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Groundwater chloride response in the Highland Creek watershed due to road salt application: A re-assessment after 20 years

Nandana Perera[a,1], Bahram Gharabaghi[a,*], Ken Howard[b]

[a] School of Engineering, University of Guelph, Guelph, ON, Canada N1G 2W1
[b] Dept. of Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, ON, Canada M1C 1A4

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SUMMARY

Chloride from road salt enters streams primarily through surface runoff and groundwater discharge. Monitoring of dry-weather flow chloride concentrations in the Highland Creek watershed of the eastern Greater Toronto Area indicates the presence of a previously unrecognised, dual porosity aquifer system whereby preferential flow associated with "urban karst" exerts a significant influence on baseflow chloride concentrations early in the year. A chloride mass balance undertaken annually over four successive salting seasons suggests that as much as 40% of the chloride applied as road salt enters the shallow aquifer resulting in a net accumulation of chloride and a gradual increase in mean baseflow chloride concentrations. Assuming current road salt application rates are continued, late summer baseflow chloride concentrations will reach around 505 mg/L, almost double present levels. Elevated chloride concentrations can affect the potability of water (the Canadian aesthetic drinking water quality guideline for chloride is 250 mg/L) and can also be toxic to aquatic organisms (CCME aquatic chronic toxicity guideline is 208 mg/L). Meeting these guidelines would require that the release of salt-laden runoff to the subsurface be reduced by over 50%.

1. Introduction

In cold climates, controlling snow and ice conditions on the road system is essential for minimizing impacts on public safety, roadway capacity, travel time and economic costs. This is achieved by a combination of mechanical ploughing and the application of chemical de-icers. In North America, the most commonly used de-icing agent is rock salt comprising sodium chloride with minor impurities (Howard and Beck, 1993). Salts lower the freezing point of water and the melting action of the salt forms brine that runs off paved areas removing snow and ice. Approximately 5 million tonnes of road salts are applied to roadways in Canada annually (Environment Canada, 2004). The City of Toronto has 5500 km of roads to maintain (City of Toronto, 2005) and applies salt to roads and sidewalks during the winter to improve safety.

Recent work indicates that both aquatic and terrestrial ecosystems can be adversely affected by exposure to high chloride concentrations associated with the typical use of road salts (US EPA, 1988; Novotny et al., 1999; Williams et al., 2000; Environment Canada and Health Canada, 2001; Ramakrishna and Viraraghavan, 2005). Aquatic organisms in smaller ponds and low flow streams are particularly susceptible to toxicity due to road salt application (Marsalek, 2003; Marsalek et al., 2000). In terms of drinking water quality, Health Canada (2010) recommends aesthetic objectives for chloride (250 mg/L) and for sodium (200 mg/L). However, due to cardiological concerns associated with sodium intake, in Ontario, local health officials must be informed if sodium concentration in drinking water exceeds 20 mg/L (Ministry of the Environment (MOE, 2002)). Chloride can also alter partitioning between adsorbed and dissolved metals, thus increasing the concentration of dissolved metals in snowmelt (Bäckström et al., 2004). Exall et al. (2011) indicated potential detrimental effects of ferrocyanides, a common additive used in road salts as an anti-clumping agent. Ferrocyanides are only mildly toxic but can dissociate to form cyanide. Cyanide will volatilise and dissipate relatively quickly in surface water, while in groundwater its mobility is significantly reduced by its tendency to adsorb to organic matter.

Beginning in 1995, road salts were subjected to a comprehensive 5-year scientific assessment under the Canadian Environmental Protection Act, 1999 (Environment Canada and Health Canada, 2001). The final report concluded that high releases of road salts were having an adverse effect on freshwater ecosystems, soil,

* Corresponding author. Address: Room 2417, Thornbrough Building, School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G 2W1. Tel.: +1 (519) 824 4120x58451; fax: +1 (519) 836 0227.
E-mail address: bgharaba@uoguelph.ca (B. Gharabaghi).
URL: http://www.uoguelph.ca/~bgharaba/ (B. Gharabaghi).
[1] Present address: Computational Hydraulics International, Guelph, ON, Canada N1H 4E9.

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vegetation and wildlife, and prompted the development of a Code of Practice for the Environmental Management of Road Salts (Environment Canada, 2004) that was designed to optimise salt application and to reduce chloride transfer to the environment. Canada is in the process of developing ambient water quality guidelines for chloride (CCME, 2011).

Chloride from road salts enters streams primarily through surface runoff and groundwater discharge (D'Itri, 1992). There are no economical treatment methods for chloride contaminated water because of the non-reactive nature of the chloride ion. Therefore, the preferred management approach has been to develop appropriate best management practices that optimise salt use under given winter snow and ice conditions, while ensuring the maintenance of roadway safety. Current best management practices focus on minimizing release of road salts into the environment during storage and handling, and salt application at an optimal rate with properly calibrated salt spreaders. There is a potential for developing innovative best management practices that target road runoff and infiltration, minimizing discharge of chlorides into receiving surface water bodies and groundwater aquifers once road salt is applied, for example, by capturing chloride laden winter road runoff and reusing it for de-icing.

A good understanding of transport dynamics of road salts is essential for developing and implementing best management practices that minimise the detrimental environmental impacts of road salts. It is particularly important to understand the hydrological factors that control the rate at which salt is transported and ultimately released to surface water bodies. For example, the impact of road salt on sensitive aquatic organisms has generated considerable interest due to very high chloride concentrations observed in surface water bodies following very rapid urban runoff (Marsalek, 2003; Godwin et al., 2003; Kaushal et al., 2005; Kilgour et al., 2012). In contrast, the gradual accumulation of salt in aquifers and its subsequent release in baseflow discharge to streams can cause chronic impacts that extend long beyond the period of salt application. In effect, chloride released in baseflow has a year-round, long-term impact on aquatic flora and fauna as compared to chloride in surface runoff that normally occurs during short events in winter and early spring.

Research by Howard and Haynes (1993) represents one of the earliest attempts to quantify effects of road salt application on groundwater using high resolution temporal data at the basin scale. Based on chloride mass balance calculations for the Highland Creek watershed in the eastern Greater Toronto Area, this work was the first to demonstrate the ability of shallow urban aquifers to store and accumulate salt, thereby postponing impacts on streams by many years. Using typical, representative values for aquifer storage and assuming no change in salt application rates, they challenged the conventional view that chloride concentrations in urban streams are a true reflection of salt loadings, by forecasting a three-fold increase in baseflow chloride concentration within a 20 year period to 426 ± 50 mg/L. The importance of chloride retention in aquifers and the resulting gradual increase of chloride concentrations in baseflow with time has more recently been documented in chloride mass balance studies conducted by Kelly et al. (2008), Novotny et al. (2009), and Perera et al. (2010).

The purpose of this paper is to re-examine the findings of Howard and Haynes (1993) using a more comprehensive dataset, and a closer consideration of the overland and near surface transport processes we now know occur in highly disturbed urban settings (Pokrajac and Howard, 2011). It examines and analyses the temporal variability of chloride concentration in Highland Creek baseflow for the purpose of gaining greater insight to the mechanisms of watershed salt transport and release. The paper concludes with a prediction of future changes to baseflow chloride concentrations, together with recommendations as to how such changes can be ameliorated.

2. Methodology

2.1. Study area

The Highland Creek watershed is approximately 100 km^2 in area and situated almost entirely within the boundary of the City of Toronto. The City of Toronto has maintained a stream chloride monitoring station at Highland Creek near Morningside Avenue since November 2004 at a location adjacent to the Water Survey of Canada (WSC) flow gauging station 02HC013 (Fig. 1). Considering both topography and the areal extent of the storm sewer system, these stations can be considered to represent approximately 84.9 km^2 of the watershed. The same monitoring locations were used by Howard and Haynes (1993) for their chloride mass balance study. The watershed typically receives approximately 840 mm of precipitation per annum including a snowfall of 115 cm or snow-water-equivalent of 115 mm (Environment Canada, 2011). Average baseflow (equivalent to aquifer recharge) was estimated to be 174 mm/year and evapotranspiration is approximately 350 mm/a (based on streamflow separation and annual water balance analyses conducted during this research). Highland Creek is not used for domestic water supply but does discharge into Lake Ontario which is the drinking water source for the Greater Toronto Area.

The watershed is highly urbanized and has a dense road network. The majority of the roads within the study area are maintained by the City of Toronto. Exceptions include Highway 401 (Fig. 1) which is under the jurisdiction of the Ontario Ministry of Transportation (MTO), a few private roads and roads that lie within the approximately 2% of the study area that fall within the Town of Markham to the north. In addition, the study area includes numerous parking lots that are salted by a range of private contractors. Approximately 14.5% of the study area is covered by road pavement while open (vegetated) areas account for 21.5%. Parking lot areas for commercial and institutional use cover approximately 2.5% of the study area while multi-family residential and industrial area parking lots account for a further 4.5% (Perera, 2010).

The surface sediments of the watershed area are mainly silty sand till, but stream valley floors contain a significant amount of recent flood plain deposits (Karrow, 1967). Based on regional studies (Ministry of Natural Resources (MNR, 1980); Meriano and Eyles, 2003), the most important aquifers in the watershed are the Scarborough Sands and the Lake Iroquois terrace deposits. These layers may be separated locally by the Sunnybrook diamict (Howard and Haynes, 1993). In all likelihood, the Scarborough Sands are too deep to have much influence on flow in Highland Creek, while the Lake Iroquois deposits may be significant only locally.

In practice, recognising the highly urban character of the area, it is reasonable to assume that the majority of subsurface flow takes place via imported fill material that has been made considerably more permeable by a dense network of trenches and tunnels that house underground utility pipes and storm drains. The thickness and properties of these characteristics this somewhat unconventional aquifer system is unknown to due to very limited borehole data. However, Howard and Haynes (1993) suggested that the aquifer has a total thickness of about 30 m and a specific yield approaching 20%.

The presence of moderately permeable, high storage, fill material permeated by networks of conduits, tunnels, and utility lines that provide secondary preferential flow paths have been documented in several cities (Sharp, 2012), and is frequently referred to as urban "karst" or "epikarst" (Sharp et al., 2001, 2003; Krothe, 2002; Krothe et al., 2002; Garcia-Fresca, 2007; Pokrajac and