7.23	4.81	520.9	333.376
CH-R-5-3-10	Cole Harbour	Road	3	10	5	1448	724	175	87.5	81	40.5	766	0.44	4.7	4.88	531.1	339.904
CH-R-5-3-20	Cole Harbour	Road	3	20	5	1211	605.5	160	80	83	41.5	828	0.27	4.01	4.58	1300	832
CH-R-15-1-10	Cole Harbour	Road	1	10	15	2793	1396.5	283	141.5	137	68.5	804	2.09	12.98	4.65	662.9	424.256
CH-R-15-1-20	Cole Harbour	Road	1	20	15	1245	622.5	153	76.5	110	55	1156	1.87	3.94	4.68	427.9	273.856
CH-R-15-2-10	Cole Harbour	Road	2	10	15	3111	1555.5	273	136.5	188	94	895	2.51	14.89	4.69	398.9	255.296
CH-R-15-2-20	Cole Harbour	Road	2	20	15	2375	1187.5	211	105.5	123	61.5	971	2.47	8.34	4.82	295.9	189.376
CH-R-15-3-10	Cole Harbour	Road	3	10	15	297	148.5	114	57	57	28.5	980	0.19	1.75	3.19	454.3	290.752
CH-R-15-3-20	Cole Harbour	Road	3	20	15	283	141.5	132	66	62	31	1206	0.37	1.96	5.03	1010	646.4
D1-C-1-1-20	Dartmouth1	Control	1	10	1	3683	1841.5	638	319	2390	1195	113	0.66	8.3	4.76	343.8	220.032
D1-C-1-1-10	Dartmouth1	Control	1	20	1	2750	1375	297	148.5	1051	525.5	127	0.5	4.21	4.5	689.9	441.536
D1-C-1-2-10	Dartmouth1	Control	2	10	1	2846	1423	374	187	1194	597	19	0.88	6.02	4.72	323.1	206.784
D1-C-1-2-20	Dartmouth1	Control	2	20	1	3062	1531	504	252	1528	764	11	0.42	3.09	4.59	442.2	283.008
D1-C-1-3-10	Dartmouth1	Control	3	10	1	2759	1379.5	356	178	1211	605.5	15	0.93	5.29	4.42	615.8	394.112
D1-C-1-3-20	Dartmouth1	Control	3	20	1	2932	1466	506	253	1744	872	10	0.44	2.17	4.49	661.5	423.36
D1-C-5-1-10	Dartmouth1	Control	1	10	5	3097	1548.5	559	279.5	1435	717.5	9	0.2	2.2	4.41	603.6	386.304
D1-C-5-1-20	Dartmouth1	Control	1	20	5	4390	2195	928	464	2889	1444.5	13	0.12	2.45	4.43	838.6	536.704
D1-C-5-2-10	Dartmouth1	Control	2	10	5	2632	1316	371	185.5	888	444	115	0.53	2.29	4.56	660.3	422.592

D1-C-5-2-20	Dartmouth1	Control	2	20	5	3676	1838	682	341	1892	946	34	0.07*	0.76	4.56	710.6	454.784
D1-C-5-3-10	Dartmouth1	Control	3	10	5	3647	1823.5	593	296.5	1156	578	210	0.37	2.36	4.55	1597	1022.08
D1-C-5-3-20	Dartmouth1	Control	3	20	5	3305	1652.5	800	400	1459	729.5	93	0.17	1.32	4.96	283.7	181.568
D1-C-15-1-10	Dartmouth1	Control	1	10	15	876	438	321	160.5	115	57.5	266	0.42	15.32	4.39	467.2	299.008
D1-C-15-1-20	Dartmouth1	Control	1	20	15	450	225	526	263	238	119	142	0.07*	5.04	4.21	784.6	502.144
D1-C-15-2-10	Dartmouth1	Control	2	10	15	683	341.5	256	128	192	96	249	0.4	6.99	4.37	560.6	358.784
D1-C-15-2-20	Dartmouth1	Control	2	20	15	1982	991	497	248.5	588	294	219	0.07*	1.4	4.43	561.9	359.616
D1-C-15-3-10	Dartmouth1	Control	3	10	15	2120	1060	368	184	650	325	266	0.27	2.32	4.42	628.8	402.432
D1-C-15-3-20	Dartmouth1	Control	3	20	15	2837	1418.5	482	241	1001	500.5	439	0.11	1.51	4.52	507.5	324.8
D1-0- 1 -1-10	Dartmouth1	Outfall	1	10	1	1677	838.5	120	60	148	74	295	13.21	84.34	4.77	405.4	259.456
D1-0-1-1- 20	Dartmouth1	Outfall	1	20	1	1187	593.5	95	47.5	215	107.5	324	18.17	65.58	4.82	839.3	537.152
D1-0-1M-2 -10	Dartmouth1	Outfall	2	10	1	727	363.5	76	38	426	213	394	15.79	92.45	4.88	442.2	283.008
D1-0-1M -2-20	Dartmouth1	Outfall	2	20	1	471	235.5	58	29	454	227	326	18.52	139.87	4.63	504.5	322.88
D1-0- 1-3 -10	Dartmouth1	Outfall	3	10	1	1258	629	106	53	170	85	352	15.11	53.57	4.71	670.5	429.12
D1-0- 1-3 -20	Dartmouth1	Outfall	3	20	1	780	390	53	26.5	636	318	470	23.79	31.13	4.26	1393	891.52
D1-0- 5-1-20	Dartmouth1	Outfall	1	10	5	655	327.5	73	36.5	245	122.5	385	9.78	117.56	4.26	269.7	172.608
D1-0-5-1-10	Dartmouth1	Outfall	1	20	5	538	269	72	36	171	85.5	321	7.19	76.19	4.71	651.8	417.152
D1-0- 5-2 -10	Dartmouth1	Outfall	2	10	5	794	397	71	35.5	309	154.5	369	7.87	126.03	3.95	262.1	167.744
D1-0- 5-2 -20	Dartmouth1	Outfall	2	20	5	522	261	56	28	307	153.5	323	5.02	130.6	4.68	623.5	399.04
D1-0- 5 - 3 -10	Dartmouth1	Outfall	3	10	5	1302	651	67	33.5	471	235.5	464	22.96	74.99	4.16	400.6	256.384

D1-0-5-3-20	Dartmouth1	Outfall	3	20	5	1193	596.5	61	30.5	488	244	428	19.53	62.74	4.46	650.6	416.384
D1-0-15-1-10	Dartmouth1	Outfall	1	10	15	2134	1067	99	49.5	193	96.5	320	12.24	89.71	4.2	222	142.08
D1-0-15-1-20	Dartmouth1	Outfall	1	20	15	2053	1026.5	97	48.5	288	144	456	23.19	95.48	4.04	295.3	188.992
D1-0-15-2-10	Dartmouth1	Outfall	2	10	15	2349	1174.5	142	71	310	155	330	11.31	84.57	5	501.5	320.96
D1-0-15-2-20	Dartmouth1	Outfall	2	20	15	1760	880	115	57.5	362	181	365	11.78	96.59	4.91	681.3	436.032
D1-0-15-3-10	Dartmouth1	Outfall	3	10	15	1647	823.5	110	55	280	140	381	13.37	87.18	4.71	586.7	375.488
D1-0-15-3-20	Dartmouth1	Outfall	3	20	15	1054	527	71	35.5	263	131.5	352	10.67	68.69	4.52	373.9	239.296
D1-R-1-1-10	Dartmouth1	Road	1	10	1	980	490	117	58.5	357	178.5	508	0.64	7.76	6.49	209.4	134.016
D1-R-1-1-20	Dartmouth1	Road	1	20	1	1197	598.5	136	68	447	223.5	584	0.07*	9.47	6.39	186.9	119.616
D1-R-1-2-10	Dartmouth1	Road	2	10	1	1085	542.5	121	60.5	381	190.5	565	1.19	6.95	6.31	132.2	84.608
D1-R-1-2-20	Dartmouth1	Road	2	20	1	1336	668	147	73.5	544	272	569	0.28	9.93	5.28	388	248.32
D1-R-1-3-10	Dartmouth1	Road	3	10	1	710	355	63	31.5	267	133.5	339	0.49	3.2	6.32	144.6	92.544
D1-R-1-3-20	Dartmouth1	Road	3	20	1	1007	503.5	83	41.5	514	257	439	0.11	3.43	6.81	105	67.2
D1-R-5-1-10	Dartmouth1	Road	1	10	5	544	272	90	45	217	108.5	457	0.44	6.58	5.23	343.1	219.584
D1-R-5-1-20	Dartmouth1	Road	1	20	5	912	456	126	63	459	229.5	651	0.07*	9.83	4.58	627.7	401.728
D1-R-5-2-20	Dartmouth1	Road	2	10	5	594	297	76	38	317	158.5	346	0.15	6.02	4.1	1153	737.92
D1-R-5-2-10	Dartmouth1	Road	2	20	5	630	315	85	42.5	297	148.5	559	3.91	11.31	4.56	758	485.12
D1-R-5-3-10	Dartmouth1	Road	3	10	5	1309	654.5	122	61	406	203	596	1.32	6.79	6.19	215	137.6
D1-R-5-3-20	Dartmouth1	Road	3	20	5	1551	775.5	138	69	599	299.5	888	0.07*	6.85	6.45	205.4	131.456
D1-R-15-1-10	Dartmouth1	Road	1	10	15	360	180	79	39.5	91	45.5	327	1.01	4.98	6.69	190	121.6
D1-R-15-1-20	Dartmouth1	Road	1	20	15	927	463.5	178	89	281	140.5	835	0.2	9.47	6.77	1533	981.12

D1-R-15-2-10	Dartmouth1	Road	2	10	15	619	309.5	119	59.5	245	122.5	650	1.28	6.96	3.63	222.5	142.4
D1-R-15-2-20	Dartmouth1	Road	2	20	15	568	284	94	47	197	98.5	399	0.16	3.8	5.81	331.7	212.288
D1-R-15-3-10	Dartmouth1	Road	3	10	15	387	193.5	71	35.5	144	72	319	0.82	4.09	6.03	377.9	241.856
D1-R-15-3-20	Dartmouth1	Road	3	20	15	645	322.5	115	57.5	330	165	696	0.35	7.31	5.03	720.5	461.12
D2-C-1-1-10	Dartmouth2	Control	1	10	1	1180	590	197	98.5	45	22.5	343	0.34	2.49	3.93	282.4	180.736
D2-C-1-1-20	Dartmouth2	Control	1	20	1	1701	850.5	317	158.5	79	39.5	389	0.23	2.96	3.42	536.1	343.104
D2-C-1-2-10	Dartmouth2	Control	2	10	1	2317	1158.5	395	197.5	96	48	678	0.07*	1.88	3.95	143.2	91.648
D2-C-1-2-20	Dartmouth2	Control	2	20	1	1995	997.5	303	151.5	65	32.5	542	0.07*	0.92	4.06	265	169.6
D2-C-1-3-10	Dartmouth2	Control	3	10	1	1166	583	205	102.5	57	28.5	439	0.33	1.78	3.94	118	75.52
D2-C-1-3-20	Dartmouth2	Control	3	20	1	2073	1036.5	360	180	91	45.5	645	0.24	2.25	3.69	284.7	182.208
D2-C-5-1-10	Dartmouth2	Control	1	10	5	1238	619	223	111.5	57	28.5	400	0.07*	3.22	3.64	223.8	143.232
D2-C-5-1-20	Dartmouth2	Control	1	20	5	1610	805	272	136	48	24	264	0.11	2.95	3.62	315.9	202.176
D2-C-5-2-10	Dartmouth2	Control	2	10	5	1043	521.5	189	94.5	52	26	370	0.32	2.08	3.73	272.4	174.336
D2-C-5-2-20	Dartmouth2	Control	2	20	5	2075	1037.5	386	193	123	61.5	568	0.24	3.78	3.65	252.5	161.6
D2-C-5-3-10	Dartmouth2	Control	3	10	5	687	343.5	157	78.5	43	21.5	241	0.25	2.01	3.54	241.5	154.56
D2-C-5-3-20	Dartmouth2	Control	3	20	5	2256	1128	418	209	93	46.5	589	0.25	4.19	3.31	1114	712.96
D2-C-15-1-10	Dartmouth2	Control	1	10	15	825	412.5	188	94	61	30.5	376	0.07*	2.26	3.84	367.2	235.008
D2-C-15-1-20	Dartmouth2	Control	1	20	15	1632	816	295	147.5	78	39	395	0.16	2.13	3.34	717.9	459.456
D2-C-15-2-10	Dartmouth2	Control	2	10	15	815	407.5	154	77	43	21.5	303	0.19	1.62	3.77	795.8	509.312
D2-C-15-2-20	Dartmouth2	Control	2	20	15	2013	1006.5	389	194.5	73	36.5	380	0.46	3.62	3.25	893.7	571.968
D2-C-15-3-10	Dartmouth2	Control	3	10	15	933	466.5	166	83	41	20.5	327	0.21	1.7	3.41	380.8	243.712

D2-C-15-3-20	Dartmouth2	Control	3	20	15	2013	1006.5	370	185	78	39	542	0.12	3.06	3.57	304	194.56
D2 -0-1-1-10	Dartmouth2	Outfall	1	10	1	1893	946.5	118	59	136	68	684	6.23	21.21	4.23	404.1	258.624
D2 -0-1-1-20	Dartmouth2	Outfall	1	20	1	1446	723	80	40	188	94	707	6.73	17.85	4.32	207	132.48
D2 -0-1-2-10	Dartmouth2	Outfall	2	10	1	2386	1193	137	68.5	98	49	717	9.39	18.41	5.27	412.9	264.256
D2 -0-1-2-20	Dartmouth2	Outfall	2	20	1	1745	872.5	80	40	188	94	797	5.72	17.62	5.24	121.6	77.824
D2 -0-1-3-10	Dartmouth2	Outfall	3	10	1	3530	1765	165	82.5	81	40.5	548	7.83	40.4	4.85	613.5	392.64
D2 -0-1-3-20	Dartmouth2	Outfall	3	20	1	2885	1442.5	131	65.5	102	51	654	10.22	34.43	4.73	435.8	278.912
D2 -0-5-1-10	Dartmouth2	Outfall	1	10	5	3378	1689	162	81	324	162	645	10.12	45.17	5.28	123.4	78.976
D2 -0-5-1-20	Dartmouth2	Outfall	1	20	5	2376	1188	113	56.5	376	188	690	11.68	39.28	4.9	190.8	122.112
D2 -0-5-2-10	Dartmouth2	Outfall	2	10	5	3008	1504	163	81.5	117	58.5	565	8.7	37.96	5.25	599.3	383.552
D2 -0-5-2-20	Dartmouth2	Outfall	2	20	5	2275	1137.5	123	61.5	161	80.5	633	10.61	33.01	5.64	165.9	106.176
D2 -0-5-3-10	Dartmouth2	Outfall	3	10	5	904	452	181	90.5	36	18	380	1.33	4.39	4.77	219.8	140.672
D2 -0-5-3-20	Dartmouth2	Outfall	3	20	5	581	290.5	142	71	34	17	391	1.31	2.52	4.84	504.5	322.88
D2 -0-15-1-10	Dartmouth2	Outfall	1	10	15	3407	1703.5	160	80	232	116	552	7.69	38.26	5.49	173.3	110.912
D2 -0-15-1-20	Dartmouth2	Outfall	1	20	15	2453	1226.5	112	56	417	208.5	682	10.01	36.35	5.02	216	138.24
D2 -0-15-2-10	Dartmouth2	Outfall	2	10	15	3538	1769	181	90.5	282	141	658	8.73	41.64	5.8	253.3	162.112
D2 -0-15-2-20	Dartmouth2	Outfall	2	20	15	2478	1239	121	60.5	398	199	728	10.49	33.26	5.9	530.5	339.52
D2 -0-15-3-10	Dartmouth2	Outfall	3	10	15	2364	1182	314	157	48	24	588	1.87	22.33	4.12	317.5	203.2
D2 -0-15-3-20	Dartmouth2	Outfall	3	20	15	1968	984	300	150	43	21.5	647	1.92	16.95	4.36	153	97.92
D2-R-1-1-10	Dartmouth2	Road	1	10	1	1212	606	123	61.5	814	407	392	2.71	25.61	5.37	3403	2177.92
D2-R-1-1-20	Dartmouth2	Road	1	20	1	742	371	64	32	928	464	531	3.36	16.15	5.52	1617	1034.88
D2-R-1-2-10	Dartmouth2	Road	2	10	1	2284	1142	145	72.5	1080	540	509	7.76	45.86	5.7	1494	956.16

D2-R-1-2-20	Dartmouth2	Road	2	20	1	1133	566.5	90	45	785	392.5	405	6.77	23.95	5.21	2700	1728
D2-R-1-3-10	Dartmouth2	Road	3	10	1	1443	721.5	99	49.5	1035	517.5	451	5.99	23.42	5.48	1948	1246.72
D2-R-1-3-20	Dartmouth2	Road	3	20	1	1637	818.5	92	46	1438	719	714	8.5	27.71	5.29	2882	1844.48
D2-R-5-1-10	Dartmouth2	Road	1	10	5	3137	1568.5	179	89.5	1524	762	654	4.34	19.44	5.11	1865	1193.6
D2-R-5-1-20	Dartmouth2	Road	1	20	5	2975	1487.5	128	64	1924	962	1133	4.18	10.02	4.87	2947	1886.08
D2-R-5-2-10	Dartmouth2	Road	2	10	5	1059	529.5	119	59.5	498	249	361	4.74	20.07	4.69	1894	1212.16
D2-R-5-2-20	Dartmouth2	Road	2	20	5	1381	690.5	97	48.5	829	414.5	493	4.76	24.2	4.83	2628	1681.92
D2-R-5-3-10	Dartmouth2	Road	3	10	5	1166	583	93	46.5	842	421	535	2.53	21.65	4.32	1262	807.68
D2-R-5-3-20	Dartmouth2	Road	3	20	5	2049	1024.5	77	38.5	1324	662	1569	3.3	8.2	4.32	1471	941.44
D2-R-15-1-10	Dartmouth2	Road	1	10	15	2705	1352.5	138	69	3007	1503.5	941	4.62	16	3.46	305.2	195.328
D2-R-15-1-20	Dartmouth2	Road	1	20	15	2100	1050	110	55	2702	1351	1609	3.6	15.11	3.46	264.3	169.152
D2-R-15-2-10	Dartmouth2	Road	2	10	15	1906	953	199	99.5	3211	1605.5	761	0.81	28.81	3.62	391.3	250.432
D2-R-15-2-20	Dartmouth2	Road	2	20	15	2114	1057	123	61.5	2846	1423	1625	2.27	15.14	3.61	417.3	267.072
D2-R-15-3-10	Dartmouth2	Road	3	10	15	2048	1024	168	84	3023	1511.5	979	1.25	28.6	3.53	1116	714.24
D2-R-15-3-20	Dartmouth2	Road	3	20	15	1814	907	109	54.5	2267	1133.5	1598	1.72	8.85	3.89	933.6	597.504
HS-C-1-1-10	HalifaxSouth	Control	1	10	1	2918	1459	214	107	274	137	883	1	6.93	5.91	209.4	134.016
HS-C-1-1-20	HalifaxSouth	Control	1	20	1	2812	1406	221	110.5	326	163	1183	1.4	8.36	5.78	746.9	478.016
HS-C-1-2-10	HalifaxSouth	Control	2	10	1	3248	1624	244	122	337	168.5	1195	1.78	9.07	6.85	376.5	240.96
HS-C-1-2-20	HalifaxSouth	Control	2	20	1	2291	1145.5	240	120	399	199.5	1207	3.76	10.86	6.23	882.8	564.992
HS-C-1-3-10	HalifaxSouth	Control	3	10	1	3242	1621	242	121	318	159	916	1.29	6.82	6.27	654.6	418.944
HS-C-1-3-20	HalifaxSouth	Control	3	20	1	3074	1537	232	116	390	195	1255	2.34	12.45	6.51	546.6	349.824
HS-C-5-1-10	HalifaxSouth	Control	1	10	5	2708	1354	246	123	316	158	1070	1.41	6.56	6.3	916.7	586.688

HS-C-5-1-20	HalifaxSouth	Control	1	20	5	2463	1231.5	256	128	415	207.5	1090	1.7	7.63	6.49	597.7	382.528
HS-C-5-2-10	HalifaxSouth	Control	2	10	5	3303	1651.5	210	105	224	112	1067	1.53	10.51	6.36	272.1	174.144
HS-C-5-2-20	HalifaxSouth	Control	2	20	5	2745	1372.5	179	89.5	213	106.5	1121	1.35	9.3	6.37	423.5	271.04
HS-C-5-3-10	HalifaxSouth	Control	3	10	5	3940	1970	280	140	300	150	987	1.2	8.56	5.83	1161	743.04
HS-C-5-3-20	HalifaxSouth	Control	3	20	5	3313	1656.5	261	130.5	343	171.5	1040	1.43	8.49	6.29	736.4	471.296
HS-C-15-1-10	HalifaxSouth	Control	1	10	15	3149	1574.5	265	132.5	328	164	1138	1.42	5.08	6.28	1227	785.28
HS-C-15-1-20	HalifaxSouth	Control	1	20	15	2689	1344.5	253	126.5	349	174.5	1039	1.17	5.19	5.99	1230	787.2
HS-C-15-2-10	HalifaxSouth	Control	2	10	15	2038	1019	166	83	201	100.5	1043	0.9	3.24	5.5	1935	1238.4
HS-C-15-2-20	HalifaxSouth	Control	2	20	15	1922	961	168	84	189	94.5	1072	1.54	4.5	5.39	1676	1072.64
HS-C-15-3-10	HalifaxSouth	Control	3	10	15	2557	1278.5	247	123.5	234	117	1039	1.51	3.77	5.56	1540	985.6
HS-C-15-3-20	HalifaxSouth	Control	3	20	15	2400	1200	251	125.5	251	125.5	1078	1.88	4.36	5.72	1074	687.36
HS -0-1-1-10	HalifaxSouth	Outfall	1	10	1	327	163.5	61	30.5	191	95.5	1360	0.95	2.14	4.18	262.5	168
HS -0-1-1-20	HalifaxSouth	Outfall	1	20	1	182	91	44	22	129	64.5	1448	0.93	1.37	3.87	302.4	193.536
HS -0-1-2-10	HalifaxSouth	Outfall	2	10	1	1579	789.5	62	31	343	171.5	1205	2.38	4.38	4.16	466.3	298.432
HS -0-1-2-20	HalifaxSouth	Outfall	2	20	1	687	343.5	33	16.5	271	135.5	1413	3.52	1.44	4.25	253.2	162.048
HS -0-1-3-10	HalifaxSouth	Outfall	3	10	1	2340	1170	80	40	418	209	1050	1.65	7.11	4.51	328.1	209.984
HS -0-1-3-20	HalifaxSouth	Outfall	3	20	1	1363	681.5	54	27	424	212	1362	2.22	2.94	4.53	336.4	215.296
HS -0-5-1-10	HalifaxSouth	Outfall	1	10	5	1005	502.5	116	58	565	282.5	1375	0.42	5.84	4.19	314.3	201.152
HS -0-5-1-20	HalifaxSouth	Outfall	1	20	5	1093	546.5	125	62.5	517	258.5	1722	0.98	5.71	4.18	283	181.12
HS -0-5-2-10	HalifaxSouth	Outfall	2	10	5	1597	798.5	107	53.5	386	193	1288	0.45	10.4	4.07	463.8	296.832
HS -0-5-2-20	HalifaxSouth	Outfall	2	20	5	1351	675.5	91	45.5	284	142	1389	0.56	11	4.16	355.8	227.712
HS -0-5-3-10	HalifaxSouth	Outfall	3	10	5	1946	973	137	68.5	724	362	1274	0.51	10.7	4.15	376.9	241.216

HS -0-5-3-20	HalifaxSouth	Outfall	3	20	5	1578	789	124	62	641	320.5	1245	0.45	7.99	4.46	447.2	286.208
HS -0-15-1-10	HalifaxSouth	Outfall	1	10	15	2170	1085	105	52.5	443	221.5	1228	0.91	14.73	3.72	372.3	238.272
HS -0-15-1-20	HalifaxSouth	Outfall	1	20	15	1639	819.5	82	41	432	216	1605	0.9	12.14	3.85	222.2	142.208
HS -0-15-2-10	HalifaxSouth	Outfall	2	10	15	2472	1236	122	61	499	249.5	1240	0.91	14.31	4.05	205.9	131.776
HS -0-15-2-20	HalifaxSouth	Outfall	2	20	15	1593	796.5	84	42	431	215.5	1428	0.85	12.96	3.76	427.6	273.664
HS -0-15-3-10	HalifaxSouth	Outfall	3	10	15	1749	874.5	84	42	490	245	1134	1.46	14.34	3.93	372.2	238.208
HS -0-15-3-20	HalifaxSouth	Outfall	3	20	15	1194	597	51	25.5	349	174.5	1381	1.15	12.86	3.96	249.9	159.936
HS-R-1-1-10	HalifaxSouth	Road	1	10	1	1897	948.5	155	77.5	499	249.5	915	1.42	4.08	5.64	120.1	76.864
HS-R-1-1-20	HalifaxSouth	Road	1	20	1	1953	976.5	166	83	363	181.5	1030	1.79	3.07	5.01	1198	766.72
HS-R-1-2-10	HalifaxSouth	Road	2	10	1	3026	1513	215	107.5	391	195.5	692	1.24	5.13	5.75	224.8	143.872
HS-R-1-2-20	HalifaxSouth	Road	2	20	1	2870	1435	202	101	421	210.5	712	1.3	6.74	5.89	135.2	86.528
HS-R-1-3-10	HalifaxSouth	Road	3	10	1	2798	1399	237	118.5	432	216	562	0.85	3.87	5.68	187.1	119.744
HS-R-1-3-20	HalifaxSouth	Road	3	20	1	2559	1279.5	225	112.5	461	230.5	739	1.54	4.51	5.82	147.6	94.464
HS-R-5-1-10	HalifaxSouth	Road	1	10	5	3002	1501	244	122	449	224.5	781	1	3.6	6.03	264.3	169.152
HS-R-5-1-20	HalifaxSouth	Road	1	20	5	2572	1286	228	114	402	201	702	0.68	2.51	5.49	439.3	281.152
HS-R-5-2-10	HalifaxSouth	Road	2	10	5	2367	1183.5	347	173.5	698	349	806	0.31	1.57	5.97	240.6	153.984
HS-R-5-2-20	HalifaxSouth	Road	2	20	5	1980	990	290	145	634	317	634	0.07*	0.76	6.02	120.1	76.864
HS-R-5-3-10	HalifaxSouth	Road	3	10	5	2581	1290.5	201	100.5	580	290	814	1.12	4.36	5.03	46.72	29.9008
HS-R-5-3-20	HalifaxSouth	Road	3	20	5	2264	1132	179	89.5	530	265	781	1.16	4.44	5.26	34.2	21.888
HS-R-15-1-10	HalifaxSouth	Road	1	10	15	2234	1117	321	160.5	611	305.5	409	0.18	2.04	5.81	423.1	270.784
HS-R-15-1-20	HalifaxSouth	Road	1	20	15	1379	689.5	309	154.5	661	330.5	569	0.12	1.36	5.91	164.7	105.408

HS-R-15-2-10	HalifaxSouth	Road	2	10	15	2248	1124	336	168	603	301.5	218	0.18	2.37	5.86	362.3	231.872
HS-R-15-2-20	HalifaxSouth	Road	2	20	15	2299	1149.5	297	148.5	580	290	261	0.07*	0.96	6.2	134.1	85.824
HS-R-15-3-10	HalifaxSouth	Road	3	10	15	2201	1100.5	339	169.5	669	334.5	448	0.17	2.1	5.68	172.3	110.272
HS-R-15-3-20	HalifaxSouth	Road	3	20	15	1896	948	367	183.5	778	389	675	0.07*	1.52	5.65	114.2	73.088
HW-C-1-1-10	HalifaxWest	Control	1	10	1	56	28	39	19.5	21	10.5	181	0.07*	0.53	4.76	782.8	500.992
HW-C-1-1-20	HalifaxWest	Control	1	20	1	47	23.5	46	23	26	13	320	0.12	0.38	4.72	653.8	418.432
HW-C-1-2-10	HalifaxWest	Control	2	10	1	66	33	90	45	39	19.5	413	0.18	0.81	5.17	589.7	377.408
HW-C-1-2-20	HalifaxWest	Control	2	20	1	65	32.5	82	41	52	26	902	0.07*	0.36	5.21	818.7	523.968
HW-C-1-3-10	HalifaxWest	Control	3	10	1	66	33	80	40	51	25.5	485	0.16	1.16	5.32	465.3	297.792
HW-C-1-3-20	HalifaxWest	Control	3	20	1	118	59	93	46.5	89	44.5	934	0.12	0.71	5.43	592.9	379.456
HW-C-5-1-10	HalifaxWest	Control	1	10	5	97	48.5	96	48	42	21	229	0.2	1.29	4.81	622.9	398.656
HW-C-5-1-20	HalifaxWest	Control	1	20	5	69	34.5	67	33.5	41	20.5	451	0.1	0.54	4.74	572.5	366.4
HW-C-5-2-10	HalifaxWest	Control	2	10	5	32	16	54	27	28	14	215	0.07*	0.46	4.27	719	460.16
HW-C-5-2-20	HalifaxWest	Control	2	20	5	36	18	53	26.5	38	19	322	0.07*	0.4	4.16	644.9	412.736
HW-C-5-3-10	HalifaxWest	Control	3	10	5	82	41	129	64.5	57	28.5	321	0.15	1.58	4.95	617.4	395.136
HW-C-5-3-20	HalifaxWest	Control	3	20	5	61	30.5	52	26	37	18.5	468	0.07*	0.3	4.95	598	382.72
HW-C-15-1-10	HalifaxWest	Control	1	10	15	54	27	70	35	27	13.5	192	0.12	0.74	4.09	506.7	324.288
HW-C-15-1-20	HalifaxWest	Control	1	20	15	58	29	60	30	32	16	278	0.07*	0.42	4.13	472	302.08
HW-C-15-2-10	HalifaxWest	Control	2	10	15	68	34	95	47.5	38	19	172	0.11	0.85	4.28	922	590.08
HW-C-15-2-20	HalifaxWest	Control	2	20	15	42	21	65	32.5	34	17	191	0.07*	0.28	4.62	757.7	484.928
HW-C-15-3-10	HalifaxWest	Control	3	10	15	59	29.5	87	43.5	27	13.5	143	0.07*	1	4.1	986.4	631.296

HW-C-15-3-20	HalifaxWest	Control	3	20	15	59	29.5	65	32.5	33	16.5	236	0.07*	0.32	4.12	465.1	297.664
HW-0-1-1-10	HalifaxWest	Outfall	1	10	1	148	74	26	13	51	25.5	1767	3.95	1.55	3.66	677.6	433.664
HW-0-1-1-20	HalifaxWest	Outfall	1	20	1	116	58	15	7.5	79	39.5	1542	3.21	0.62	3.87	409.9	262.336
HW-0-1-2-10	HalifaxWest	Outfall	2	10	1	307	153.5	31	15.5	152	76	1606	2.3	1.59	4.03	331.7	212.288
HW-0-1-2-20	HalifaxWest	Outfall	2	20	1	636	318	63	31.5	260	130	1860	0.47	0.9	4.09	259.9	166.336
HW-0-1-3-10	HalifaxWest	Outfall	3	10	1	630	315	62	31	234	117	1649	1.31	2.81	3.9	489.4	313.216
HW-0-1-3-20	HalifaxWest	Outfall	3	20	1	1016	508	107	53.5	207	103.5	1657	0.66	1.58	3.91	340.7	218.048
HW-0-5-1-10	HalifaxWest	Outfall	1	10	5	161	80.5	21	10.5	69	34.5	1549	3.83	0.93	3.78	558.5	357.44
HW-0-5-1-20	HalifaxWest	Outfall	1	20	5	237	118.5	32	16	178	89	1655	5.58	0.92	3.68	482.6	308.864
HW-0-5-2-10	HalifaxWest	Outfall	2	10	5	130	65	16	8	38	19	1532	4.55	0.7	3.88	331.7	212.288
HW-0-5-2-20	HalifaxWest	Outfall	2	20	5	163	81.5	25	12.5	98	49	1573	4.46	0.76	3.65	537.7	344.128
HW-0-5-3-10	HalifaxWest	Outfall	3	10	5	106	53	15	7.5	89	44.5	1549	2.84	0.68	4.02	497.5	318.4
HW-0-5-3-20	HalifaxWest	Outfall	3	20	5	131	65.5	14	7	84	42	1465	3.1	0.64	3.79	350.4	224.256
HW-0-15-1-10	HalifaxWest	Outfall	1	10	15	191	95.5	24	12	182	91	1554	3.84	1.09	4.11	576.9	369.216
HW-0-15-1-20	HalifaxWest	Outfall	1	20	15	302	151	39	19.5	305	152.5	1988	5.06	2.14	3.93	1622	1038.08
HW-0-15-2-10	HalifaxWest	Outfall	2	10	15	107	53.5	17	8.5	94	47	2391	3.53	1.24	3.87	337.8	216.192
HW-0-15-2-20	HalifaxWest	Outfall	2	20	15	77	38.5	11	5.5	73	36.5	1306	2.14	0.47	3.73	664.9	425.536
HW-0-15-3-10	HalifaxWest	Outfall	3	10	15	419	209.5	35	17.5	176	88	1910	3.34	1.68	3.79	359.1	229.824
HW-0-15-3-20	HalifaxWest	Outfall	3	20	15	659	329.5	57	28.5	221	110.5	1924	2.89	2.28	3.83	436.8	279.552
HW-R-1-1-10	HalifaxWest	Road	1	10	1	2484	1242	104	52	214	107	803	0.77	3.25	4.69	187.2	119.808
HW-R-1-1-20	HalifaxWest	Road	1	20	1	2412	1206	112	56	281	140.5	815	0.78	3.38	4.63	349	223.36
HW-R-1-2-10	HalifaxWest	Road	2	10	1	1303	651.5	91	45.5	118	59	1204	1.22	4.92	5.98	193.4	123.776

HW-R-1-2-20	HalifaxWest	Road	2	20	1	1454	727	99	49.5	115	57.5	1084	1.31	4.69	5.31	256.1	163.904
HW-R-1-3-10	HalifaxWest	Road	3	10	1	597	298.5	85	42.5	136	68	833	0.76	4.36	5.79	235.6	150.784
HW-R-1-3-20	HalifaxWest	Road	3	20	1	555	277.5	99	49.5	114	57	983	0.82	3.8	6.05	249.1	159.424
HW-R-5-1-10	HalifaxWest	Road	1	10	5	2506	1253	124	62	472	236	1345	1.27	3.6	4.89	526.4	336.896
HW-R-5-1-20	HalifaxWest	Road	1	20	5	2270	1135	143	71.5	395	197.5	1071	0.94	5.5	4.92	791.9	506.816
HW-R-5-2-10	HalifaxWest	Road	2	10	5	3396	1698	205	102.5	362	181	1247	1.7	7.08	4.82	565.1	361.664
HW-R-5-2-20	HalifaxWest	Road	2	20	5	2349	1174.5	132	66	288	144	1118	1.33	3.82	4.84	580.8	371.712
HW-R-5-3-10	HalifaxWest	Road	3	10	5	1350	675	133	66.5	175	87.5	1228	0.38	3.12	4.93	588	376.32
HW-R-5-3-20	HalifaxWest	Road	3	20	5	1705	852.5	165	82.5	244	122	1347	0.82	3.64	4.98	506.8	324.352
HW-15-1-10	HalifaxWest	Road	1	10	15	1759	879.5	150	75	237	118.5	762	0.68	6.24	5.22	399.4	255.616
HW-15-1-20	HalifaxWest	Road	1	20	15	2067	1033.5	134	67	393	196.5	1136	0.66	4.41	5.1	508.3	325.312
HW-15-2-10	HalifaxWest	Road	2	10	15	2455	1227.5	122	61	779	389.5	1515	0.9	4	5.21	598.8	383.232
HW-15-2-20	HalifaxWest	Road	2	20	15	2359	1179.5	110	55	708	354	1439	1.03	3.3	5.15	442.1	282.944
HW-15-3-10	HalifaxWest	Road	3	10	15	2052	1026	147	73.5	463	231.5	953	1.01	47.1	5.49	363.8	232.832
HW-15-3-20	HalifaxWest	Road	3	20	15	1251	625.5	123	61.5	340	170	915	0.72	4.3	4.97	463.6	296.704