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4 authors, including:

Beth L Parker
University of Guelph

Bahram Gharabaghi
University of Guelph

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PAPER

CAD-DRASTIC: chloride application density combined with DRASTIC for assessing groundwater vulnerability to road salt application

Mansour Salek[1] · Jana Levison[1,2] · Beth Parker[1,2] · Bahram Gharabaghi[1]

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Abstract
Road salt is pervasively used throughout Canada and in other cold regions during winter. For cities relying exclusively on groundwater, it is important to plan and minimize the application of salt accordingly to mitigate the adverse effects of high chloride concentrations in water supply aquifers. The use of geospatial data (road network, land use, Quaternary and bedrock geology, average annual recharge, water-table depth, soil distribution, topography) in the DRASTIC methodology provides an efficient way of distinguishing salt-vulnerable areas associated with groundwater supply wells, to aid in the implementation of appropriate management practices for road salt application in urban areas. This research presents a GIS-based methodology to accomplish a vulnerability analysis for 12 municipal water supply wells within the City of Guelph, Ontario, Canada. The chloride application density (CAD) value at each supply well is calculated and related to the measured groundwater chloride concentrations and further combined with soil media and aquifer vadose- and saturated-zone properties used in DRASTIC. This combined approach, CAD-DRASTIC, is more accurate than existing groundwater vulnerability mapping methods and can be used by municipalities and other water managers to further improve groundwater protection related to road salt application.

Keywords CAD-DRASTIC · Road salt · Groundwater protection · Vulnerability mapping · Canada

Introduction

The population of North America is mainly concentrated in urban areas. This urban demography has altered the natural landscape and has adversely impacted water resources (Paul and Meyer 2001). One of the most consistent and pervasive of these effects is the adversarial increase in imperviousness of the surface cover in urban watersheds; this can affect the hydrology as well as the geomorphology of nearby streams (Findlay and Kelly 2011). In addition, runoff in urbanized watersheds leads to increased loading of contaminants, which consist of road salt residues and/or other solvents, to surface-water bodies (Cooper et al. 2014). The process eventually leads to steady declines in the abundance of wildlife in urban water resources and deterioration of water quality (Crowther and Hynes 1977). Since road salt generally enters and dissolves in surface-water systems and also infiltrates into groundwater (Huling and Hollocher 1972; Meriano et al. 2009; Perera et al. 2009, 2010, 2013; Trenouth and Gharabaghi 2016), it is important that precautionary measures be taken in order to mitigate its detrimental effects on the hydrology of streams, groundwater, and wildlife.

This research uses a methodology by Betts et al. (2015) which applied readily-available geographical information system (GIS) data in order to establish road-salt-vulnerable areas by means of assessing the effects of de-icing salt on freshwater quality. For this research, the chloride application density (CAD) value from Betts et al. (2015) is combined with the DRASTIC methodology. DRASTIC is a GIS-based methodology that incorporates the unconsolidated media, aquifer heterogeneity and hydrogeological characteristics, introduced by Aller et al. (1987) for the US Environmental Protection Agency (EPA), and is used widely by other researchers (e.g., Kim and Hamm 1999; Panagopoulos et al. 2006; Hamza et al. 2007; Al-Hanbali and Kondoh 2008; Neukum et al. 2008; Ahmed 2009; Martínez-Bastida et al.

✉ Jana Levison
jlevison@uoguelph.ca

✉ Bahram Gharabaghi
bgharaba@uoguelph.ca

1 School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada

2 G360 Institute for Groundwater Research, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada

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2010; Sener and Devraz 2013; Hernández-Espriú et al. 2014; Khan et al. 2014). Seven hydrogeological parameters are considered including—depth to groundwater; recharge rate; aquifer media; soil media; topography; the impact of the vadose zone media; and aquifer hydraulic conductivity. While the use of the DRASTIC method can be limited by the availability of data, the methodology by Betts et al. (2015) considers only road salt application rate, land use, and road networks; however, the Betts et al. (2015) methodology does not establish a connection to the variable hydrogeological conditions of the study area. The combined new method described in this paper uses information typically collected from accessible databases.

Various approaches to distinguish different vulnerable areas have been presented in a number of studies (Secunda et al. 1998; Al-Adamat et al. 2003; Lake et al. 2003; Thunqvist 2004; Panagopoulos et al. 2006; Jin et al. 2011; Kronvall 2013; Betts et al. 2014; Betts et al. 2015). Dedewanou et al. (2015) outline the effectiveness of methods that can guide groundwater managers and decision-makers through a physical approach to vulnerability assessment, whereas Kronvall (2013) used a flowchart method to distinguish salt-vulnerable areas in Norwegian watersheds. Readily accessible data or methods, produced by the Norwegian Public Road Administration (NPRA) were used and the results were processed and presented in a GIS. Similarly, Betts et al. (2015) developed a novel methodology which helps in identifying salt-vulnerable areas using GIS. Numerical investigations (groundwater flow and contaminant transport modeling) have been shown to be reliable tools to help understand the adverse effects of salt on aquifers through investigation of plume movement in groundwater systems (Coster et al. 1994; Lang et al. 2005; Bester et al. 2006)—for instance, the transport of salt plumes was simulated over a long time period and considering various parameters (Lang et al. 2005). Different types of aquifers have been investigated using numerical modeling approaches—for example, Bester et al. (2006) studied the impact of road salt on a well-field in a complex glacial aquifer system located in an urban setting, whereby they assessed the efficacy of mitigation measures designed to reduce the impact.

Numerical modeling efforts assisted by GIS generally have two major constraints—firstly, they need a significant amount of data, which can potentially cause time-delays and/or economic strains to obtain; secondly, the models generally do not clarify the relationship between salt propagation and the hydrogeological characteristics of the study area. Thus, a method that uses publicly available data, is not cumbersome to carry out and incorporates hydrogeological properties would be beneficial. A method is presented herein that employs the prevalently used GIS-based mass balance technique, in order to consider chloride application density, road-salt-application rate, and net recharge rate and distinguish chloride concentration within baseflow pathways while being cognizant of hydrogeological conditions in combination with the methodology by Betts et al. (2015). The modified calculated chloride application density (CAD-DRASTIC) is calculated using factors including land use and geology and can provide better insights for the salt management plans in the respective municipal supply well capture zones. This research, henceforth, attempts to quantify groundwater vulnerability in an endeavor to implement beneficial management practices *au courant* with the well-being of the groundwater reservoir and hydrogeological implications.

Instead of using detailed process-based flow and transport modeling software, this research endeavors to use the prevalently traditional GIS for an accurate vulnerability assessment that simultaneously considers heterogeneity, over-burden thickness, and other geological factors known to influence recharge distributions and groundwater flow systems. The primary objective of this research, therefore, is to use publically available data and information and combine them with the two previously separate and well-established scientific frameworks in order to provide new insights by spatial association within a well-established hydrogeologic paradigm. This research advances prior methods used by Betts et al. (2015) and the DRASTIC approach. The specific aims are to: (1) improve the CAD algorithm by combining it with DRASTIC to associate the spatial variability of the source/inputs to the receptor; and (2) capitalize on existing data commonly collected and stored in public databases informing the variability of subsurface conditions relevant to land management and planning. It is important to note that this approach does not intend to replace quantitative, process-based flow and transport modeling across the board; nevertheless, the spatial association modeling afforded by this novel method can assist in determining priority risk areas recognizing that the adverse effects of a particular problem can be further investigated through use of more process-based modeling software. Notwithstanding these inherent limitations in the application, the method presented herein can further the understanding of the variability in road salt impacts to aquifers related to important hydrogeological parameters and their spatial association in order to create an objective framework for the integration of those factors. This can assist the predictability of groundwater aquifer vulnerability across regions based on the variability of known conditions in land surface and subsurface layers.

Therefore, it is fair to say that this research can be applied to help municipalities, especially smaller ones, to distribute their limited financial resources to where it is most needed. That is, the focus can be on the application of best management practices to the most vulnerable areas using well-established science-based frameworks in the modeling programs and existing databases collected and managed by various jurisdictions. Hence, this research can benefit salt application practices tailored to each site condition; although mitigation in the amount of salt used has become common knowledge during the last decades, the environmental vulnerability has not been differentiated from one location to another. In order for the decision-maker to be able to identify key vulnerable areas, this research can prove an efficient initial step to be done quickly and inexpensively using existing programs and data, equipping the decision-maker to understand the salt propagation process.

Materials and methods

The present research makes use of a methodology previously employed by Betts et al. (2015) and modifies it by the addition of hydrogeological parameters applied by the DRASTIC method. Easily available GIS datasets are used in order to identify areas most vulnerable to road salts through quantitative evaluations of the impact of road salt on groundwater quality. The method incorporates salt application rates, chloride application density, and recharge rates in order to distinguish chloride concentrations and loadings. The risk denomination is calculated based on the chloride application density at each water-supply-well location, and the vulnerability ranges derived from GIS-based DRASTIC analysis, which highly depends on the land use, hydrogeology, and salt management plans within the respective municipal supply well capture zones. This methodology is particularly beneficial in locating and prioritizing the vulnerable areas using existing data, henceforth assisting in the implementation of management practices that aim to lessen the adverse effects of road salt application on the most vulnerable groundwater.

Study area

Guelph, one of the largest cities in Canada to rely almost exclusively on groundwater for its potable water supply, is located within the Grand River watershed in Ontario, Canada (Fig. 1) and encompasses an area of about 87 km^2 containing an approximate population of 131,000 people (City of Guelph 2017). Twelve water supply wells located within the city are used in this study to evaluate the vulnerability of groundwater to road salt application.

The geology of the region is varied, resulting in differences in the hydrologic conditions within the area. In general, the watershed has a flat topography with gentle slopes with an elevation change of approximately 180 m along the length of the Grand River. Gravels underlie the watershed and provide relatively high permeability (Matrix Solutions 2014). The surficial Quaternary sediments are comprised of a mixture of finer-grained sediments of silty sand to silt in the north to a mix of the finer-grained sediments with gravel and sand towards the south, with glacial features specifically in the southeast of the city (OMNDM 2014). The groundwater supplies in the City of Guelph are predominantly drawn from bedrock aquifers (e.g., Gasport and Guelph Formations), but are also derived from overburden deposits (e.g., outwash sands and gravels) and a mixture of overburden and weathered/shallow bedrock (Matrix Solutions 2014). The bedrock aquifer is mainly comprised of dolostone of Silurian Age that subcrops below the Quaternary sediments along a band from Niagara Falls to Bruce Peninsula along the length of the Niagara Escarpment (Brunton 2008, 2009, Brunton and Brintnell 2011). This Silurian sequence is a very important source of fresh groundwater due to its high transmissivity, and serves as a reliable source of water supply for the City of Guelph inhabitants (Munn 2012). The Guelph Formation, the uppermost bedrock unit in the study area, consists primarily of medium to thickly bedded cross-stratified crinoidal grainstones and wackestones. This unit acts as a shallow, unconfined bedrock aquifer in the region (Brunton 2008). The deeper Gasport Formation is made up of cross-bedded grainstone-packstone successions (Brunton 2009). It is a crinoidal grainstone finely crystalline and cross-laminated.

In terms of the climate conditions, the natural temperature of the Grand River watershed is considered moderate to cool. Four distinct seasons are expected in this area, including winters when snowfall is the most prevalent form of precipitation. Precipitation is distributed throughout the year in a quasi-uniform way, i.e., there is no particular rainy season, and the annual average precipitation in this catchment ranges from approximately 800–1,025 mm/year (Environment Canada 2005). Snowfall typically begins in late November and ends around April, with average annual snowfall (liquid water equivalent) ranging from 98 to 245 mm/year, which makes the application of road salt necessary during the cold season (City of Toronto 2004).

Even though human-induced sources of chloride in the study area include road salt application, septic tanks, and wastewater treatment plants, it is assumed that the only source of chloride in this area is applied road salt because other possible factors comprise a minor fraction of the road salt application rate. The upper limit of acceptability for chloride in drinking water is 250 mg/L as per the Ontario Drinking Water Quality Standards (ODWQS).

Data collection

The data sources used in this analysis are summarized in Table 1. All road network geospatial files are available online, including Route file (RTE; DMTI Spatial Inc. 2014a, b), Road Network file (RNF; Statistics Canada 2014), Ontario Road Network (ORN; OMNR 2012), MNR road segment (OMNR 2007), Local Road Casements (LRC; DMTI Spatial Inc. 2014a, b), and Guelph double line street network (GSN; City of Guelph 2010). The RTE and ORN files chosen for this

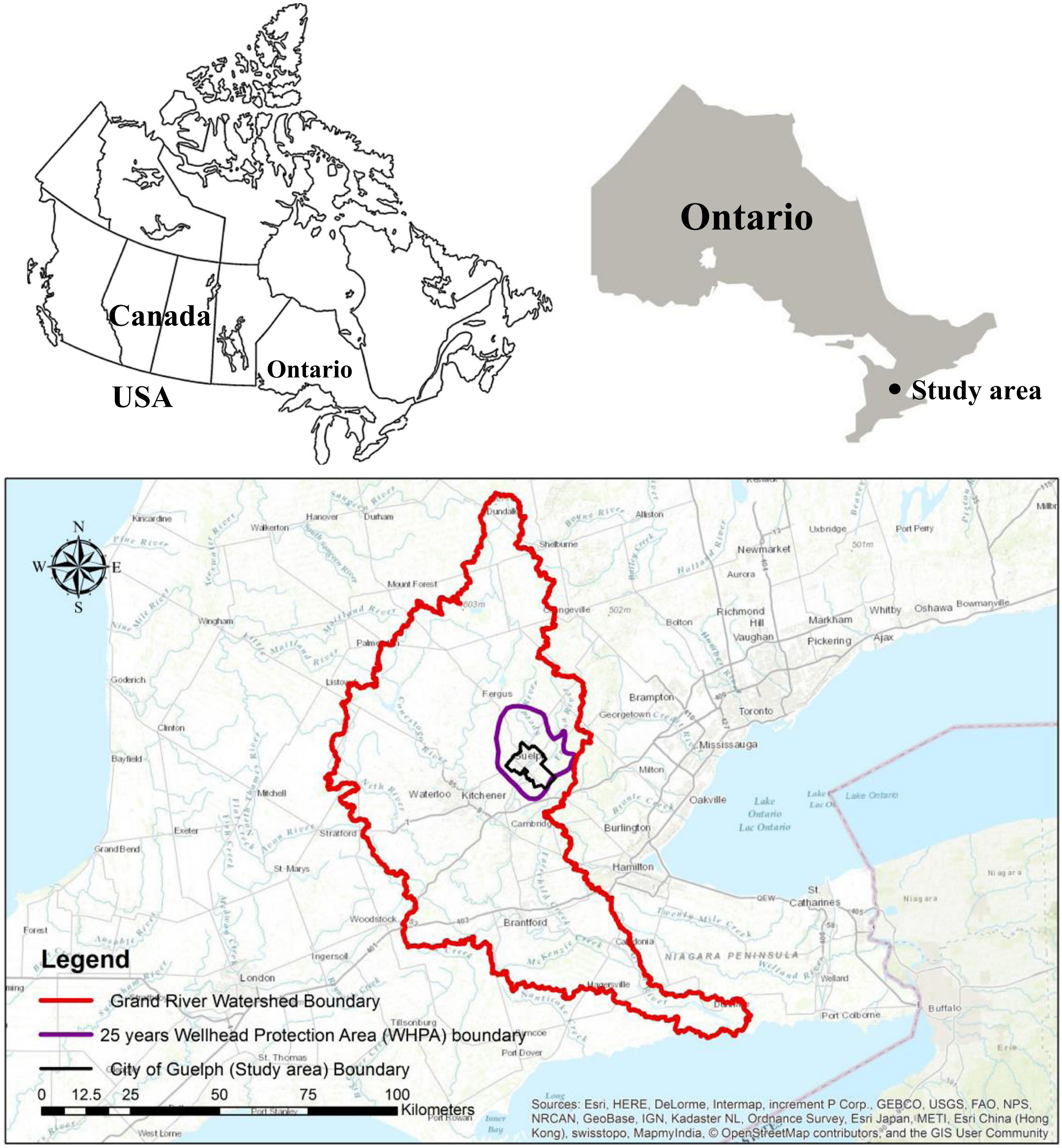


Fig. 1 City of Guelph location within the Grand River watershed in southern Ontario, Canada

research are the ones most pertinent to the required data including road length, the number of lanes, and road type. Road classes used in this research are varied from highways to local roads and drives. The classes include all road classes, but for simplicity and making the map more understandable the following ones are shown: avenue (AVE), boulevard (BLVD), circle (CIR), crescent (CRES), crest (CRT), drive (DR), glen, highway (HWY), lane, parkway (PKY), place (PL), road (RD), run, square (SQ), street (ST) and terrace (TERR). The land use map is prepared by the City of Guelph (2010). It contains polygons, each one representing a land use zone situated within the City of Guelph boundaries. Each parcel includes information like area, perimeter, and land use. This map was imported into a GIS-based software and edited to

Table 1 Data used in this research

Data	Reference(s)
Road network	OMNR 2012; AquaResource Inc. 2010a, b
Land use	City of Guelph 2010
Surficial Quaternary geology	OMNDM 2014
DEMs and elevation maps	OMNR 2015; MNR 1979
Soil maps and bedrock geology maps	OMNDM 2011
Water-table data map	GRCA 2016a
Net recharge data map	GRCA 2016b
Road salt application rate	Betts et al. (2015)
Measured chloride concentration	City of Guelph (2010)

be appropriate for the research objectives. That is, coding and weights were added to the related database for each land-use type. The surficial geology map (OMNDM 2014) was imported into GIS, and hydraulic conductivity values based on Fetter (2000) were assigned in the attribute table for each material. The surface digital elevation map, DEM (OMNR 2015), and the bedrock elevation map (MNR 1979) were obtained, and the overburden thickness was derived by subtracting one layer from the other; this map was secondarily compared with the overburden thickness map prepared previously by the Ontario Ministry of Northern Development and Mines (2006). Measured chloride concentrations are derived from available graphs presented in the City of Guelph Source Protection Project, Water Quality Threats Assessment Report (AquaResource Inc. 2010a).

A crucial aspect considered in this research is heterogeneity and spatial variability of many parameters, which makes the calculations of CAD (see section 'Chloride Application Density (CAD)') more realistic and closer to real site conditions. However, due to the uncertainty in the assigned hydraulic conductivity values for each overburden sediment type and the heterogeneity within each unit, the calculations herein are vulnerable to some errors. In order to minimize this uncertainty, field work and measurements are strongly suggested for future applications of this method, particularly when tolerance for risk is small. However, there may always be some uncertainty associated with the input data that is collected by external sources and variable methods that deserve to be considered when interpreting the results. Land use maps only cover the area within the domain of the City of Guelph and do not include the neighboring suburbs, which make it impossible to relate the suburb land use effect on the down-gradient areas within the city. In regard to the road network geospatial mapping, available maps are diverse, each with a shortage of accurate data—for example, some maps did not include road classes, and others lacked road lengths; therefore, a combination of readily available maps is used.

Average annual recharge is obtained from the Grand River Conservation Authority (GRCA) database (GRCA 2016b), which was prepared previously based on the Quaternary geology, land use, and rainfall data. Each polygon in this layer represents an area that responds similarly to precipitation in terms of runoff, recharge, and evapotranspiration. This recharge water is capable of transporting road salt vertically towards the water table. In addition, it controls the volume of water available for dilution and dispersion of the contaminant in the vadose and saturated zones. Slope percentages are calculated using the DEM (OMNR 2015). The slope was thereon classified and rated for use in the topography component map. The factors considered important in defining the impact of the vadose zone include Quaternary geology, assigned permeability, and depth to water table. The hydraulic conductivity layer is chosen based on the soil media component map (OMNDM 2010) which classifies multiple media into ranges, wherby high permeability means higher pollution vulnerability and slow permeability is associated with lower pollution potentials.

Data analysis

Chloride application density (CAD)

Readily accessible data and methods (Betts et al. 2015) have been modified and used to identify and map salt vulnerable areas for a sub-selected number of supply wells located in Guelph. The results have been processed and presented using a GIS-based software. For the purpose of this assessment, related salt application areas must be identified. Similar to the imperviousness of a watershed, chloride application density (CAD), which represents the total area within a catchment that receives chloride applied to the road surfaces, can be extracted; this is a unit-less parameter based on the percentage of land use subject to salt application multiplied by a weighted

Table 2 Weighting factor and fraction of area receiving road salt application for each land use (Betts et al. 2015)

Land use type	Portion of area receiving road salt application (Betts et al. 2015)	Salt application weighting factor (Perera et al. 2010)
Commercial	0.56	2.0
Industrial	0.47	1.0
Institutional	0.15	2.0
City roads	1.00	1.0
Highways	1.00	1.0
Residential	0.24	0.5
Open spaces (parks and agricultural)	0	0

Table 3 Summary of land use percentages and calculated chloride application density (CAD)

City of Guelph supply wells	Commercial	Industrial	Institutional	Residential	Park	Agricultural	City roads	CAD
Burke	2.3	0.0	0.0	45.0	12.0	38.0	2.7	0.12
Dean	11.2	0.0	3.3	48.4	29.1	0.0	8.0	0.36
Downey	2.3	0.0	4.6	26.1	57.0	0.0	10.0	0.19
Edinburgh	4.7	20.0	0.0	48.0	18.2	0.0	9.0	0.33
University	1.4	0.0	26.7	37.0	29.9	0.0	4.9	0.40
Water	0.0	0.0	14.2	54.3	24.0	0.0	7.4	0.19
Membro	0.0	0.0	30.0	50.0	13.8	0.0	6.2	0.35
Emma	0.0	0.0	0.0	90.0	0.1	0.0	9.9	0.31
Helmar	0.0	0.0	0.0	8.2	39.0	50.3	2.5	0.03
Clythe	0.0	30.0	0.0	0.0	0.0	66.5	3.5	0.13
Smallfield	0.0	51.9	2.0	8.0	2.2	30.4	5.5	0.35
Calico	10.4	54.0	0.0	0.0	0.0	34.0	1.5	0.01

salt application rate per land use type (Eq. 1) within well-defined surface-water catchment zones. Since each land use type has a particular percentage of surface area that captures road salt, the salt application rate has been weighted based on each land use type (Perera et al. 2010; Table 2).

$$\mathrm{CAD} = \%\mathrm{Area\ receiving\ salt} \times \mathrm{Weighted\ salt\ application\ rate} \qquad (1)$$

In order to calculate the percentage of land use subject to the application of road salt, land use mapping and aerial imagery are used in a GIS-based software to manually convert each area to access maps relevant to sites of salt application. Digitization is performed in a manner that separates parking lots and green spaces from road surfaces. This was carried out on four land use types (residential, industrial, commercial and open spaces) spread across the study area within the City of Guelph. The land area receiving road salt application was then averaged for each land use type (Table 2).

Area of contaminant contribution

The area that contributes chloride to a pre-identified salt vulnerable area is referred to as the influence area. Delineated well capture zones surrounding municipal supply wells are used in this study for the influence areas for groundwater recharge (Betts et al. 2015). The influence areas associated with time-of-travel zones (e.g., 25 years) are used in this research to approximate the groundwater-chloride-application concentration. In Ontario, these time-of-travel well capture zones are called well-head-protection areas (WPHAs) and have been delineated for municipal well systems in the province under the Government of Ontario's Clean Water Act (2006).

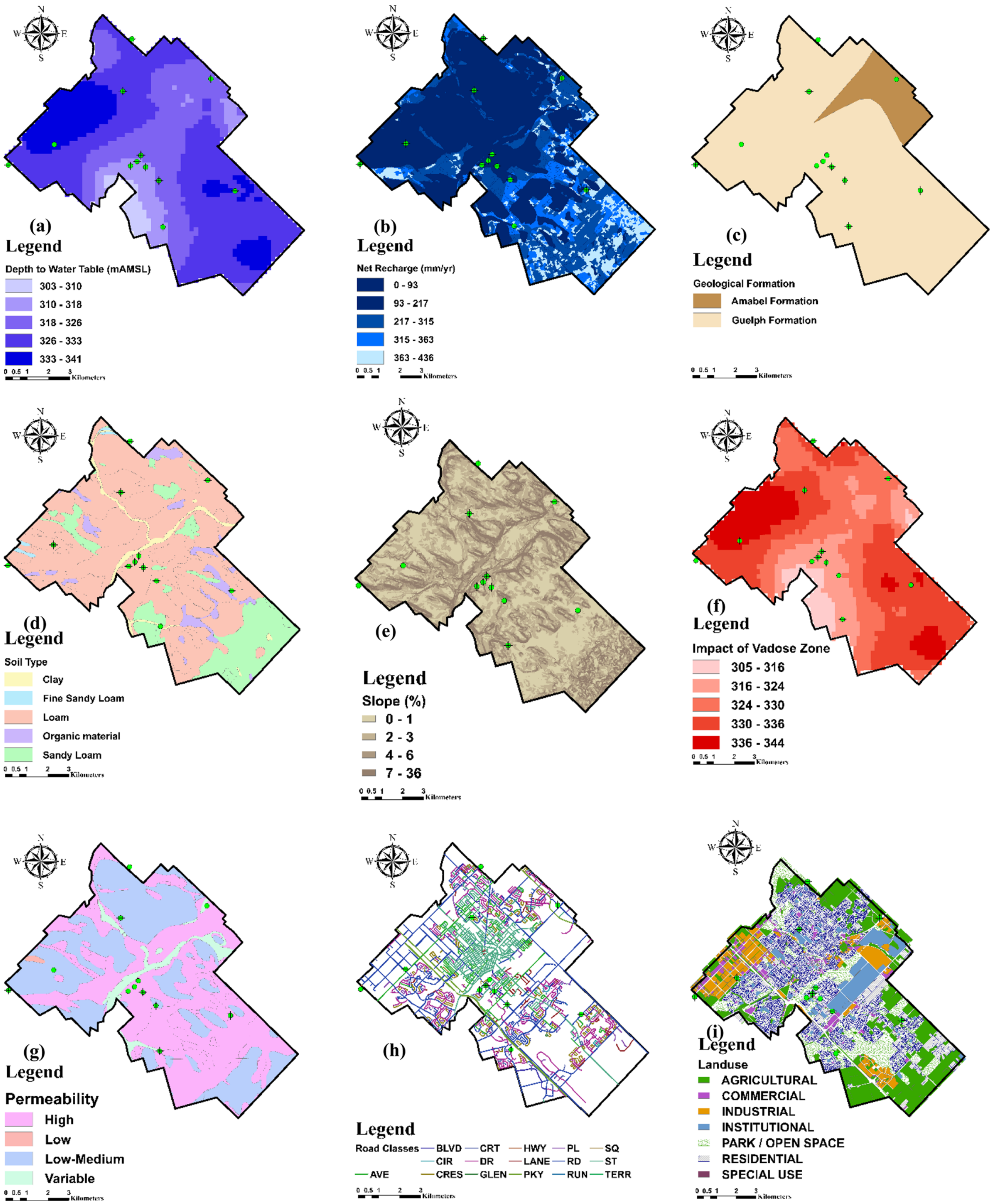
Table 4 Assigned weights for each geospatial layer

Layer	Weight, *w*
Depth to water table	5
Net recharge	4
Aquifer type	3
Soil media	2
Topography (slope)	1
Impact of vadose zone	5
Hydraulic conductivity	3

CAD-DRASTIC mapping method

The DRASTIC vulnerability mapping method used widely by various researchers (including Aller et al. 1987; Kim and Hamm 1999; Al-Adamat et al. 2003; Lake et al. 2003; Panagopoulus et al. 2006; Hamza et al. 2007; Al-Hanbali

Fig. 2 Geospatial mapping layers used in the CAD-DRASTIC method. ▶ Green circles represent supply wells and black outline is the City of Guelph boundary: **a** depth to water-table map (GRCA 2016a). Map shows prepared data provided by the GRCA database: **b** average annual recharge map (GRCA 2016b), based on the Quaternary geology, land use, and rainfall data. Each polygon in this layer represents an area that responds similarly to precipitation in terms of runoff, recharge, and evapotranspiration: **c** aquifer type layer (OMNDM 2011). This geospatial layer is prepared based on the bedrock-lithology-distribution layer: **d** soil type distribution (OMAFRA 2003); **e** slope distribution (OMNR 2015). Slope percentages are calculated using the digital elevation model (DEM) datamap. The slope was thereon classified and ranked for use in the topography component map: **f** impact of vadose zone map. The factors considered important in defining the impact of the vadose zone include Quaternary geology, permeability and depth to water table: **g** permeability distribution layer (OMNDM 2014). The hydraulic conductivity layer is chosen based on the soil media component map which classifies various media into ranges: **h** Road classes distribution (OMNR 2012; DMTI Spatial Inc. 2014a, b): **i** land use map (City of Guelph 2010); each polygon represents a land use zone situated within the city boundary



and Kondoh 2008; Neukum et al. 2008; Ahmed 2009; Martínez-Bastida et al. 2010; Shirazi et al. 2012; Wang et al. 2012; Sener and Devraz 2013; Hernández-Espriú et al. 2014; Khan et al. 2014; Hamza et al. 2015) is a groundwater vulnerability assessment method. Spatial datasets on seven parameters are included and considered relatively: depth to groundwater (D), recharge by rainfall (R), aquifer type (A), soil properties (S), topography (T), impact of vadose zone (I), and the hydraulic conductivity of the aquifer (C) (Piscopo 2001). The DRASTIC vulnerability map is delineated as per Eq. (2) (Aller et al. 1987):

$$\mathrm{DRASTIC} = \mathrm{DwDr} + \mathrm{RwRr} + \mathrm{AwAr} + \mathrm{SwSr} + \mathrm{TwTr} + \mathrm{IwIr} + \mathrm{CwCr} \tag{2}$$

In which w stands for weight and r stands for the rating. The weight and rating values are assessed by qualitative, rather than quantitative criteria (i.e., see Tables 4, 5 and 6). Weights are treated as constants in this methodology; each of the parameters in the model is grouped into ranges of values that are given a rating from 1 to 10.

The computed (via GIS) DRASTIC index identifies areas within the domain that are most likely to be contaminated. A high DRASTIC index is an indication of greater groundwater pollution potential. The DRASTIC technique can effectively offer planners and developers a categorization of areas, based on the level of site investigation expectation. It is, therefore, reasonable to consider the end-results of DRASTIC methodology in combination with other techniques. For the purpose of the current research, the DRASTIC method output is used in conjunction with the previously calculated CAD in order to achieve a more realistic value of the chloride application density. This is obtained by multiplying DRASTIC by CAD values, following the DRASTIC notation with w and r for weight and rating, respectively (Eq. 3):

$$\mathrm{CAD{-}DRASTIC} = \mathrm{DRASTIC} \times \mathrm{CADwCADr} \tag{3}$$

This method achieves a spatially refined map of groundwater vulnerability by combining the spatial distribution of road salt application and the spatial variability of subsurface conditions.

Data analysis

CAD-DRASTIC analysis is a robust method which uses various geospatial layers that tend to mitigate the errors in the assessment result by taking into account various geological and hydrological peculiarities. However, the selection of weights and ratings for every map layer used in this method is qualitative and leads to an inevitable subjectivity, which in turn leads to a degree of uncertainty in the resultant vulnerability map. Sensitivity analysis is a crucial way to deal with such uncertainties, performed in order to evaluate the influence of single parameters on aquifer vulnerability analysis using CAD-DRASTIC; therefore, sensitivity analysis is essential to perform in order to increase the viability of the procedure's results.

The procedure of single-parameter sensitivity analysis (Napolitano and Fabbri 1996) is used in this research through which the GIS-based analysis produces a statistical table consequently used to reclassify the input maps. In this method, a comparison between the effective weight of each input parameter and the theoretical weight is performed. The effective weight is derived using Eq. (4) (Napolitano and Fabbri 1996):

$$W_{\mathrm{p}} = \frac{\mathrm{PrPw}}{\mathrm{vul}} \times 100 \tag{4}$$

where W_{p} is the effective weight, Pr and Pw are the ratings and the weights of the parameter P, and vul is the vulnerability index as computed in Eqs. (2) and (3).

Results

This section presents the results obtained from the calculation of the input parameters to the CAD equation, and the modified vulnerability ranking method to groundwater recharge.

Area of contribution

The influence area of the City of Guelph is derived based on the monitoring locations and is used as the boundary layer for the determination of the CAD parameter. Using a GIS-based software, the influence area is plotted and used for the purpose of clipping the required GIS input layers, namely land use, road network, and Quaternary geologic maps, for each of the input parameters. The well capture zones are obtained from AquaResource Inc. (2010a). The delineated WHPA for the City of Guelph contains four zones (1, 2, 3, and 4), based on horizontal time of travel to the well, with zone 4 encompassing the largest area (25-year time-of-travel to the well); however, the CAD values are only calculated within zone 4, because it includes all the other zones. Figure 1 presents the groundwater influence area for the study areas located in the Grand River watershed for the zone 4 (25 years) influence area.

Chloride application density (CAD)

An important parameter in the modified vulnerability analysis method is the chloride application density (CAD) relevant to the total area that receives a salt application (Betts et al. 2015). Also, every land use typically has a specific percentage of area that gets a regular amount of road salt. Table 2 presents the fraction of the area receiving road salt application (Betts et al. 2015) and the salt application weighting factor for each land use type (Perera et al. 2010, 2013; Kilgour et al. 2013; Trenouth et al. 2015, 2017).Table 3 provides a summary of the percentages of the land type distribution for the 12 City of

Table 5 Ratings used for each layer and class for depth to water table (GRCA 2016a), net recharge (GRCA 2016b), aquifer media, soil media (OMNDM 2011), topography (slope %), the impact of the vadose zone, and hydraulic conductivity. The "impact of the vadose zone" is derived by multiplying the water-table elevation by the Quaternary geology geospatial layer, yielding a unit-less number

Layer	Class	Rating, *r*
Depth to water table (m AMSL)	303–313	10
	313–321	8
	321–327	6
	327–333	4
	333–341	1
Net recharge (mm/year)	388–436	10
	339–388	8
	290–339	7
	242–290	6
	194–242	5
	145–194	4
	97–145	3
	48–97	2
	<48	1
Aquifer media	Dolostone 2 (Guelph Formation)	10
	Dolostone 1 (Amabel Formation)	8
Soil media	Sandy loam (SL)	10
	Fine sandy loam (FSL)	8
	Loam (L)	6
	Clay (C)	2
	Organics (ORG)	1
Topography (slope %)	<1	10
	03-Jan	9
	07-Mar	7
	12-Jul	5
	19-Dec	3
	19–37	1
Impact of vadose zone	305–316	10
	316–324	8
	324–330	6
	330–336	4
	336–344	1
Hydraulic conductivity (permeability rating)	High (>3 m/day)	10
	Variable (0.3–1 m/day)	8
	Medium (3–1 m/day)	6
	Low-medium (1–0.01 m/day)	4
	Low (0.01–0.05 m/day)	1

Guelph municipal supply wells used for the calculation of the CAD values. These values were calculated within zone 4 (25 years WHPA) capture zone, since it encompasses all the other zones.

CAD-DRASTIC vulnerability map

This research attempts to predict the degree of contamination of the Guelph area aquifer due to the application of road salt while using data from the geological and anthropogenic factors that contribute to prioritization of vulnerable sites. Hence, vulnerability to a contaminant is assessed using the DRASTIC methodology; specifically related to depth to water table, annual average recharge, aquifer type, soil media distribution, ground surface slope, impact of the vadose zone, the permeability of surficial geology material, and geospatial layers are considered as significant parameters. Land-use and road network are previously considered in the GIS-based CAD calculations. Each parameter used in this method is multiplied by a weight value (Table 4) which is assessed by qualitative, rather than quantitative criteria used similarly by other researchers (Kim and Hamm 1999; Panagopoulos et al. 2006; Hamza et

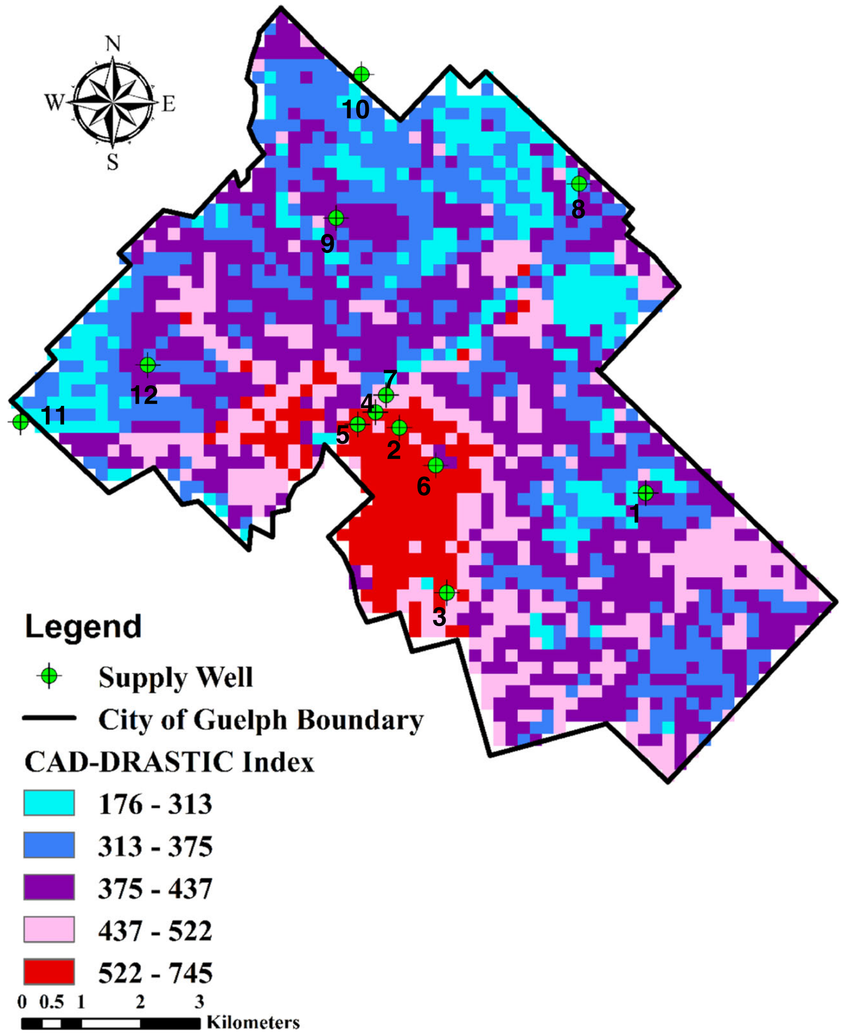


Fig. 3 CAD-DRASTIC vulnerability map for the City of Guelph

al. 2007; Al-Hanbali and Kondoh 2008; Neukum et al. 2008; Ahmed 2009; Martínez-Bastida et al. 2010; Sener and Devraz 2013; Hernández-Espriú et al. 2014; Khan et al. 2014).

The index is calculated in a GIS-based software in order to map the groundwater vulnerability of the study area (Fig. 2). All the parameters are converted into a raster format so that arithmetic operations can be performed; henceforth, the datasets of each parameter are modified in a way that weighting and ranking can be added to each layer. Finally, after assigning the weighting and ranking for each layer (Tables 4 and 5), the final map is generated for the study area (based on the boundary of the 25-year time-of-travel influence area), by using the DRASTIC equation (Eq. 2).

Complementing the previous DRASTIC model with this new layer (CAD) after assigning a weight (w) of 3 and the relevant ratings from high ($r = 10$) at the value of CAD = 0.4 and low ($r = 1$) for CAD = 0.1, the resultant vulnerability output is derived. Five classes of vulnerability are considered to describe the relative probability of groundwater salt contamination—low (176–313), low-moderate (313–375), moderate (375–437), moderately high (437–522), and high (522–745)—these classes are presented as distinct colors on the CAD-DRASTIC vulnerability map (Fig. 3). Once this figure

Table 6 Vulnerability output based on the modified DRASTIC method (CAD-DRASTIC), derived from Eq. (3) (multiplying DRASTIC by CAD values)

Well code	Supply well	CAD-DRASTIC index	Vulnerability class
1	Burke	400	Moderate
2	Dean Ave.	546	High
3	Downey Rd.	478	Moderately high
4	Edinburgh	529	High
5	Membro	561	High
6	University	406	Moderate
7	Water Street	481	Moderately high
8	Clythe Creek	371	Low-moderate
9	Emma	385	Moderate
10	Helmar	286	Low
11	Calico	267	Low
12	Smallfield	355	Low-moderate

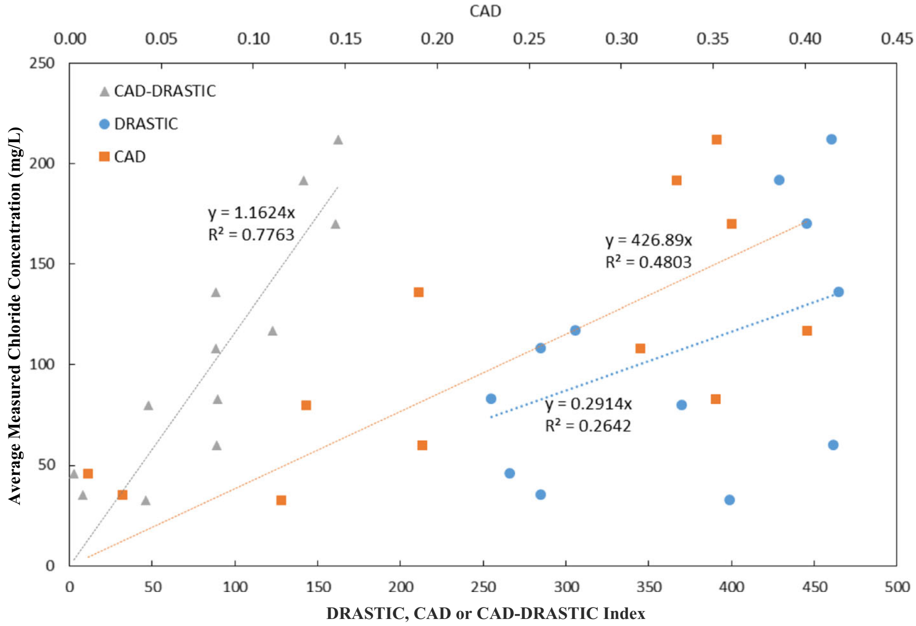


Fig. 4 The annual average measured chloride concentrations (1991–2007) for each of the 12 City of Guelph municipal supply wells plotted with calculated DRASTIC, CAD or CAD-DRASTIC index

was derived, the output vulnerability grading for each supply well was extracted from the resultant figure (Table 6). Each well is then assigned to a particular vulnerability zone accordingly.

The CAD-DRASTIC method better predicts average annual measured groundwater concentrations ($R^2 = 0.78$) at the 12 City of Guelph municipal supply wells, in contrast to either CAD alone ($R^2 = 0.48$) or DRASTIC alone ($R^2 = 0.26$); Fig. 4). Quantitative statistical evaluation techniques have been used to verify the three different models by comparing simulated outputs with measured data. As shown in Table 7, it is concluded that the CAD-DRASTIC method provides a higher accuracy of results compared to DRASTIC or CAD alone.

Sensitivity analysis

The results of the sensitivity analysis are provided in Table 8. A statistical analysis was performed in order to analyze the results of each parameter of the model. In the single-parameter-sensitivity-analysis method, the effective weights are compared with the theoretical weights in order to evaluate the accuracy of the weight assigned to each factor (Babiker et al. 2005). As expected (Table 8), the effective weights of the model's parameters showed a partial deviation from the theoretical weights. CAD, along with the net recharge and aquifer type, tend to have the highest effective parameters in the vulnerability analysis. The effective weight of CAD exceeds the theoretical weight assigned to it by the model. The rest of the parameters, excluding aquifer and soil layers, exhibit lower effective weights compared to the theoretical weights. The significance of CAD, net recharge, and aquifer type layers highlights the importance of obtaining accurate, detailed, and representative information about these factors.

Discussion

Considering additional geospatial modifiers to DRASTIC models have been used widely by various researchers (Al-Hanbali and Kondoh 2008; Ahmed 2009; Martínez-Bastida et al. 2010; Sener and Devraz 2013; Hernández-Espriú et al. 2014), it is reasonable to include CAD in road salt vulnerability mapping by using it to modify the DRASTIC calculation.

Table 2 highlights the areas with the highest percentage of the land mass that receives road salts and its application rate, with commercial areas receiving the bulk of the salt. This is expected because higher human traffic in these regions can typically mean more revenue; therefore, parking spaces are given priority over green spaces. Furthermore, private business owners may gravitate towards avoiding injury lawsuits rather than attention to environment-friendly practices forged by the city with minimal enforcement.

Table 7 A comparison between different statistics: R^2 (coefficient of determination); *RMSE* (root mean square error); *NASH* (Nash and Sutcliffe coefficient of efficiency); and *MAPE* (mean absolute percent error). Observed (measured) values and predicted values are compared through these statistical measures

	R^2	RMSE	NASH	MAPE
DRASTIC	0.26	101.9	−5.1	17.99
CAD	0.48	9.34	0.98	8.3
CAD-DRASTIC	0.78	3.89	0.9	3.34

Table 8 Statistics of sensitivity analysis. *SD* standard deviation

Parameter/layer[a]	Theoretical weight	Theoretical weight (%)	Effective weight (%)	SD (%)	Median (%)	Min. value (%)	Max. value (%)
CAD	3	11.54	44.7	28.19	12.65	7.48	86.1
D	5	19.23	6.58	2.68	7.41	1.25	9.85
R	4	15.38	10.78	1.6	10.82	8.28	13.12
A	3	11.54	12.71	2.1	12.71	2.8	15.62
S	2	7.69	9.67	2.86	3	3	13.3
T	1	3.85	1.96	1.21	2.67	0.11	4
I	5	19.23	9.15	3.89	10.81	1.48	12.54
C	3	11.54	4.45	2.91	4.45	1.64	7.25

[a] DRASTIC depth to groundwater *(D)*, recharge by rainfall (*R*), aquifer type (*A*), soil properties (*S*), topography (*T*), impact of vadose zone (*I*), and the hydraulic conductivity of the aquifer (*C*)

Applying this new method, it was determined that high vulnerability groundwater is located predominantly in the southwest areas (Fig. 3), while low vulnerability ranked groundwater is found in the northern parts of the Guelph. This qualitative conclusive process can add more depth to the understanding of groundwater vulnerability due to road salt application and furnish the decision-maker with wider insights by offering spatial vulnerability scores based on surface and underground factors.

While all supply wells in Guelph show an increase in chloride concentration (presented in AquaResource Inc. 2010b), the mass balance performed and validated indicate that the CAD-DRASTIC index can be used as a reliable indicator to rank the vulnerability of one well compared to another. Results (Fig. 4) also suggest that a good correlation ($R^2 = 0.78$) exists between measured groundwater chloride concentration in the Guelph drinking water wells and the modified calculated groundwater chloride concentration (CAD-DRASTIC). This application indicates that the methodology can endure estimating different trends of chloride concentration amongst several wells. The combined CAD-DRASTIC method is more accurate than the CAD ($R^2 = 0.48$) and the popular DRASTIC ($R^2 = 0.26$) methods individually. This is because CAD focuses solely on the salt application density but does not consider groundwater recharge rates. In contrast, DRASTIC considers recharge and other hydrological properties but does not incorporate salt application density.

The single-parameter sensitivity analysis has shown that CAD, net recharge and aquifer type are the most significant environmental factors which can greatly impact the results. This in effect underscores the importance of having precise and accurate information and data available for these factors. The least sensitive factor is topography and it had the least effect on the model vulnerability.

The combination of these two established methods contributes to a better understanding of the vulnerability of groundwater to road salt contamination. Applying the DRASTIC method into the calculation of CAD makes the results more realistic because of the application of the hydrogeological factors affecting the infiltration of soluble road salt into the vadose zone and later to the saturated zone.

Conclusion and recommendations

Unlike other cold-climate nations, Canada uses millions of tonnes of road salt every winter as de-icing and anti-icing agents on roads and parking lots (Trenouth et al. 2017). However, roughly one third of the population in Canada receive all or part of their drinking water supply from groundwater, and chloride concentrations in the groundwater in some urban watersheds has gradually and steadily increased from less than 50 mg/L in the 1960s to over 350 mg/L in 2010, exceeding the Ontario Drinking Water Quality Standards (ODWQS) of 250 mg/L. Therefore, it is essential to develop more accurate approaches for mapping the salt vulnerable areas that can be performed readily and inexpensively using available datasets. The resulting outcomes of such data analysis tools can be conveyed to municipalities and governmental agencies thereon with the aim of lessening the adverse effects of road salt on groundwater resources for the present as well the future generations by reducing salt application rates within the mapped vulnerable areas.

This paper presents a significantly modified method for mapping salt vulnerable areas by combining the best ideas of the two available approaches previously employed by Betts et al. (2015) and the popular DRASTIC method to develop a significantly more accurate method. The City of Guelph, Ontario, is selected as the case study site for demonstration of the new method because of the commendable proactive approach of the city in protecting its groundwater. The hydrogeology of Guelph is well characterized due to long-term groundwater monitoring and advanced mapping stemming from source water protection initiatives carried out in the province of Ontario. This can be a major factor in the application of the DRASTIC methodology with very minimal effort. The results from this research further the understanding of the effects of road salts on groundwater and can help in the development of salt management plans by focusing efforts on areas most vulnerable to road salts by calculating and ranking spatial vulnerability. Key recommendations for further research and application of this method include the following:

- Having reliable geospatial mapping and long-term groundwater monitoring data are of paramount importance. Municipalities and provincial or state governments should continue to collect this type of data to facilitate rapid and accurate groundwater vulnerability assessment. There is a continued need to invest in high resolution and accurate data collection and storage with reliable access to use with such models.
- This research can be beneficial when dealing with limited municipal resources by improved use of existing datasets in order to spatially-refine vulnerable areas; areas with an infrequent but heavy application of salt and regions with the frequent but light application can be planned accordingly.
- Public entities can conduct research in conjunction with private firms working in vulnerable areas to optimize the use of the limited water resources or to selectively deploy enhanced engineering control structures. It is recommended that once functioning in adjacent or common-authority areas, free exchange and sharing of data and information can be beneficial to facilitate this type of analysis.

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