FACETS
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RESEARCH ARTICLE

Salty summertime streams—road salt contaminated watersheds and estimates of the proportion of impacted species

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Abstract

Road salt runoff is a leading cause of secondary freshwater salinization in north temperate climates. Increased chloride concentrations in freshwater can be toxic and lead to changes in organismal behavior, lethality, biotic homogenization, and altered food webs. High chloride concentrations have been reported for winter months in urban centers, as road density is highest in cities. However, summer chloride conditions are not typically studied as road salt is not actively applied outside of winter months, yet summer is when many taxa reproduce and are most sensitive to chloride. In our study, we test the spatial variability of summer chloride conditions across four watersheds in Toronto, Canada. We find 89% of 214 sampled sites exceeded the federal chronic exposure guidelines for chloride, and 13% exceeded the federal acute guidelines. Through a model linking concentration to cumulative proportion of impacted species, we estimate 34% of sites show in excess of one-quarter of all species may be impacted by their site-specific chloride concentrations, with up to two-thirds of species impacted at some sites. Our results suggest that even presumed low seasons for chloride show concentrations sufficient to cause significant negative impacts to aquatic communities.

Key words: chloride, freshwater salinization, ecotoxicology, pollution, urban ecology, urban stressor

OPEN ACCESS

Citation: Lawson L and Jackson DA. 2021. Salty summertime streams—road salt contaminated watersheds and estimates of the proportion of impacted species. FACETS 6: 317–333. doi:10.1139/facets-2020-0068

Handling Editor: John P. Smol

Received: August 25, 2020

Accepted: November 25, 2020

Published: March 11, 2021

Published by: Canadian Science Publishing

Introduction

Salt (sodium chloride) has played a significant role for humans, ranging from being an essential dietary component and preservative to serving as a currency (Brigand and Weller 2016). Beginning in 1938, the use of salt expanded to include winter de-icing of roads and walkways as salt lowers the freezing point of water (Kelly et al. 2010). While reducing danger to humans of winter road conditions, the impacts of road salt on freshwater ecosystems is of growing concern (Cañedo-Argüelles et al. 2013). Freshwater ecosystems naturally range from levels of approximately <1 mg/L to nearly 500 mg/L chloride (Venice system 1959; Canadian Council of Ministers of the Environment 2011; Cañedo-Argüelles et al. 2013), with primary salinization deriving from bedrock weathering, sea spray, precipitation, and saline aquifers, particularly in areas where evapotranspiration exceeds precipitation (Gibbs 1970; Cañedo-Argüelles et al. 2013). However, introduction of additional salt has led to "secondary salinization", a term coined to represent the anthropogenic input of salt into the environment and the negative impacts it incurs.

Salt is a pervasive compound that it is not biologically transformed like nitrogen. Salt is diluted and flushed through watersheds (Cooper et al. 2014) or can accumulate where inputs exceed exports.

Secondary salinization impacts numerous aquatic ecosystems including wetlands, rivers, and large lakes (Dugan et al. 2017). The primary source of secondary salinization in north temperate regions is road salt runoff from road de-icing and anti-icing agents, whereas in other regions it may be caused by mining, wastewater effluents, irrigation for agriculture, and (or) climate change (Cañedo-Argüelles et al. 2013; Olson 2019). The United States and Canada, respectively, apply roughly 24.5 and 7 million tonnes of road salt annually (Betts et al. 2014; Bolen 2016).

The effects of freshwater salinization can be physical, chemical, biological, and socio-economic. Salt-laden water can lead to more corrosion and heavy metals leaching into wells and freshwater systems (Kaushal 2016; Pieper et al. 2018; Kaushal et al. 2019) and to increased rates of corrosion of concrete bridge piers (Gode and Paeglitis 2014). Changes in salinity have also been found to affect seasonal mixing of lakes and ponds, contributing to long-term or permanent stratification (Thunqvist 2004; Dupuis et al. 2019).

The biological effects of increasing salinity span multiple levels of ecosystems and impacts of chloride and salinity are largely species and life-stage dependent. For example, Collins and Russell (2009) found larval American toads to have median acute lethal concentrations of chloride (3925.8 mg/L Cl^-) nearly double that of larval wood frogs (1721.1 mg/L Cl^-) and over threefold higher than spotted salamanders (1178.2 mg/L Cl^-). Matlaga et al. (2014) found no difference in lethality of chloride to American bullfrog tadpoles at all chronic test concentrations up to 1000 mg/L Cl^-. Additionally, background conditions like water hardness can impact toxicity (Schuler et al. 2019), as Elphick et al. (2011) and Gillis (2011) have shown reduced sensitivity in harder waters. Arnott et al. (2020) showed chronic chloride exposure in soft water led to negative impacts on Daphnia at concentrations as low as 5 mg/L. At the community level, changes in salinity can cause changes in species richness and community composition (Morgan et al. 2012; Wallace and Biastoch 2016), with more tolerant taxa dominating over time (Cañedo-Argüelles et al. 2014). Within a watershed, salinity can impact riparian vegetation as well, reducing shade and increasing light (Millán et al. 2011) and potentially water temperature in streams. Moreover, the results of experimental and field studies differ vastly, with field studies indicating biological and community effects of chloride below the acute and chronic guidelines set by governments (reviewed in Hintz and Relyea 2019). The varying results between experimental and field studies makes field studies all the more critical, and there is a crucial need to identify hot spots of chloride that can serve as potential long-term field study sites to monitor the effects of chloride on ecosystems.

Long-term water-quality monitoring in Ontario under the Provincial Stream Water Quality Monitoring Network (PSWQMN) is extensive with 1970 sites where chloride data have been collected at varying intervals since 1964. Eleven of the 1970 sites in the PSWQMN are within Toronto watersheds. Forty-five years of sampling at various sites show upward trends in chloride levels over time at some sites, with summer concentrations that may surpass federal acute levels (**Fig. 1** shows trends for a Toronto sampling location; acute level = 640 mg/L and chronic level = 120 mg/L; Canadian Council of Ministers of the Environment 2011). Both summer and winter concentrations show increasing values over time at these Toronto locations and similar patterns elsewhere, but the general focus of published studies about chloride has been trends in winter concentrations or annual means that are heavily influenced by winter concentrations (e.g., Kaushal et al. 2005, 2018; Corsi et al. 2015; Dugan et al. 2017). However, there is a lag effect of chloride transport as it can be stored in soils and infiltrate groundwater, subsequently leading to increased chloride concentrations in nonwinter months (Evans and Frick 2001; Kelly et al. 2008; Perera et al. 2009; Roy et al. 2019). Shallow groundwater contributes the baseflow of many low-order streams during summer months in many temperate regions. Groundwater can become contaminated as spring rain pushes salt-laden water from winter into groundwater reservoirs, which is ultimately released during summer months as groundwater

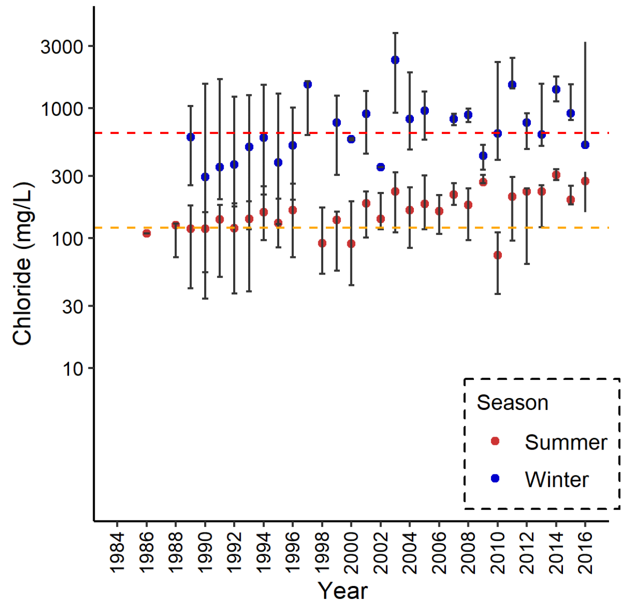

Fig. 1. Ontario Provincial Stream Water Quality Monitoring Network chloride data 1984–2016 for the Don River Pottery Road (06008501402) sampling station in Toronto, Canada (Site I in **Fig. S1**). Circles represent median chloride levels per year and season, and error bars indicate the 5th and 95th quantiles. Summer period includes the months of June, July, and August, while winter period includes January, February, and March. Data available sampled from 1986 to 2016 ($n = 395$). The orange dashed line represents the Canadian government threshold for chronic chloride exposure (120 mg/L), the red dashed line represents the Canadian government threshold for acute chloride exposure (640 mg/L). Note the logarithmic scale for chloride concentrations.

returns to surface waters and raises chloride concentrations. (Williams et al. 1999; Daley et al. 2009; Cockerill et al. 2017).

In north temperate regions, summer and early fall conditions are expected to represent the lowest "baseline" concentrations typically observed for chloride conditions and the "best" ecological conditions for species that may inhabit freshwater ecosystems impacted by road salt runoff as de-icing agents are not applied during the summer (Corsi et al. 2015). Moreover, many species reproduce in the spring and summer, often moving to locations different from where they may have been during wintertime, and these changes in location may put them at increased risk. Egg or juveniles stages of species may show greater sensitivity to chloride concentrations than adults (Gillis 2011; Hintz and Relyea 2017a, 2019). For example, many aquatic insects emerge and may disperse to new locations to mate and lay eggs (Malmqvist 2002; Danks 2007). Fish may move upstream from lakes and downstream reaches to spawn (Pritt et al. 2015), aiding in dispersal of larval freshwater mussels (glochidia) (Schwalb et al. 2011). Despite the importance of summertime conditions to the reproduction and growth of taxa, little work has been done to even define the conditions that taxa may experience during these early life-history stages. Our study tests chloride spatial variability and concentrations relative to established government regulatory thresholds in several urban watersheds during summertime, the period of time when most species having early life stages are likely to be more vulnerable, and chloride levels are expected to remain high as a result of contaminated groundwater influx and longer-term chloride storage in soil. The conditions we document are long-term levels of exposure that taxa experience, even when these conditions are at their best (i.e., baseflow chloride concentrations are at their annual minima). In addition to documenting summertime chloride conditions, we use the observed conditions to estimate the percentage of freshwater taxa that could be negatively impacted under these "best" conditions via a general response relationship for freshwater taxa. To find these estimates, we use guidelines and a species response model developed by governments from Canada within the Canadian Water Quality Guidelines for Chloride (Canadian Council of Ministers of the Environment 2011). While acute and chronic thresholds of chloride are often used as benchmarks in analyses to compare results, we go one step further by estimating the percentage of the community potentially impacted by chloride by implementing the model used to develop such acute and chronic thresholds.

Methods

We sampled the Humber River (watershed area = 911 km^2), Don River (360 km^2), Etobicoke Creek (211 km^2), Mimico Creek (77 km^2), and their associated tributaries from headwater locations located north and northwest of Toronto, down to their outlets to Lake Ontario within the City of Toronto (**Fig 2**). Headwaters of the Humber River are typically forested or agricultural land use transitioning to urbanized areas further downstream (33% natural, 37% urban, and 30% rural). The Don River has more limited regions of the headwaters that are nonurbanized but is largely urbanized otherwise (14% natural, 85% urban, and 1% rural), and both Etobicoke and Mimico creeks are largely urbanized for their entire watershed (14% natural, 67% urban, 19% rural and 10% natural, 90% urban, 0% rural, respectively) (TRCA 2018a, 2018b, 2018c, 2018d). Subsurface grab samples were collected in new

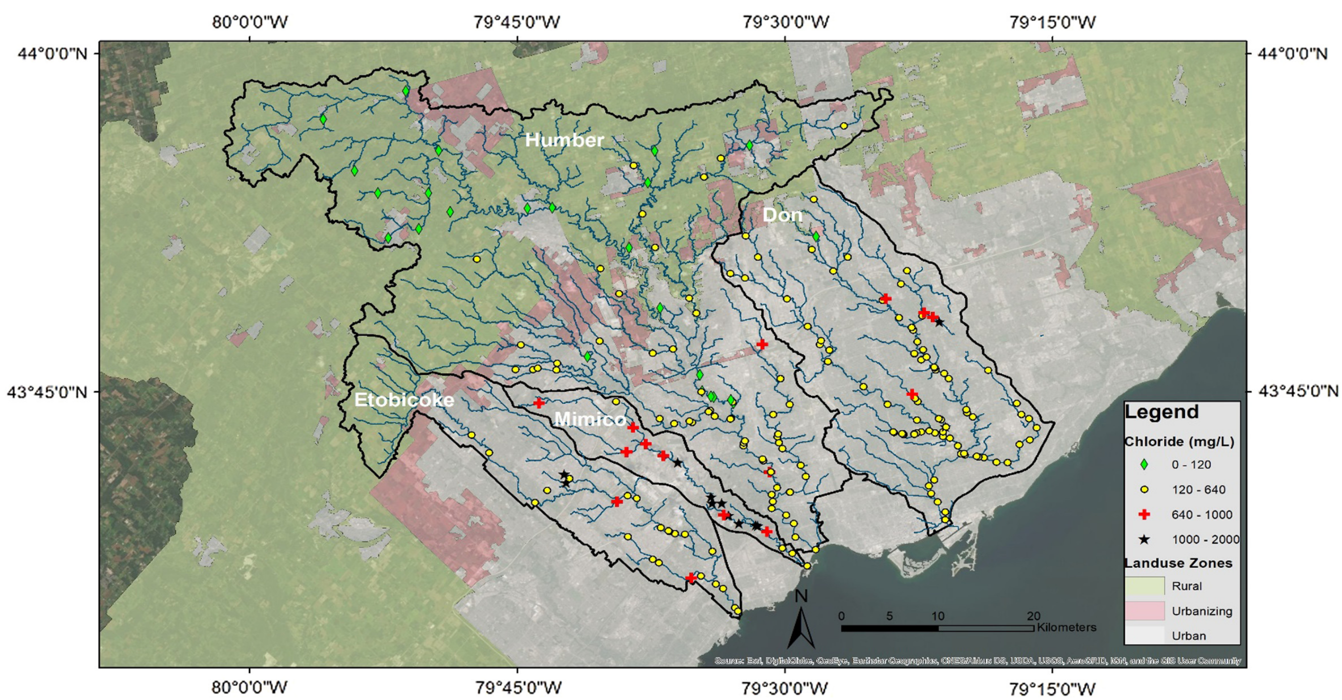

Fig. 2. Map of the sites in the current study ($n = 214$). Green diamond points indicate chloride concentrations less than the federal chronic threshold of 120 mg/L. Yellow circle points indicate chloride concentrations over the chronic threshold and below the acute threshold of 640 mg/L. Red cross points indicate chloride concentrations over the acute threshold and below 1000 mg/L. Black star points indicate chloride concentrations over 1000 mg/L. Green background layer indicates rural zone, red indicates urbanizing zone, and grey indicates urban zone (Land use source: Toronto Region Conservation Authority GIS Department, 2013). Black lines represent watershed boundaries. A similar map without the land-cover layer can be found in the supplementary information (**Fig. S1**). Basemap source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Watershed data source: services1.arcgis.com/d0ZCwU7eGKVeNiEE/arcgis/rest/services/Watersheds_TRCA/FeatureServer/0. Watercourse source: ws.lioservices.lrc.gov.on.ca/arcgis1071a/rest/services/LIO_OPEN_DATA/LIO_Open01/MapServer/26.

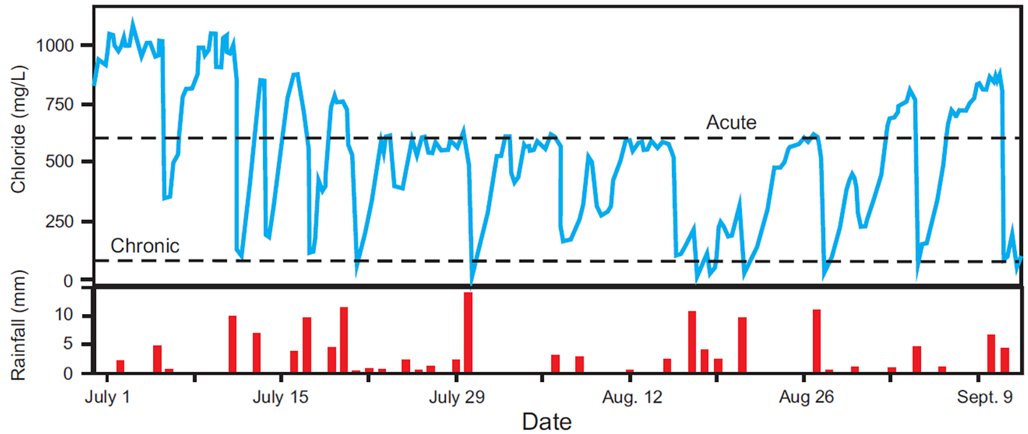

Fig. 3. Sheridan Creek continuous chloride levels for July and August 2019, including the sampling period of the current study. Data source: Credit Valley Conservation. Blue line represents chloride concentrations, and red bars represent rainfall in millimetres. The acute dashed line represents 640 mg/L Cl, and the chronic dashed line represents 120 mg/L Cl. This site exists slightly west (approximately 12 km) of the current study watersheds and is used as there is no continuous chloride monitoring data readily available within the watersheds sampled in the current study.

100 mL polyethylene containers from numerous locations along the tributaries and main stems of these river systems. Samples were collected during July and the first two weeks of August in 2019. July and August represent the months averaging lower chloride concentrations annually; thus, are the most appropriate to sample for baseflow chloride concentrations. Samples were taken on days with no rainfall nor rainfall during preceding nights, as rainfall dilutes chloride concentrations (Fig. 3); in this region, baseflow will be heavily influenced by groundwater sources (Roy et al. 2019). We used a Hach Conductivity probe model CDC40101 and Hach multi-reader desktop meter model HQ440d to measure specific conductance to provide standardized measurements of conductivity, manufacturer reported accuracy is within ±0.5% of recorded reading. The meter was calibrated using a laboratory KCl standard (1413 uS/cm). The meter was checked for drift or error in measurement using the standards after every 10 samples, and recalibrated if required.

Chloride and conductivity are strongly correlated in Southern Ontario (Wallace and Biastoch 2016); thus, conductivity values were converted to chloride concentrations. To convert conductivity, a relationship was established between the two variables for the Toronto region using data from the Ontario PSWQMN database from 1964 to 2016. A linear relationship ($r^2 = 0.99$, Fig. S3) was established between chloride and conductivity for sites from the Ontario PSWQMN located within our study watersheds (Figs. S2, S4–S10), this was then used to convert the conductivity values found at sites in the current study using eq. (1).

$$\text{chloride concentration}\,(\text{mg/L}) = 0.3372\,\text{conductivity}\,(\mu\text{S/cm}) - 153.0755 \qquad (1)$$

To compare chloride differences between the four watersheds sampled, we used a Kruskal–Wallis test as the data were not normally distributed (R Core Team 2020). We then used a Dunn test to determine which watersheds showed significantly different chloride values (Ogle et al. 2020). Finally, we showed differences among watersheds using violin plots with boxplots overlain.

To estimate the percentage of taxa that would be negatively impacted at particular chloride levels, we used the equation for long-term exposure guidelines from the Canadian Water Quality Guidelines for the Protection of Aquatic Life (Canadian Council of Ministers of the Environment 2011).

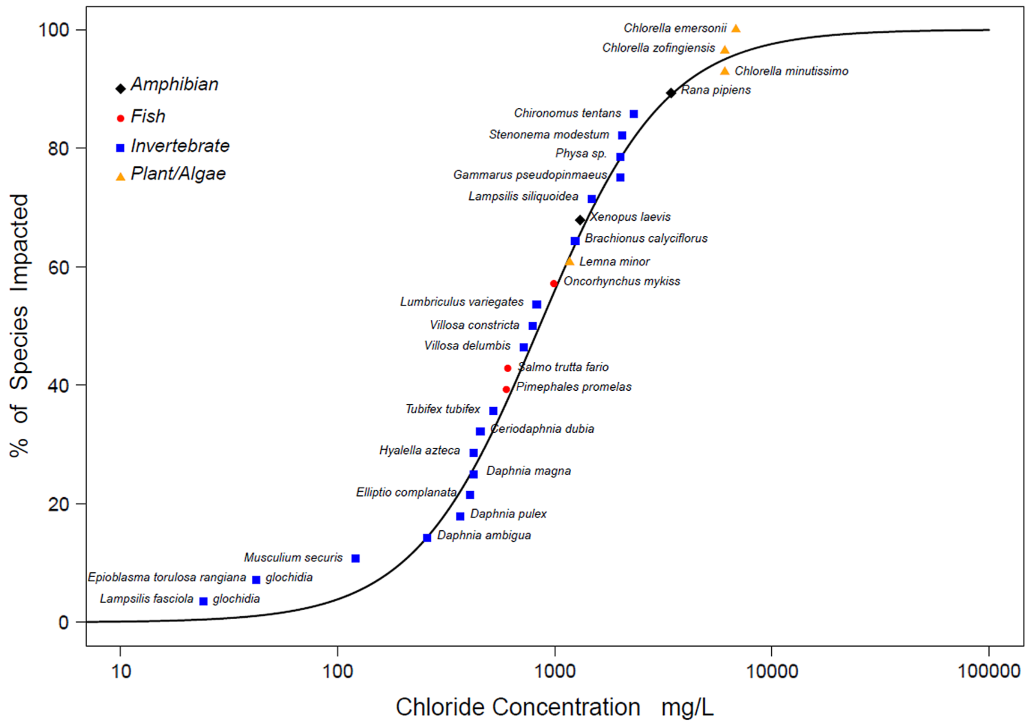

Fig. 4. Long-term chloride toxicity results from a log-logistic model derived and presented in the Canadian Water Quality Guidelines for the Protection of Aquatic Life—Chloride (Canadian Council of Ministers of the Environment 2011). Twenty-eight taxa are included including algae, plants, amphibians, invertebrates, and fish. Data derive from published studies collated in Table 5 of the Canadian Water Quality Guidelines for Chloride (Canadian Council of Ministers of the Environment 2011) and follows the model described in eq. (2). Note the logarithmic scale for chloride concentration.

This equation (eq. (2)) was developed using previously published toxicity data for taxa to estimate the cumulative percentage of taxa that were impacted at various chloride levels. Previously published data and information on toxicological tests performed are listed in Table 5 of the Canadian Water Quality Guidelines for the Protection of Aquatic Life: Chloride (Canadian Council of Ministers of the Environment 2011). Twenty-eight different taxa were used to develop a log-logistic model (eq. (2)) expressing the cumulative percentage of taxa impacted relative to the concentration of chloride (Canadian Council of Ministers of the Environment 2011). Taxa included in the development of this species-sensitivity distribution (SSD) of long-term exposure guidelines include plants, algae, fish, amphibians, and invertebrates, listed in the original guidelines (see Table 5 in Canadian Council of Ministers of the Environment 2011), and these taxa are shown in our Fig. 4. Most of these taxa are found in southern Ontario and therefore provide a nonrandom representation of the types of taxa that may be impacted by road-salt runoff in this region. From this modeled relationship, the concentration associated with the fifth percentile of the chronic species sensitivity distribution, 120 mg/L Cl^-, was set as the chronic exposure threshold (Canadian Council of Ministers of the Environment 2011). We calculated the percent of species theoretically impacted at each site in the current study assuming that the species used in developing the model (Canadian Council of Ministers of the Environment 2011) provide a generalized representation of sensitivity of taxa present, or formerly present, at each of our sampling sites (eq. (2)). All statistical analyses were performed in R version 3.6 and RStudio version 1.2.1 and mapping was performed in ArcMap 10.7.1.

$$y = \frac{1}{\left[1 + e^{-((x-\mu)/\sigma)}\right]} \quad (2)$$

where $x = \log$(concentration of chloride mg/L), y is the proportion of species affected, $\mu = 2.93$, and $\sigma = 0.29$.

Results

In total, 214 water samples, one per sampling location, were taken across the four watersheds: the Don River ($n = 87$), Humber River ($n = 82$), Etobicoke Creek ($n = 24$), and Mimico Creek ($n = 21$) (Fig. 2). The samples showed a right-skewed distribution, and 89% of the locations had chloride concentrations above the federal chronic limit (120 mg/L Cl) and 13% had chloride concentrations above the federal acute limits (640 mg/L Cl) (Figs. 2 and 5). Ten percent of sites had chloride concentrations below the chronic limits set by the Canadian government (Figs. 2 and 5) and were found almost exclusively in the headwaters of the Humber River, with a single site in the headwaters of the Don River. Additionally, about 6% of sites had concentrations >1000 mg/L, and these sites were predominantly located in Mimico Creek, with a few sites in Etobicoke Creek and Don River (Fig 2). Typically, concentrations increased from headwaters as sampling moved downstream into the more densely urbanized regions, although there are some localized areas that show elevated concentrations in mid-sections of the watersheds.

We found significant differences in chloride concentration among the four watersheds ($p < 0.0001$). Mimico Creek had the highest chloride concentrations with more than 75% of the sites exceeding the acute threshold (Fig. 6). Etobicoke Creek had all values exceeding the chronic threshold and several above the acute level. Similarly, the values obtained from the Don River typically exceeded the chronic threshold, but most samples had chloride levels below those found in Etobicoke Creek

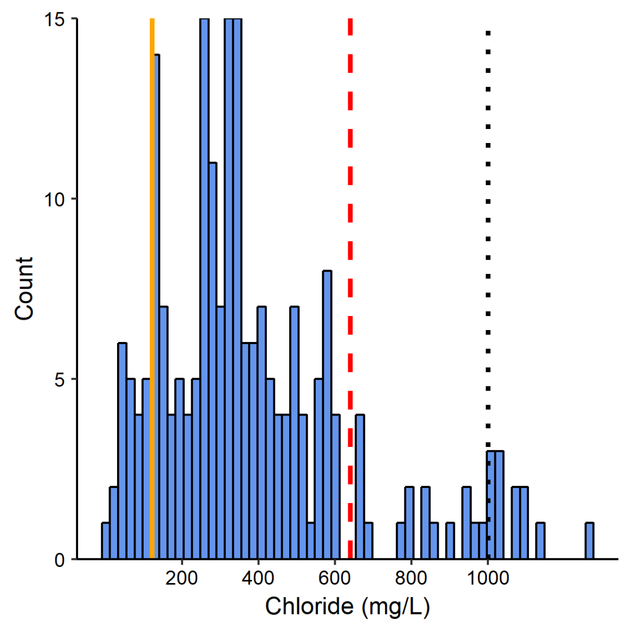

Fig. 5. Histogram of summer chloride concentrations found at sites in the current study ($n = 214$). Yellow solid line indicates the federal chronic threshold of 120 mg/L Cl. Red dashed line indicates the federal acute limit of 640 mg/L Cl. Black dashed line indicates 1000 mg/L Cl.

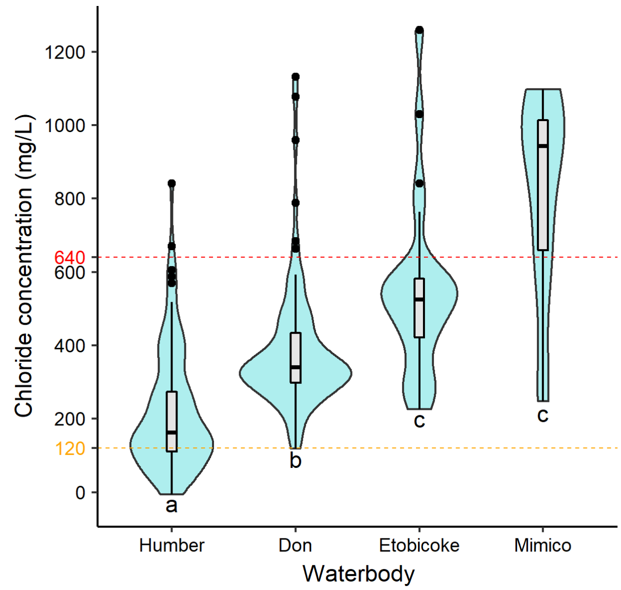

Fig. 6. Violin plots of chloride concentrations from the Humber River ($n = 87$), Don River ($n = 82$), Etobicoke Creek ($n = 24$), and Mimico Creek ($n = 21$) with boxplots overlain. Thickness of the violin plot indicates frequency of value and boxplots indicate median, first and third quartile, maximum and minimum, and outliers. Letters indicate significant differences between watersheds. The orange dashed line represents the federal chronic chloride threshold, and the red dashed line represents the federal acute chloride threshold.

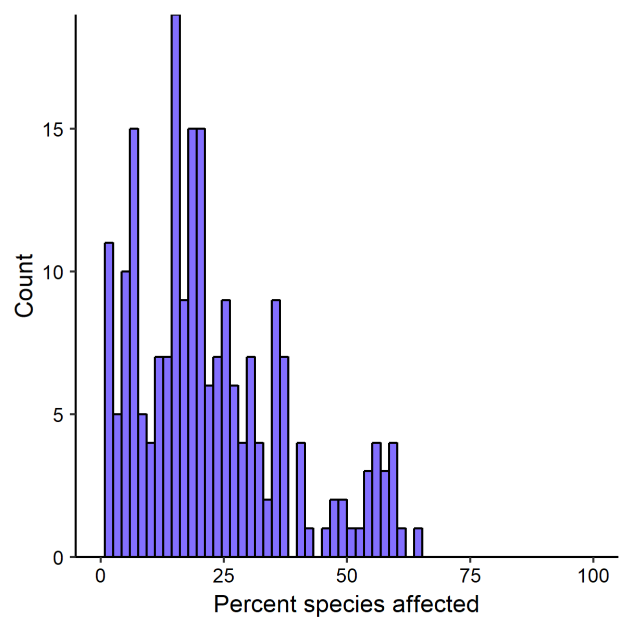

Fig. 7. Percent species affected ($n = 214$) calculated through eq. (2) from summer chloride concentrations found in the current study.

or Mimico Creek. The Humber River showed the lowest chloride concentrations in general, with about one-quarter of the sampling locations having values below the chronic threshold and most samples showing values below 250 mg/L. The Humber River and Don River concentrations were significantly different between the two watersheds and both differed from Etobicoke Creek and Mimico Creek. Chloride concentrations were not different between Etobicoke Creek and Mimico Creek (**Fig. 6**).

The estimates of cumulative species impacts due to chronic chloride exposure allowed us to estimate that theoretically 8.5% of sites would experience >50% species being negatively affected under the annual minimum concentrations found during summertime (**Fig. 7**). Furthermore, 34% of sites would have >25% species impacted according to the chronic guidelines set by the Canadian Water Quality Guidelines for the Protection of Aquatic Life—Chloride (**Fig. 7**).

Discussion

We set out to test spatial patterns in summertime chloride concentrations for four river systems that range from forested to heavily urbanized conditions and to estimate what impacts these background conditions may have on freshwater taxa. Our sampling was restricted to July and August and avoided periods of rainfall such that temporary dilution effects would be minimized. As a consequence, it is likely that discharge was close to baseflow and that groundwater contributions would be maximum to these rivers; thus, our results likely approximate baseflow concentrations of chloride. Our results show that chloride conditions in these Toronto region rivers typically exceed the Canadian federal chronic threshold, and frequently exceed the acute threshold, even during the summer when it is months after road salt had been applied. Given these concentrations and applying the generalized SSD, we estimate up to two-thirds of freshwater taxa to be negatively affected in various locations, under the best conditions experienced annually, and a much higher proportion during winter and early spring when the chloride concentrations may be more than an order of magnitude greater than we observed. Given the SSD includes taxa encompassing a broad range of animal and plant taxa, and that the majority of the taxa used in developing the SSD are present in waters of southern Ontario, it may serve as a general framework to estimate the proportions of taxa impacted. We do not assume all of these taxa from the SSD were likely to have occurred at each of the various sampling locations historically. However, given the diverse range of taxa included in the SSD, it is reasonable to assume that they may provide a generalized response of taxa to chloride concentrations for these sampling locations. Moreover, documented changes in community composition are estimated to have occurred at chloride concentrations lower than the current federal guidelines within the study region, as Wallace and Biastoch (2016) found changes in benthic macroinvertebrate communities at concentrations as low as 50 mg/L Cl^- and defined community thresholds at 81 mg/L. Thus, if the findings of Wallace and Biastoch (2016) can be generalized from benthic macroinvertebrates to other taxa, our results may actually underestimate the proportions of aquatic communities impacted by chloride despite the large impacts we suggest.

As with many other jurisdictions, salt management efforts have been made in Toronto, including covering salt storage facilities, equipping salt trucks with electronic monitoring systems, and prewetting roads with more effective brine solutions in preparation for winter storms. However, it is clear the continued accumulation of chloride in soils and contamination of groundwater contributes to high chloride levels even in summer months (Perera et al. 2009). Within sites closer to the core of Toronto, specifically the lower reaches of each river system flowing through the more heavily urbanized area, almost all sites surpassed the chronic threshold for chloride of 120 mg/L (**Fig. 2**). For the most part, only upstream sites away from the urbanized areas, such as largely forested regions sampled in the less urbanized upper Humber River, show concentrations below the chronic threshold (**Fig. 2**). The Humber River watershed has the lowest urban land cover of the four watersheds sampled, and chloride concentrations were significantly lower than the other more urbanized watersheds (Fig. 6). While Humber River chloride concentrations were relatively lower than the other watersheds, many sites within the Humber watershed surpassed the chronic threshold set by the Canadian government, and these sites were typically in the lower, more urbanized section of the watershed. We found significantly higher chloride concentrations in Mimico Creek watershed than the Don River and Humber River and higher chloride concentrations than Etobicoke Creek (Fig. 6). Mimico Creek watershed has the highest percentage urban land cover, and several sites were found to have chloride concentrations over 1000 mg/L (Figs. 2 and 5). This gradient of urbanization, both within and among watersheds, is characteristic of the urban stream syndrome, as streams in more heavily urbanized areas tend to have higher chloride levels reported due to the impermeability of surface layers and heavy density of roads (Wallace et al. 2013). The urban stream syndrome characterizes urban streams as having altered channels and hydrology, lower biotic richness, lower prevalence of sensitive species, elevated water temperatures, and higher concentrations of pollutants, of which chloride is one of many found in temperate urbanized streams (Walsh et al. 2005; Wallace et al. 2013).

Elevated chloride concentrations can cause physiological stress in freshwater organisms. Changing chloride concentrations can severely disrupt osmoregulation of aquatic organisms and disruptive changes can be lethal (Karraker and Gibbs 2011; Griffith 2017). Additionally, the region of southwestern Ontario represents the distributional range for many Canadian endangered species of fish and mussels. For example, the minnow species Redside Dace (*Clinostomus elongatus*) is predominantly found around the greater Toronto region, including areas within the Humber River, and its critical habitat may be negatively impacted by chloride levels. Pollution, including road contaminants such as road salt, is considered by the Committee on the Status on of Endangered Wildlife in Canada to be a threat to the survival of Redside Dace (COSEWIC 2017). Moreover, nonlethal effects of chloride, like reduced reproductive success and additive effects of chloride and predation stress, can be found in organisms and communities (Beggel and Geist 2015; Hintz and Relyea 2017b).

Responses to stressors are often determined by species, population-specific tolerances, and the length of exposure to stressors. Both acute and chronic stressors may be lethal. On the other hand, acute and chronic stressors may lead to acclimation as there may be some capacity to induce developmental plasticity and adaptation, and ultimately serve as selective pressures (Hoffmann and Hercus 2000; Badyaev 2005; Bijlsma and Loeschcke 2005). Behaviorally, species with a high dispersal capacity may be able to move away from stressors. However, if entire watersheds are impacted by high chloride values, species may have no suitable habitat for dispersal to avoid chloride stress or may disperse to the few suitable sites resulting in increased intraspecific and (or) interspecific competition (Kefford et al. 2016). Dispersal is also only possible for highly mobile species, and it assumes other barriers to dispersal do not exist (e.g., dams on streams and rivers), and other necessary habitat features can be located; thus, some species may be essentially trapped in habitat with high chloride concentrations where failure to acclimate to local conditions will be lethal. In addition, sensitive life stages such as eggs and larvae may lack the ability to move and reduce their exposure. Given the multiple stressors imposed on rivers and streams in urbanized areas and their increasing fragmentation of habitat, the opportunities for species to disperse and find required habitat are becoming increasingly challenging (Bond and Lake 2003).

High chloride concentrations have been found to alter communities and food webs (Van Meter et al. 2011; Hintz et al. 2017). As we estimate a high percentage of species may be affected at many of the sites in our study even during summer conditions, it is important to consider potential changes in communities in response to chloride. For example, high chloride concentrations can cause biotic homogenization, as only highly tolerant species can survive such stressful conditions (Morgan et al.

2012; Cañedo-Argüelles et al. 2013; Tiwari and Rachlin 2018). As cautioned by Tiwari and Rachlin (2018), biotic homogenization can alter interspecies relationships as predator and prey systems become disturbed due to differences in road salt tolerance. Additionally, we stress that our estimation is of species affected only by chloride. In light of the multiple pollutants found in urban watersheds, the "cocktail of chemicals" to which species are subjected may put an even higher percentage of communities at risk which potentially may influence the impacts at lower thresholds of chloride concentrations identified by Wallace and Biastoch (2016).

Using established chronic and acute thresholds to analyze effects on species communities should be taken only as a preliminary starting point for assessing effects of secondary salinization on freshwater species. Toxicity studies are often done in controlled laboratory studies and focus on a single contaminant with cultured specimens; thus, natural populations and communities may see more severe impacts. While it is conceivable populations subjected to more chronic chloride stress may select for improved tolerance over generations as shown in spotted salamanders (Brady 2012), more recent studies suggest populations near roads may exhibit lower chloride tolerance than forest reference species (Brady et al. 2017). As well, elevated chloride is often only one of various stressors that aquatic life may experience during summer as water temperatures may reach stressful levels and lead to decreased dissolved oxygen levels, thereby contributing towards multiple stressors impacting simultaneously (Jackson et al. 2001). Moreover, diverse suites of contaminants plague urban aquatic systems, of which chloride is only one stressor, making multistressor studies ever the more crucial. It is evident further field studies focusing on the impacts of road salt are vital to compare laboratory results to field conditions, and that studying road salt pollution within a multistressor framework is critical within highly polluted urban environments.

Our study provides site-specific chloride results for 214 sites in Toronto, ranging from relatively unimpacted forested headwaters to heavily impacted urbanized areas. Our study adds to a growing body of literature on chloride. Our focus was summer chloride levels, whereas most previous studies have addressed winter conditions when road salt is actively applied. Our results suggest that even in seasons when concentrations are expected to be lower, chloride levels exceed recognized government thresholds. As well, we translate these chloride concentrations into estimates of the proportion of species theoretically affected by chloride, recognizing it as being one of multiple stressors on these ecological communities. As our study was conducted during summer, a time when many of these taxa would reproduce and have more vulnerable life stages, our results may well underestimate the vulnerability of ecological communities to chloride. Additionally, the Guidelines were based on the best available chloride toxicity data, including 28 taxa ranging from algae to fish; thus, the sensitivity of communities or components of the communities may be over- or underestimated due to the representativeness of the sensitivity of the species in the communities native to each of our 214 sampling sites relative to those species which were included in the model development. Community sensitivity may be overestimated if the model was estimated on taxa that are inherently more sensitive to chloride than the set of taxa that would have lived in our sampling locations prior to chloride concentrations becoming elevated. Alternatively, community sensitivity may be underestimated if most taxa from our study region had greater sensitivity than those used in developing the model. Given the model was developed using the 28 taxa for which chloride toxicity was available from the literature, there is potential for error in either direction. As well, the greater sensitivity of early life stage to chloride increases the likelihood that our results underestimated the impacts within these ecosystems. Although we recognize the uncertainty in applying a generalized model derived from lab studies to more natural systems, it provides a framework through which we may be able to estimate relative degrees of impact. While the majority of road salt research traditionally determined patterns in concentrations, particularly during wintertime, work addressing the associated impacts on freshwater biota has been more recently developed (e.g., Arnott et al. 2020). Nevertheless, increased research

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through lab, mesocosm, and field studies is necessary to close the gap between field-based concentration pattern research and researching the impacts of road salt on freshwater biota.

Acknowledgements

We thank Loraine Price for her assistance with field sampling. Research funding was provided by an NSERC Discovery Grant and funding from Fisheries and Oceans Canada to DAJ. We thank Credit Valley Conservation for providing continuous chloride data depicted in **Fig. 3**, the Provincial Stream Water Quality Monitoring Program for data depicted in **Fig. 1** and **Figs. S2**–**S10**, and the Toronto Region Conservation Authority for land-use data used in **Fig. 2**. We thank anonymous reviewers for their useful comments regarding our study.

Author contributions

LL and DAJ conceived and designed the study. LL and DAJ performed the experiments/collected the data. LL and DAJ analyzed and interpreted the data. LL and DAJ contributed resources. LL and DAJ drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper and in the Supplementary Material.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:10.1139/facets-2020-0068.

Supplementary Material 1

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