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Salt vulnerability assessment methodology for urban streams

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SUMMARY

De-icing agents such as road salts while used for winter road maintenance can cause negative effects on urban stream water quality and drinking water supplies. A new methodology using readily available spatial data to identify Salt Vulnerable Areas (SVAs) for urban streams is used to prioritize implementation of best management practices. The methodology calculates the probable chloride concentration statistics at specified points in the urban stream network and compares the results with known aquatic species exposure tolerance limits to characterize the vulnerability scores. The approach prioritizes implementation of best management practices to areas identified as vulnerable to road salt. The vulnerability assessment is performed on seven sites in four watersheds in the Greater Toronto Area and validated using the Hanlon Creek watershed in Guelph. The mean annual in-stream chloride concentration equation uses readily available spatial data – with province-wide coverage – that can be easily used in any urban watershed.

1. Introduction

One of the most commonly employed management strategies implemented by winter road maintenance agencies is application of de-icing agents as anti-icing methods before an expected winter precipitation event or as de-icing methods after ice has formed on the road surface. In North America, the most commonly used de-icing agent by winter road maintenance agencies and for large industrial/commercial parking lots is rock salt comprised of sodium chloride with minor impurities (Perera et al., 2013). Road salts work by lowering the freezing point of water, thereby inhibiting the formation of ice.

In Canada, approximately 5 million tonnes of road salts are applied annually on roadways across the country (Environment Canada, 2004). In the US, approximately 18 million tonnes of road salts are applied each year (Jackson and Jobbagy, 2005). The majority of the road salts used in both Canada and the US are applied in major urban centers, mainly due to the high density of road networks and parking lots.

Various studies have documented that both aquatic and terrestrial ecosystems are adversely affected by exposure to high chloride concentrations associated with the typical use of road salts in urban streams (CCME, 2011; D'Itri, 1992; Adelman et al., 1976). Further, there is significant evidence of increasing chloride concentrations in both surface waters and groundwaters in urban watersheds due to the application of road salts (Mayer et al., 1999; Williams et al., 2000; Godwin et al., 2003; Thunqvist, 2004; Kaushal et al., 2005; Lundmark and Olofsson, 2006; Perera et al., 2009; Winter et al., 2011). This is a major concern for the ecological health of sensitive aquatic species as well as the quality of drinking water supplies.

Recent studies have shown that high concentrations of chloride ions associated with road salts have the potential for both immediate and long-term adverse effects on surface water systems (CCME, 2011; US EPA, 1988). High chloride concentrations in surface waters increase metal bioavailability, affect community food web structure, diversity and productivity of aquatic species (Environment Canada and Health Canada, 2001).

Chlorides do not biodegrade nor readily precipitate, volatilize, or bio-accumulate (CCME, 2011). The persistence of chlorides in the environment does not allow easy treatment, and, therefore, most of the effort in minimizing the impact of road salt is focused on optimizing salt application rates and implementing various best management practices (TAC, 2003). Currently, there are no federal regulations for the use of road salts in Canada or the United States. Several studies have developed thresholds and guidelines for road salts (US EPA, 1988; Environment Canada and Health Canada, 2001; TAC, 2003; Environment Canada, 2004; CCME, 2011). The US EPA developed toxicity thresholds for chlorides, which include

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Nomenclature

A	Contributing area (m^2)
CGVD28	Canadian Geodetic Vertical Datum 1928 (–)
BFC	Baseflow Chloride Concentration (mg/L)
BFI	Base Flow Index (–)
CAD	Chloride Application Density (–)
CCME	Canadian Council of Ministers of the Environment (–)
Cl^-	Chloride Ion (–)
EC	Electrical Conductivity (–)
EPA	Environmental Protection Agency (–)
LC_{50}	Lethal Concentration 50% (–)
GIS	Geographical Information System (–)
GPS	Global Positioning System (–)
SCC	Mean Annual Stream Chloride Concentration (mg/L)
SVA	Salt Vulnerable Areas (–)
UAR	Unit Chloride Application Rate (g/m^2)
MAF	Normalized Mean Annual Flow (m)
MOE	Ontario Ministry of the Environment (–)
MTO	Ontario Ministry of Transportation (–)
PGMN	Provincial Groundwater Monitoring Network (–)
US EPA	United States Environmental Protection Agency (–)

chronic freshwater quality criterion of 230 mg/L and an acute freshwater quality criterion of 860 mg/L (US EPA, 1988). Canadian Council of Ministers of the Environment (CCME) developed Canadian drinking water standards that outlined aesthetic objectives for chloride and sodium at 250 mg/L and 200 mg/L, respectively.

Environment Canada (2012) concluded that attention to salt vulnerable areas was significantly lacking in provincial and municipal salt management plans (SMP). Less than 30% of the SMP inventoried salt vulnerable areas. Salt vulnerable areas are defined as any area susceptible to adverse impact to the health of the aquatic species or quality of drinking water sources as a result of the application of road salts during winter maintenance activities on roads and parking lots. The low rate of participation of road agencies in identifying salt vulnerable areas may be due to a lack of clear guidance of the methods and the concern that the process of identifying salt vulnerable areas may require expensive and advanced data collection and analysis (Environment Canada, 2012). Salt vulnerable areas are those which would benefit most from Best Management Practices (BMPs) outlined in salt management plans and hence it is prudent to identify these key areas in which to take action and reduce risk.

This paper describes a methodology, using readily available Geographical Information System (GIS) data, to identify areas vulnerable to road salts, through evaluation of the impact to aquatic species caused by the application of road salts. The methodology quantifies the vulnerability to identified areas in order to prioritize implementation of best management practices.

2. Study areas

Six different urban watersheds (Study Rivers) are considered within the City of Toronto boundary: Etobicoke Creek, Mimico Creek, Humber River, Don River, Highland Creek, and Rouge River. Estimation of the vulnerability to road salt application was performed on seven sites in four of the watersheds in the City of Toronto, Ontario (Fig. 1) and validated using Hanlon Creek Watershed in the City of Guelph, Ontario (Fig. 2).

Data were acquired from the City of Toronto Stream Chloride Monitoring Program. The Study Areas included two sites on the Humber River (at Steeles Ave. and Old Mill Rd.), the Don River (at Bloor St.), Highland Creek (at Morningside Ave.), and the Morningside Creek tributary of the Rouge River (at Finch Ave.). To supplement the City of Toronto monitoring data, Perera et al. (2009) added two additional stations in the Highland Creek watershed in 2007. These two locations were selected to represent the two main tributaries of Highland Creek, West Highland Creek (at Bellamy Rd.) and Malvern Branch (at Mammoth Hall Trail). Data for the Hanlon Creek watershed was collected as part of this research project for the water year of November 2010 to October 2011. This station was located just downstream of Highway 6 on Hanlon Creek.

2.1. Data collection

As a result of the Code of Practice for Road Salts, the City of Toronto Stream Chloride Monitoring Program collects hourly electrical conductivity readings, as a surrogate for chloride concentration, using a Hach conductivity sensor (model no. 5798A) with a Hach Sigma 900 Max autosampler attached (Perera et al., 2009). As part of this research project, electrical conductivity (as a surrogate for chloride concentration) was also monitored in the Hanlon Creek watershed using CTD-Diver (a Schlumberger product) with a depth range of 10 m and electrical conductivity range of 80 microSiemens per centimeter (μS/cm) on 10 min intervals.

The seven monitoring sites within Toronto cover a wide range of watershed areas and land use characteristics. The contributing watersheds to the seven monitoring sites range in size from 15 to 878 km^2. Land use characteristics also cover a wide range within the Study Areas with predominant land use changing from industrial, institutional, residential to open area.

The Hanlon Creek monitoring station was selected to provide an additional study area outside of Toronto for purposes of methodology validation. The contributing watershed area to the Hanlon Creek is small compared to the other seven Study Areas (10.7 km^2), but the land use characteristics include a wide range with almost an even split of industrial (27.1%), residential (28.1%) and open land use (29.3%), with the rest of the area consisting of city roads (11.9%), commercial (1.6%) institutional (1%) and MTO highway (1%). Table 1 presents the summary statistics of stream chloride concentrations for the eight case study watersheds, showing roughly sevenfold differences in the mean annual chloride concentrations ranging from 118 to 765 mg/L.

2.2. Electrical conductivity and chloride concentration

The monitoring program established by the City of Toronto was developed to collect continuous chloride concentration data. The monitoring program utilized measurements of specific conductance, also known as electrical conductivity (EC), as a surrogate for chloride concentrations (Cl^-). In order to establish the correlation between EC and Cl^- readings, grab samples were collected and analyzed by the Toronto Water Laboratory for EC and major ions (sodium, calcium, magnesium, potassium, chloride, sulfate, and bromide). A number of studies (e.g. Howard and Haynes, 1993; Granato and Smith, 1999; Guan et al., 2010; Kilgour et al., in press, and Perera et al., 2013) identified that a strong linear relationship exists between EC and Cl^-. Perera et al. (2009) indicated that at low EC values a simple linear relationship resulted in poor accuracy and at

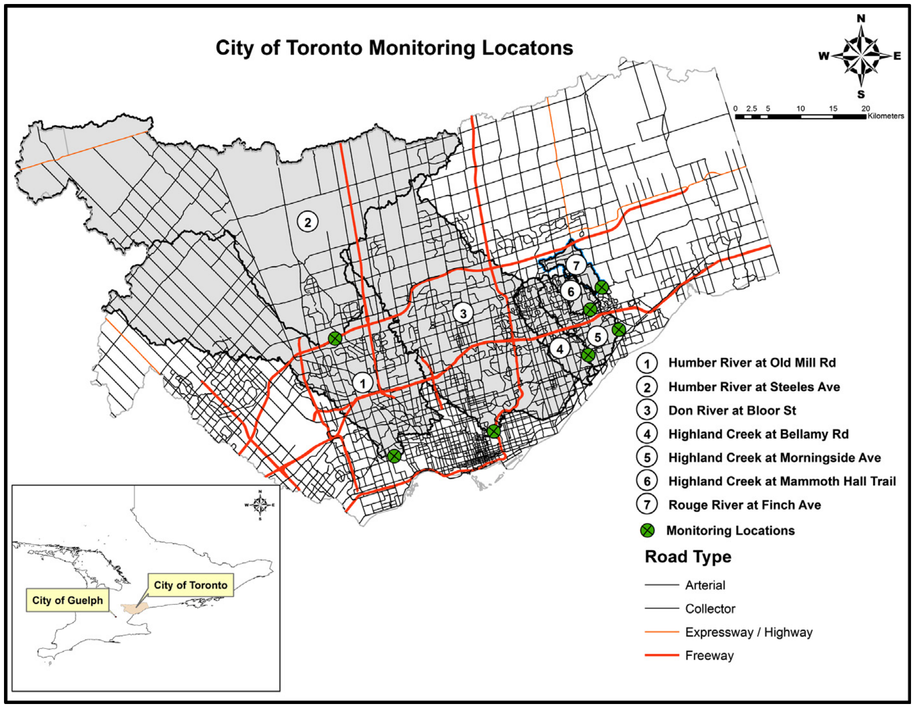

Fig. 1. The study watersheds in the City of Toronto, Ontario.

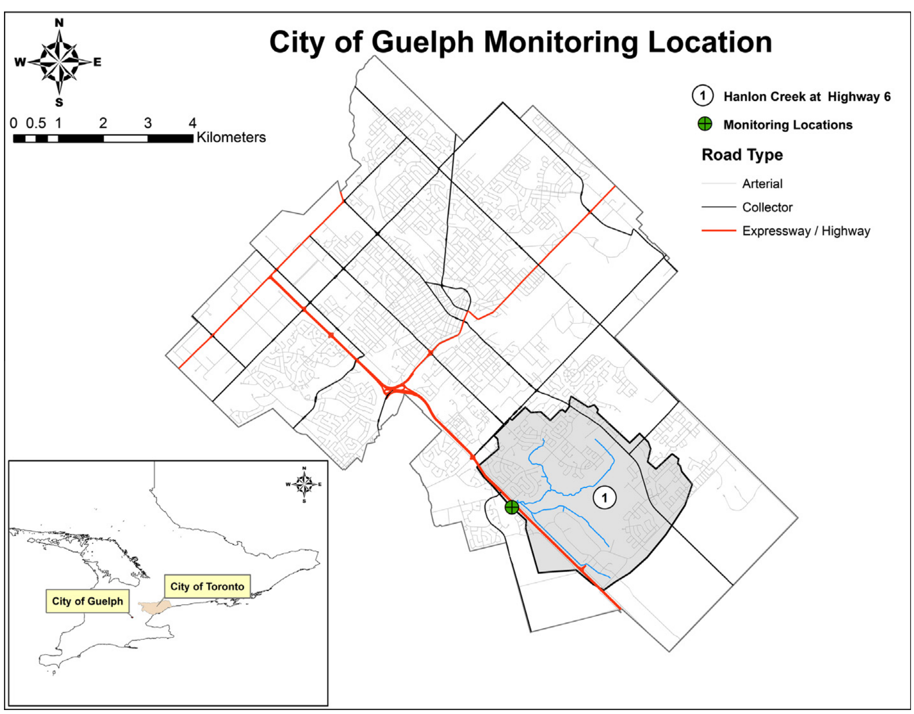

Fig. 2. The Hanlon Creek watershed in the City of Guelph, Ontario.

times resulted in an erroneous negative chloride concentration due to the effect of other ions (calcium, magnesium, potassium, and sulfate); however, a bi-linear relationship improves the accuracy at low EC values and removes the negative chloride concentrations caused by the simple linear relationship (Perera et al., 2009).

3. Methodology

A mass balance equation can be developed to estimate the mass loading of chlorides entering urban streams. Perera et al. (2010) and Novotny et al. (2009) used a mass balance approach to determine

Table 1
Summary statistics of stream chloride concentrations for case study watersheds.

Study area	Mean (mg/L)	Median (mg/L)	Standard deviation (mg/L)	Kurtosis	Skewness
Don River at Bloor St.	504	251	557	2.6	1.7
Highland Creek at Bellamy Rd.	718	327	966	11.2	3
Highland Creek at Mammoth Hall Trail	765	193	1171	5.4	2.4
Highland Creek at Morningside Ave.	596	297	761	7.7	2.6
Humber River at Old Mill Rd.	335	152	402	2	1.8
Humber River at Steels Ave.	132	87	119	87.3	9.1
Rouge River at Finch Ave.	118	104	131	1.5	1.4
Hanlon Creek at Hwy 6	283	281	21	3.1	0.1

the annual discharge of road salt in urban streams using measured stream flow rate and chloride concentrations.

Chloride ions are transported from roads and parking lots to receiving waters along three pathways: (1) rapid runoff to stormwater drainage systems, (2) shallow soil infiltration through interflow, and (3) a deeper and slower pathway through aquifers (Novotny et al., 1999). As a result, there are temporal and spatial variations in chloride concentrations in streamflow and groundwater recharge (Novotny et al., 2009).

Four key assumptions were considered in the road salt mass balance calculation: (i) road salts applied in a study area are transported by either surface runoff or groundwater recharge (infiltration); (ii) in-stream chloride concentration is a result of the combination of surface runoff and groundwater discharge (baseflow). This assumption is valid for the Study Areas of interest herein since there are no atmospheric contributions (not a coastal environment), and, other anthropogenic inputs (such as sewage, industry, water softening, agricultural use, or bedrock weathering) are comparatively small relative to the contributions from road salt application; (iii) chloride concentration in surface runoff is the same as the chloride concentration in groundwater recharge when spatially averaged for a given watershed. This is premised on groundwater recharge originating from surface runoff in urban areas (i.e. what does not infiltrate as groundwater recharge becomes surface runoff); (iv) the volume of water in groundwater recharge is, on an annual long-term average, equal to the volume of water discharged into the stream as baseflow (Conservation Ontario, 2010).

3.1. Surface water vulnerability assessment

The contributing area to a point of interest (potential salt vulnerable area) is considered to be the drainage area that contributes surface water runoff from rain or snowmelt. Identifying if an area is vulnerable to road salt application is based on the adverse impact of chlorides on aquatic species (i.e. if the inputs of chloride ions will have a negative impact on the local ecosystem). Vulnerability scores for urban streams are calculated by counting the number of aquatic species that will likely be impacted due to sensitivities to acute or chronic chloride exposure limits – presented in CCME (2011) – based on the stream chloride concentration probability distribution function.

The CCME (2011) document presents credible scientific methods and data that went into calculation of the short-term LC50 toxicity data for the chloride ion for a comprehensive list of commonly found freshwater aquatic species, including many fish, frogs and bugs. However, the collection and identification of aquatic species is not needed as part of the methodology proposed by this study; this study uses exactly the same comprehensive list of fish, frogs and bugs as identified by the CCME (2011) guide for all urban streams for calculation of the vulnerability score.

The vulnerability score for surface water resources for each of the Study Areas was calculated based on the probability of occurrence of in-stream chloride concentration reaching or exceeding the LC_{50} values for the sensitive species outlined in CCME Canadian Water Quality Guideline for Chloride. The probability of occurrence for each exposure limit value was calculated using one minus the lognormal cumulative distribution function in EXCEL (Eq. (4)). The cumulative distribution function calculates the probability of having a value less than or equal to X, where X represents a species exposure limit. Therefore, one minus the cumulative distribution function is the probability of having a value greater than or equal to X. The probability of occurrence was calculated for 59 sensitive species exposure limits for each Study Area (Betts, 2013). Therefore, the maximum score a Study Area can receive is 59 (i.e. a probability of occurrence greater than 0.011 for all sensitive species).

Any Study Area that produces a vulnerability ranking score greater than or equal to one means that it can be considered, to some degree, a vulnerable area to road salts. However, the list of 59 sensitive species may not all live in the Study Area. Therefore, to determine whether a Study Area is considered vulnerable to aquatic species in its current state, it may be advantageous to conduct a species monitoring program and determine what species in fact do live within the Study Area stream network and re-calculate the vulnerability ranking scores.

3.1.1. Chloride concentration probability distribution

Betts (2013) determined that the lognormal probability distribution provides the best fit to the in-stream chloride concentration data measured in the Study Rivers. To estimate the probability of occurrence for any chloride concentration, the lognormal cumulative distribution function is used. Two parameters, the mean and standard deviation, are required to calculate the probability distribution function for the lognormal probability distribution.

Eq. (1) calculates the mean annual in-stream chloride concentration (SCC) mean annual mass balance calculation at a watershed scale. The total amount of salt entering to an urban stream originates from two main pathways, surface runoff and groundwater. The total amount of salt in surface runoff is proportional to paved surfaces that receive salt application in a watershed and the mean annual salt application rate per unit area (which is depends on the level of winter maintenance service for each type of paved surface). The mean annual salt load in groundwater seeping into an urban stream is proportional to the baseflow quantity and its salt concentration. The input parameters for Eq. (1) are assigned based on the data collected from the case study watersheds.

$$\mathrm{SCC} = \frac{A * \mathrm{CAD} * \mathrm{UAR} * (1 - \mathrm{BFI}) + \mathrm{BFC} * \mathrm{BFI} * A * \mathrm{MAF}}{A * \mathrm{MAF}} \quad (1)$$

where SCC is Mean Annual Stream Chloride Concentration at a point of interest, (mg/L); A is Contributing area, (m^2); CAD is Chloride Application Density; UAR is Unit Chloride Application Rate (g/m^2); BFI is Base Flow Index; BFC is Baseflow Chloride Concentration (mg/L); MAF is normalized Mean Annual Flow (m).

Eq. (2) is used to calculate the standard deviation (σ_x) of the mean stream chloride concentration (SCC).

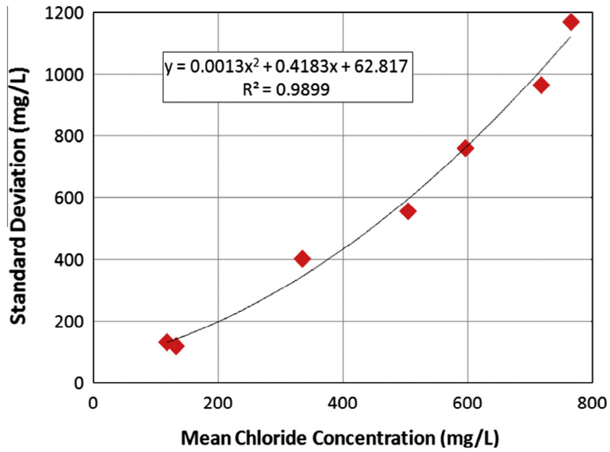

Fig. 3. Correlation of mean and standard deviation of stream chloride concentrations.

$$\sigma_X = \log(0.0009 * SCC^2 + 0.7454 * SCC) \quad (2)$$

Eq. (2) was developed based on the correlation between the measured mean and standard deviation – presented in Fig. 3 – from the in-stream chloride concentration data collected for Toronto.

To convert the calculated standard deviation into the logarithm standard deviation – required in the calculation of the probability of occurrence of a given stream chloride concentration – Eq. (3) (from Miller et al. (1990)) is used.

$$\sigma_y = \sqrt{\ln\left(1 + \frac{\sigma_x^2}{\mu_x^2}\right)} \quad (3)$$

where σ_y is Logarithm Standard Deviation of the Mean; σ_x is Standard Deviation (mg/L) and μ_x is SCC (mg/L).

The probability of occurrence for each of the aquatic species exposure limits is calculated from one minus the cumulative probability distribution to calculate the probability of concentration equal to or greater than the chloride concentration will occur.

$$\text{Probability of occurrence} = 1 - \text{LOGNORM.DIST}\ (X,\ \text{mean},\ \text{standard}_{\text{dev}}) \quad (4)$$

3.1.2. Chloride concentration exposure limits

CCME (2011) developed guidelines for short-term (24–96-h) and long-term ($\geqslant$7-day exposures for fish and invertebrates) exposure limits – Lethal Concentration 50% (LC50) to chloride concentration, based on severe effects data for aquatic species. The guidelines are intended to protect against direct toxic effects of chloride, based on NaCl and $CaCl_2$ salts. The total number of aquatic species, in a given urban stream, that will likely be exposed to acute chloride concentrations ($\geqslant$LC50 thresholds) are calculated using mean daily stream chloride cumulative probability distribution function and reported as the salt vulnerability scores of the urban stream. The vulnerability ranking for each area of interest are sorted in descending order and this creates a prioritized list of sites most vulnerable to road salts (Betts, 2013).

3.2. Input parameters

The following describes the methodology and data requirements used to determine each of the input parameters for Eq. (1).

3.2.1. Contributing area

The drainage area that contributes chloride ions to a potential identified salt vulnerable area is referred to as the contributing area. For surface water, the contributing area is defined as the area upstream of a point enclosed by a topographic divide such that all surface runoff drains by gravity toward that point.

For surface water, the potential contributing area for a salt vulnerable area is determined by the topography of the landscape. The Ontario Ministry of Natural Resources has just (in 2014) released the Ontario Flow Assessment Tool as a new public-domain (http://www.giscoeapp.lrc.gov.on.ca/web/mnr/wrip/ofat/Viewer/viewer.html) online spatial application that provides easy access to data packages, known as Ontario Integrated Hydrology Data, to provide a collection of related elevation and mapped features with complete coverage for the entire province of Ontario.

Using a Digital Elevation Model (DEM) and a stream network shapefile, the contributing drainage area (contributing area) is determined in a GIS by using the ArcHydro toolkit. ArcHydro is a model developed for building hydrologic features that support hydrologic modelling. The result is a geo-referenced polygon shapefile that outlines the land area that influences the quantity and quality of water draining to the user-selected point.

3.2.2. Chloride Application Density (CAD)

Land use has direct and indirect effects on physical, chemical and biological characteristics of streams and has been modelled using a variety of land-use/land-cover descriptors (Stanfield and Kilgour, 2006). Studies of overall stream health suggest that the factor most predictive of variation in stream health ranking is percent impervious cover (Snyder et al., 2005; Goetz et al., 2003; Schueler, 1994).

The Chloride Application Density (CAD) is the total area within the contributing area that receives chloride applications. For a given land use type, CAD is calculated as:

$$C\ AD = \%\text{Area receiving road salt application} \times \text{Salt application weighting factor} \quad (5)$$

Table 2 present the assumed (based on Perera et al. (2010)) Fraction of Area Receiving Road Salt Application and the Salt Application Weighting Factors for the typical urban land use categories, including: Commercial, Industrial, Institutional, City Roads, Provincial Highways, Residential, and Open Areas.

For a given urban watershed, the area-weighted CAD is a unitless parameter based on the weighed-sum of percent land use receiving salt application multiplied by the chloride application density per land use type, as:

$$\text{Total}\ C\ AD = \sum_i (\%\text{Area covered by a land use} \times \text{CAD for the land use}) \quad (6)$$

To calculate the percentage of land use receiving road salt application, land use mapping and aerial imagery were used in a GIS to manually digitize the area within each land use category where road salts are applied. The manual digitization is used to separate parking lots and roads from roof tops and green space. This was performed on approximately 50 individual properties for four land use types

Table 2
Salt application weighting factors (Perera et al., 2010).

Land use type	Fraction of area receiving road salt application	Salt application weighting factor (Perera et al., 2010)	Chloride Application Density (CAD)
Commercial	0.560	2.0	1.12
Industrial	0.465	1.0	0.47
Institutional	0.154	2.0	0.31
City roads	1.000	1.0	1.00
Highways	1.000	1.0	1.00
Residential	0.240	0.5	0.12
Open	0.000	0.0	0.00

(commercial, industrial, institutional, and residential) spread amongst the seven Study Areas within the Toronto. The land area receiving road salt applications for each land use type was then averaged and applied to each contributing area.

The weighted application rate represents the different application rates that are applied to each land use. Toronto and Ministry of Transportation of Ontario (MTO) equip their salt application trucks with calibrated spreader controls and geographical positioning system (GPS) units so they can maintain detailed daily records of salt application rates. Perera et al. (2009) quantified daily salt application quantities for both Toronto and MTO for three subcatchments in Highland Creek as part of the mass balance calculation. Perera et al. (2009) concluded that on a long term average basis, Toronto and MTO had very similar application rates on a unit area basis. The largest uncertainty in chloride application rates is the quantity applied on parking lots and private roads/driveways. Based on a mass balance calculation, Perera et al. (2009) estimated that commercial and institutional properties received a rate two times higher in comparison with road networks on a unit area basis. A landscape contractor in the Kitchener area indicated that their road salt application rate is approximately 2.5 times the rate used by MTO (Perera et al., 2009). The weighted application rate for each land use type used in this study was based on the research presented in Perera et al. (2009).

To calculate the CAD value for a Study Area the distribution of land use was determined using a GIS, within the boundary of the contributing area, with land use and road network map shapefile layers. The land use and road network maps were clipped using the contributing area map and total areas were summed for each land use and road type.

The CAD value was calculated by multiplying the land use areas by the fraction of land use receiving road salt application and the salt application weighting factor, then dividing by the total contributing area (Eq. (5)).

3.2.3. Unit Chloride Application Rate (UAR)

Road authorities define road salt application rates on a mass per unit area. The largest contributors of road salts within the City of Toronto are City of Toronto Transportation Services and MTO, and typical application rates are 70–180 kg per lane km (kg/lane-km) (City of Toronto, 2005).

Quantification becomes difficult when multiple road maintenance agencies employ different application rates within the same study area. This method is based on the application rates of one maintenance agency as a surrogate for all application agencies (with the difference being accounted for through the CAD parameter). It is therefore important to determine the unit area application rate of the representative agency and to have an understanding as to how the other road maintenance agencies compare. The City of Toronto Transportation Services has over 25 years of salt application record and they are the organization responsible for the largest portion of road salt application in the Study Areas. Therefore, the City of Toronto was selected as the representative road maintenance agency on which to base the unit chloride application rate. The unit chloride application rate (UAR) is:

$$\mathrm{UAR}\left(\frac{\mathrm{g}}{\mathrm{m}^2}\right)=\frac{\text{Annual road salt application mass (tonnes)}*10^6\,\frac{\mathrm{g}}{\mathrm{tonnes}}}{\text{Total road length (2-lane km)}*1000\,\frac{\mathrm{m}}{\mathrm{km}}*7.0\,\frac{\mathrm{m}}{\text{2-lane}}}*60.66\%\,\frac{\mathrm{Cl}^-}{\mathrm{NaCl}} \tag{7}$$

The inputs to the UAR calculation (annual quantity of road salts applied and total road length) can be readily obtained from the annual SMP reports produced by the road maintenance agency (Municipal, Regional or Provincial) as required as part of the Code of Practice.

A total of 25 years of salt application data were collected from the City of Toronto annual road salt management report submitted to Environment Canada as part of the Code of Practice. In addition to salt application quantities, total road length receiving salt application was collected. Dividing the quantity of salt applied by the total road length for each year then converts the result into g/m^2 and averaging all years provided the average UAR.

3.2.4. Baseflow Index (BFI)

Groundwater is a significant component of the hydrologic cycle. This is especially true in many southern Ontario watersheds, where groundwater levels are close to the ground surface. Groundwater effects water supply and in-stream water quality and quantity. Groundwater discharge to surface water sustains streamflow during extended dry periods as well as the in-stream water temperature and is commonly referred to as baseflow. Baseflow is a more constant, less fluctuating component of streamflow, than runoff.

Spatial distribution of groundwater discharge to surface water for the case Study Areas was calculated using the baseflow index regional map – which is influenced by climate, topography, landscape, and geological characteristics (Santhi et al., 2007). Numerous computer methods of baseflow separation have been established, making predictions of baseflow easy and inexpensive. Selection of a method to estimate recharge is largely an exercise of weighing trade-offs and making compromises between scale and resolution (Neff et al., 2005). Santhi et al. (2007) used Pearson's correlation table and a stepwise multiple regression to determine the relative importance of geologic characteristics and concluded that relief and percentage of sand were highly correlated to baseflow index. Neff et al. (2005) used baseflow separation coupled with surficial geology classes and percentages of surface water to estimate baseflow at ungauged sites within the Great Lakes. Piggot and Sharpe (2007) developed a revised method of analysis for the UK Institute of Hydrology (UKIH) method that provides a more detailed resolution than the results reported by Neff et al. (2005) for the Province of Ontario.

The methodology used herein is based on the methodology developed by Piggot et al. (2005) and Piggot and Sharpe (2007), utilizing streamflow data for 268 gauged watersheds and completed hydrography separation. Baseflow index (BFI), defined as the long-term average of baseflow relative to total streamflow, is a dimensionless value between zero and one. BFI is interpreted by Piggot and Sharpe (2007) using geological mapping and stratigraphy in order to estimate the quantity and distribution of groundwater discharge to surface water.

Ontario Geological Survey (1997), Quaternary Geology, seamless coverage of the Province of Ontario (ERLIS Data Set 14, Ontario Ministry of Northern Development and Mines), which is at a scale of 1:50,000, along with calculated baseflow index for the 32 geological units represented in Quaternary Geology were used to calculate BFI for each Study Area in a GIS. This methodology is similar to that adopted by Neff et al. (2005), but more fully utilizes the detail of mapping of Ontario that is provided in Quaternary Geology (1997) (Piggot and Sharpe, 2007). The estimates of BFI are a combination of the assigned BFI for each geological unit and the weighted thickness of the corresponding strata. Table 3 provides the calculate BFI for each of the 32 geological units in the Ontario Quaternary Geology map (Piggot and Sharpe, 2007).

Using the contributing areas for each Study Area to "clip" – using GIS tools – the resulting BFI map and spatially-average the BFI values within the Study Area, weighted by the respective percentage of total area, a weighted average BFI value was obtained.

3.2.5. Normalized Mean Annual Flow (MAF)

Chloride concentration in-stream or in groundwater recharge is a ratio of the mass of available chlorides and the volume of water.

Table 3
Calculate BFI for each of the 32 geological units in the Ontario Quaternary Geology map (Piggot and Sharpe, 2007).

Geologic component	Description	BFI
1	Bedrock (Precambrian)	0.685
2	Bedrock (Paleozoic)	0.467
3, 5, 7, 9, 10, 11, 12, 16, 17, 19	Till (silt matrix)	0.363
4, 6, 8, 15, 21	Till (clay matrix)	0.179
13, 14, 18, 20	Till (sand matrix)	0.669
22	Glaciofluvial ice-contact deposits	0.713
23, 28, 31	Glaciofluvial outwash deposits and fluvial deposits	0.807
24, 26, 29	Glaciolacustrine, glaciomarine, marine, and lacustrine deposits (fine textured)	0.174
25, 27, 30	Glaciolacustrine, glaciomarine, marine, and lacustrine deposits (coarse textured)	0.656
32	Organic deposits	0.435

The methodology proposed here uses the Normalized Mean Annual Flow (MAF) as the dilution factor for in-stream chloride concentration. The normalized MAF is the average depth of water per unit area (m), in a year that would flow past a defined point.

Environment Canada's Water Survey of Canada collects, interprets and distributes gauged streamflow data for over 2500 active hydrometric gauges across Canada. For each gauging station, Environment Canada calculates the mean annual flow (m^3/s). The data from the gauging stations are collected under a federal–provincial joint program. There are a total of eleven monitoring stations within the City of Toronto Study Area; five stream gauges available in Humber River, three in Don River, two in Highland Creek and one in Rouge River. The longest data range available for each gauging station, up to a maximum of 30 years (1980–2010), were collected and the normalized MAF was calculated for each watershed using Eq. (8).

$$\text{Normalized MAF (m yr)} = \frac{\text{MAF}\left(\frac{m^3}{s}\right) * 3600\,\frac{s}{h} * 24\,\frac{h}{day} * 365\,\frac{days}{yr}}{\text{Drainage area km}^2 * \frac{10^6\ m^2}{km^2}} \tag{8}$$

Using the average mean annual flow (m^3/s) calculated from the data range (up to 30 years) for each of the 12 Environment Canada gauge station and dividing by the drainage area (Eq. (8)), the normalized MAF was calculated for all of the Study Areas.

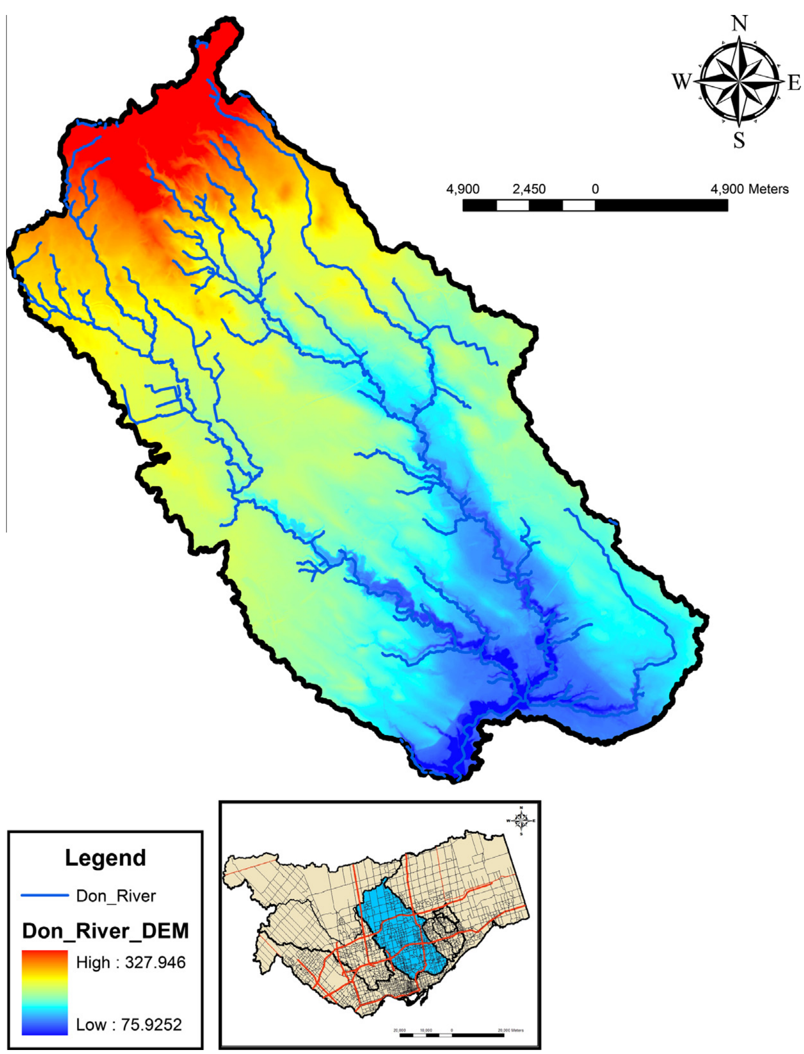

Fig. 4. Surface water contributing area for the Don River at Bloor St. station.

3.2.6. Baseflow Chloride Concentration (BFC)

Due to the importance of understanding the quantity and quality of groundwater resources for drinking water purposes in Ontario, municipalities regularly collect groundwater quality data, which includes chloride concentration. In addition the MOE established a comprehensive groundwater database for Ontario in 2000, known as the Provincial Groundwater Monitoring Network. The PGMN is operated in partnership with the thirty-six Ontario Conservation Authorities and eight participating Municipalities. The network currently consists of 474 groundwater monitoring wells across Ontario, 380 of which have been selected for long-term annual water chemistry monitoring. The long-term groundwater monitoring parameters include: general chemistry, metals and major ions, including chloride concentration.

Table 4
Chloride Application Density (CAD).

Location	Watershed area (km^2)	Land use types in urban watersheds												Total CAD
		Commercial		Industrial		Institutional		Open		Roads		Residential		
		Area (%)	CAD	Area (%)	CAD	Area (%)	CAD	Area (%)	CAD	Area (%)	CAD	Area (%)	CAD	
Highland Creek at Mammoth Hall Trail	12.4	4.2	1.12	42.4	0.47	4.4	0.31	15.9	0	11.4	1	21.7	0.12	0.400
Highland Creek at Bellamy Rd	36.9	7.8	1.12	11.6	0.47	7.1	0.31	14.8	0	13.7	1	45.0	0.12	0.355
Highland Creek at Morningside Ave	84.9	8.0	1.12	13.9	0.47	6.8	0.31	18.6	0	13.5	1	39.2	0.12	0.358
Don River at Bloor St	300.6	1.7	1.12	13.8	0.47	4.3	0.31	23.9	0	9.1	1	47.2	0.12	0.245
Humber River at Old Mill Rd	877.6	0.5	1.12	5.0	0.47	1.6	0.31	74.0	0	2.7	1	16.2	0.12	0.081
Humber River at Steeles Ave	567.4	0.1	1.12	1.3	0.47	1.0	0.31	83.2	0	2.2	1	12.2	0.12	0.047
Rouge River at Finch Ave	14.6	0.0	1.12	0.6	0.47	8.0	0.31	49.9	0	4.3	1	37.2	0.12	0.115
Hanlon Creek at Highway 6	10.7	1.6	1.12	27.1	0.47	1.0	0.31	39.2	0	3.0	1	28.1	0.12	0.212

Note: Total CAD is the area-weighted average of the CAD values for the six different type of land uses typically found in an urban watershed

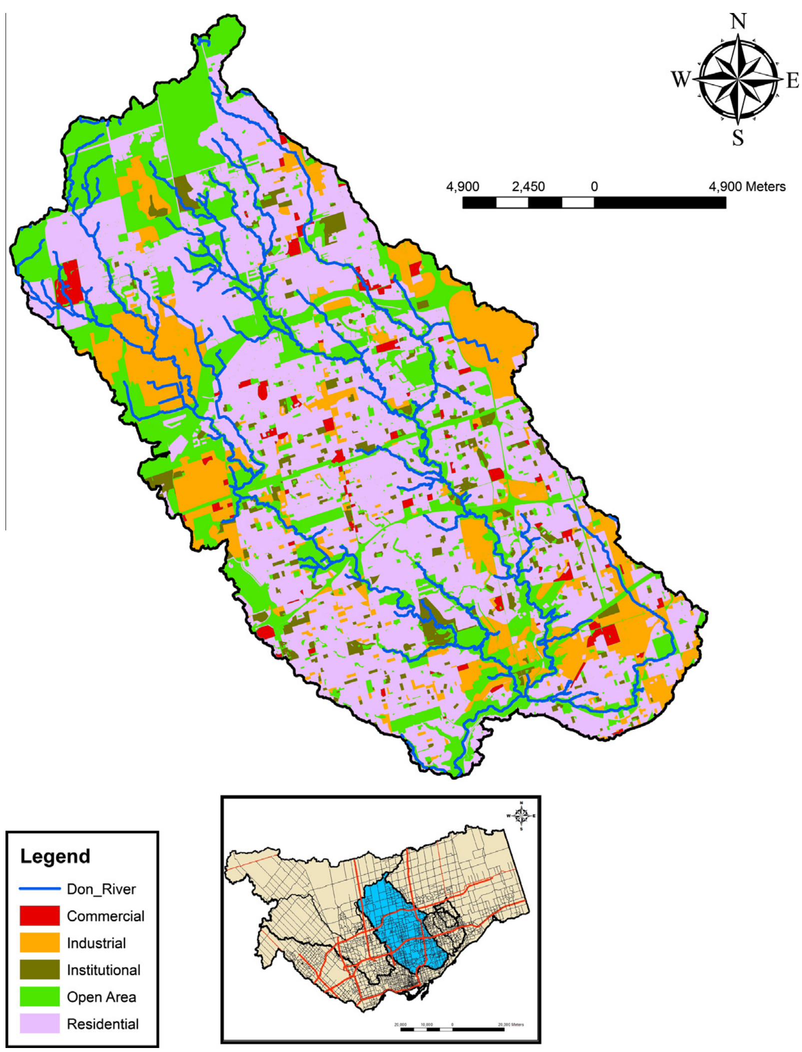

Fig. 5. Distribution of land use for the contributing area of Don River at Bloor Street.

The groundwater quality data collected by the municipalities and the MOE were collected for each of the Study Areas in the City of Toronto and the City of Guelph and used as the ambient (baseline) Baseflow Chloride Concentration (BFC) levels.

Baseflow chloride concentrations were obtained from the Ontario Ministry of the Environment Provincial Groundwater Monitoring Program (PGMN) for the monitoring wells within each Study Area, except for the three Study Areas in Highland Creek. Perera et al. (2010) performed a road salt mass balance in each of the three Study Areas in Highland Creek (Mammoth Hall Trail, Bellamy Rd. and Morningside Ave.) and calculated the baseflow chloride concentration throughout the year for each Study Area in Highland Creek. Perera et al. (2010) determined chloride concentration in baseflow using the stream monitoring data for dry-weather flow conditions in late summer (July–August).

4. Results and discussions

4.1. Contributing area

Using a combination of ArcHydro toolkit, DEM and stream network shapefile the contributing area for each of the eight surface water case study sites was determined. Fig. 4 presents the surface water contributing area (300.6 km^2) for the Don River at Bloor St. station. The Don River watershed upstream of Bloor St. has a maximum elevation of 328 m CGVD28 in the northern reaches to a low of 76 m CGVD28 to the south. The Don River has an average slope of approximately 0.44% within the reach of the Study Area.

4.2. Chloride Application Density (CAD)

Chloride Application Density (CAD) refers to the total weighted area within the Study Area that receives salt application. The value is weighted based on typical salt application rates for a particular land use (Perera et al., 2010).

Table 4 presents the fraction of area and its contribution to the total CAD for each land use type in each case study watershed.

Fig. 5 presents distribution of land use for the contributing area of Don River at Bloor St. Study Area. Chloride Application Density (CAD) is calculated for each watershed using land use distribution data for each watershed.

The resulting CAD values range from the low value of 0.047 for the Humber River at Steeles Ave. – due to the dominant land use of open space – to the high value of 0.400 for the Highland Creek at Mammoth Trail – due to the dominant land use of industrial area. This was an expected result since Highland Creek is one of the most urbanized watersheds in Canada and included one of the smallest percentages of open area (16.9%). It was anticipated that Humber River at Steeles would result in the lowest SCC CAD value because Humber River is entirely located outside of the City of Toronto and includes the largest percentage of open area of all the SCC Study Areas (83.2%).

4.3. Unit Chloride Application Rate (UAR)

Table 5 presents 25 years of road salt application data for the City of Toronto with long-term average annual chloride application per unit area of 868 g/m^2.

Many variables contribute to the variability of application rates from year to year, including but not limited to climate conditions and road salt availability and budgeted cost. However, for the case Study Areas in the City of Toronto, the average UAR values that were used in the SCC calculations were based on the data for the same years that the in-stream chloride concentration monitoring data were collected.

Table 5
City of Toronto road salt application quantity and total road length receiving road salt used for UAR calculation.

Year	Total road salt applied (tonnes)	Total road length (2-lane km)	UAR salt (g/m^2)	UAR Cl^- (g/m^2)
1986/87	124,381	12,337	1440	874
1987/88	119,621	12,337	1385	840
1988/89	128,386	12,337	1487	902
1989/90	165,312	12,337	1914	1161
1990/91	154,044	12,337	1784	1082
1991/92	112,528	12,337	1303	790
1992/93	148,473	12,343	1718	1042
1993/94	149,647	12,343	1732	1051
1994/95	95,130	12,343	1101	668
1995/96	127,977	12,343	1481	898
1996/97	157,585	12,415	1813	1100
1997/98	101,939	12,493	1166	707
1998/99	140,410	12,493	1606	974
1999/00	142,869	13,846	1474	894
2000/01	176,595	13,800	1828	1109
2001/02	56,893	13,800	589	357
2002/03	208,230	13,800	2156	1,308
2003/04	108,152	13,800	1120	679
2004/05	147,433	15,052	1399	849
2005/06	94,673	15,052	899	545
2006/07	89,112	15,052	846	513
2007/08	195,645	15,052	1857	1126
2008/09	147,130	15,052	1396	847
2009/10	81,484	15,052	773	469
2010/11	158,811	15,052	1507	914
		Average		868

4.4. Baseflow Index (BFI)

Fig. 6 presents the Baseflow Index map (BFI) for the surface water contributing area for Don River at Bloor St.

The results of the BFI calculation confirm the importance of groundwater to water supply and in-stream conditions in Ontario. These results highlight the variability of groundwater discharge within a relatively small study area (City of Toronto). This information has considerable relevance to water and aquatic habitat management and source water protection. Paved surfaces in urban areas create a limitation of the proposed methodology for estimating BFI values due to the reduced infiltration abilities of the surficial soils – although most municipalities require retention and infiltration of stormwater such that post-development groundwater recharge volumes and peak runoff rates to remain the same as pre-development conditions.

4.5. Normalized Mean Annual Flow (MAF)

The normalized MAF results in Table 6 show that there is significant variability in normalized MAF from one watershed to another; however, multiple gauge stations within a watershed, once normalized, show strong similarities and less variability.

4.6. Baseflow Chloride Concentration (BFC)

Table 6 presents CAD, BFC, BFI, MAF, and SCC values for the case study watersheds.

The Study Area with the lowest chloride concentration in baseflow was Humber River at Steeles Ave., with a baseflow chloride concentration of 122 mg/L. This is expected since the Humber River at Steeles Ave has a majority land use of open area. For the most part, the Study Areas with a larger percent of urbanized land coincide with higher baseflow chloride concentration measurements.

4.7. In-Stream Mean Annual Chloride Concentration (SCC)

Table 5 presents a summary of the input parameters to Eq. (1). Highland Creek at Mammoth Hall Trail has the highest calculated SCC value of all the Study Areas in the City of Toronto. This was expected due to the high percentage of industrial area and low percentage of open space within the Study Area. As can be seen in the results in Table 5 the Study Areas with high calculated CAD value typically coincide with a high SCC value. Fig. 7 presents the comparison plot of observed vs calculated SCC for the Study Areas in the City of Toronto. Fig. 7 indicates that there is a strong relationship between observed and calculated SCC (R^2 = 0.96).

Error bars were added to each SCC Study Area to indicate one standard deviation from the mean, in both the positive and negative direction.

4.8. Validation of SCC calculation method

The calculated Hanlon Creek Study Area SCC compares favourably with the measured SCC, R^2 value of 0.97 and, as such, the

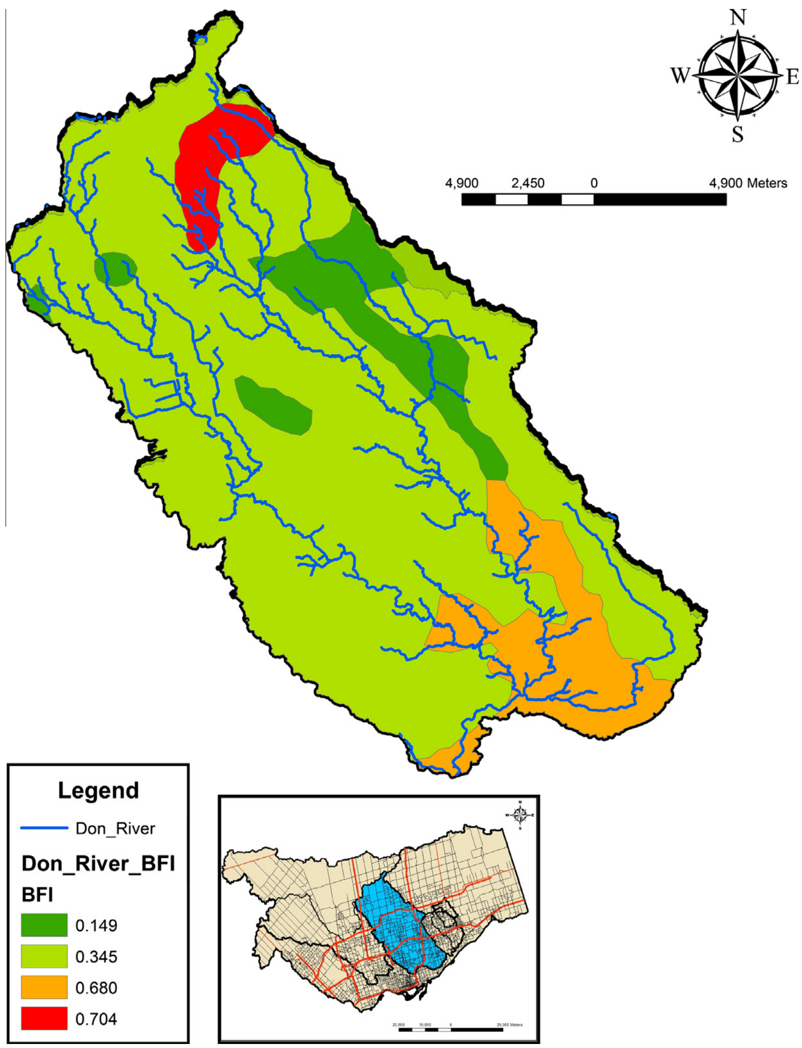

Fig. 6. Baseflow Index map (BFI) for the Don River at Bloor Street.

Table 6
Summary of key parameters calculated for the Study Areas.

Locations	Chloride Application Density (CAD) (–)	Unit Application Rate (UAR)	Baseflow Chloride Concentration (BFC) (mg/L)	Baseflow Index (BFI) (–)	Mean Annual Flow (MAF) (m)	Mean Annual Stream Chloride Concentration (SCC) (mg/L)
Highland Creek at Mammoth Hall Trail	0.400	1126	325	0.345	0.497	705
Highland Creek at Bellamy Rd	0.355	1126	475	0.345	0.497	690
Highland Creek at Morningside Ave	0.358	758	400	0.345	0.497	496
Don River at Bloor St.	0.245	993	250	0.400	0.421	446
Humber River at Old Mill Rd	0.081	787	441	0.402	0.267	320
Humber River at Steels Ave	0.047	787	122	0.463	0.242	138
Rouge River at Finch Ave	0.115	691	32.7	0.327	0.300	189
Hanlon at Highway 6	0.212	868	111	0.670	0.311	269

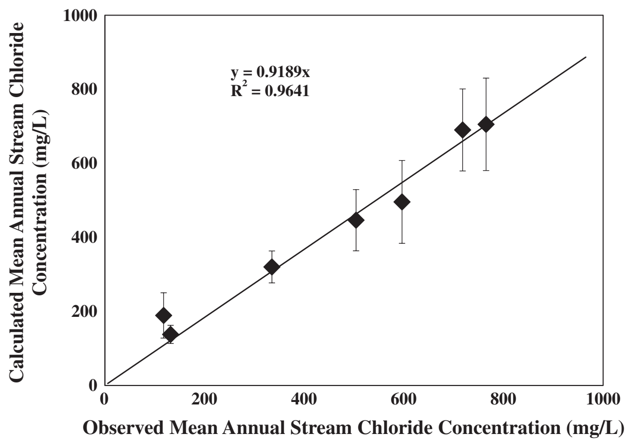

Fig. 7. Correlation between observed and calculated SCC.

Table 7
Summary of vulnerability ranking scores of all Study Areas.

Study Area	Salt vulnerability score	Vulnerability ranking
Highland Creek at Bellamy Rd	43	1
Highland Creek at Mammoth Hall Trail	43	1
Don River at Bloor St.	37	3
Highland Creek at Morningside Ave	31	4
Humber River at Old Mill Rd	20	5
Rouge River at Finch Ave	4	6
Humber River at Steels Ave	3	7
Hanlon at Highway 6	2	8

SCC equation was taken to be a good predictor of mean annual in-stream chloride concentration for streams in southern Ontario. This also validates the use of the average UAR value based on the City of Toronto salt application rates. Although using City of Guelph salt application data may produce a better correlation between observed and calculated SCC for Hanlon Creek, the results prove using the UAR based on City of Toronto data to be sufficient in the absence of local data.

4.9. Surface water vulnerability score

A summary of the vulnerability score for all Study Areas is presented in Table 7, which ranks the calculated scores in descending order to highlight the Study Areas that would benefit the most from implementation of BMPs.

All three Study Areas in Highland Creek and Don River at Bloor Ave. have the highest vulnerability scores, with Highland Creek at Bellamy Rd. and Mammoth Hall Trail having the highest at 43. Hanlon Creek at Highway 6 presents the lowest vulnerability ranking score of 2.

5. Conclusions

Clean water is essential for the health of watersheds and the rivers and lakes to which they contribute. Several of the Study Areas in the City of Toronto (Don River, Highland Creek and Humber River) indicated that high chloride concentrations exist during winter months. These high chloride concentrations create toxic environments for sensitive aquatic species.

A methodology was developed, using readily available spatial data, to rank urban streams based on salt vulnerability. The methodology calculates the probable chloride concentration statistics at specified points in the urban stream network and compares the results with known aquatic species exposure tolerance limits to characterize the vulnerability scores. The total number of aquatic species, in a given urban stream, that will likely be exposed to acute chloride concentrations (⩾LC50 thresholds) are calculated using mean daily stream chloride cumulative probability distribution function and reported as the salt vulnerability scores of the urban stream. The log-normal probability distribution can be used to describe the mean daily chloride concentration data in urban streams. The mean and the standard deviation of the stream chloride concentration were strongly correlated. The vulnerability ranking for each area of interest are sorted in descending order and this creates a prioritized list of sites most vulnerable to road salts and in need of better salt management plans and control measures. The results from this research further the understanding of the effects road salts have on waterways and aid in developing better salt management plans.

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