Bioretention: assessing effects of winter salt and aggregate application on plant health, media clogging and effluent quality

Chris Denich, Andrea Bradford and Jennifer Drake

ABSTRACT

Bioretention offers the potential to better match pre-development water balances while improving stormwater quality. The now extensive body of research shows bioretention to be a viable and effective option in the management of stormwater, however there continues to be a demand for information related to cold climate design and performance. To study the impact of winter road salting on bioretention functions, a salt and aggregate mixture was applied to outdoor, bioretention mesocosms with soil, mulch and vegetation layers. Freezing of the media within mesocosms was found to increase the infiltration rates. Smaller increases in infiltration rates occurred for mesocosms exposed to the salt and aggregate mixture, suggesting that media clogging due to high suspended solids loading may be counteracting the effects of expansion due to freezing. Sodium and chloride were temporarily retained in the bioretention media, but were subsequently flushed by infiltrating water. Plant species, *Aster nova angliae 'Red Shades'* and *Panicum virgatum* were shown to be capable of withstanding high salt exposure. The exposure of the bioretention soils to de-icing materials did not alter the media's ability of the media to remove contaminants. No evidence of increased heavy metal mobility during this study was observed. Overall, results support the potential for application of bioretention facilities in cold climate regions.

Key words | bioretention, chloride, cold climate, infiltration, sodium, stormwater quality

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INTRODUCTION

Bioretention, including soil, mulch and plants, can help to maintain or restore pre-development storage, infiltration and evapotranspiration processes, improve stormwater quality and provide a landscaped aesthetic. Bioretention systems have become popular in regions of Canada, the United States (Morzaria-Luna *et al.* 2004; Jones & Hunt 2009; Davis *et al.* 2012), Australia (Goyen *et al.* 2002; Kazemi *et al.* 2011) and New Zealand (Trowsdale & Simcock 2011) where they are used in a variety of applications including the treatment of parking lot and rooftop runoff on commercial sites (Davis *et al.* 2003; Hunt & Jarrett 2004; Hsieh & Davis 2005a) as well as in residential areas (Morzaria-Luna *et al.* 2004).

Researchers have shown that filtering stormwater through bioretention media can allow for substantial removal of numerous stormwater pollutants including suspended solids, heavy metals, oil and grease, polycyclic aromatic hydrocarbons and pathogens (Davis *et al.* 2003; Kim *et al.* 2003; Hsieh & Davis 2005a; Hong *et al.* 2006; Hunt *et al.* 2006; Sun & Davis 2007; Roy-Poirier *et al.* 2010). Bioretention systems have been shown to have variable nutrient removal which is dependent on media composition and drainage design (Roy-Poirier *et al.* 2010). Commonly cited concerns associated with infiltration systems are the potential for rapid deterioration due to clogging, and contamination of both native soils and groundwater (Alfakih *et al.* 1999; Barraud *et al.* 1999). In cold climates, winter road maintenance practices may accelerate the rate of clogging and contamination (Claytor & Schueler

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1996; Pitt *et al.* 2004). Canada utilises approximately 5.0 million tonnes of de-icers a year (EC 2004).

The Na^+ ions from road de-icers interact with exchangeable cations in the soil, buffering the direct effect of the Na^+ ion itself on groundwater quality. Indirectly, the ion exchange processes within the soil as a result of Na^+ exposure can increase the mobilisation of divalent cations and trace heavy metals (Löfgren 2001; Norrstrom & Bergstedt 2001; Backstrom *et al.* 2004). Therefore, the water quality concern associated with Na^+ loading includes the potential of increased heavy metal mobilisation.

The effect of the Cl^- ion on groundwater is more direct and therefore is the main focus of many groundwater and surface water quality studies dealing with salt application (Ostendorf *et al.* 2001, 2006; Thunqvist 2004). The Cl^- ion is highly soluble, is not subject to retardation or degradation (Löfgren 2001; Thunqvist 2004; Ramakrishna & Viraraghavan 2005; Ostendorf *et al.* 2006) and is freely transported through the subsurface (Norrstrom & Bergstedt 2001). In regions with road salt applications, Cl^- concentrations as high as 2,800 mg/L have been measured in groundwater (EC 2001). The temporary storage of residual Cl^- in soils, well beyond the de-icing season, has been reported by others (ECHC 2001; Kaushal *et al.* 2005; Ramakrishna & Viraraghavan 2005). Ostendorf *et al.* (2001) found stored Cl^- to be transported by subsequent precipitation throughout the year. An advantage of this mechanism is that it may act to both delay and dilute salt laden runoff concentrations, thereby buffering the effect of high concentration pulses on surface water and groundwater discharge points. On the other hand, a source of Cl^- may remain into the low flow season at which time there is less surface flow to dilute the chloride that continues to be flushed from soils, and aquatic organisms may be less able to cope with increased concentrations due to other stresses associated with low flows (e.g. higher temperature, lower dissolved oxygen (DO)).

While a substantial foundation of bioretention research does exist, there continues to be demand for knowledge regarding cold climate challenges. Cold climate concerns include effects of salt and sand loads on bioretention performance; trade-offs between groundwater quantity and quality; and system lifespan, specifically media clogging and the effects of winter maintenance materials on biochemical processes and vegetation. The goal of the research was to address these concerns, specifically to assess the effectiveness of bioretention areas in the management of runoff from roads and parking lots, subjected to snow, salt, and sand, and enhance bioretention functionality to achieve multiple stormwater management objectives in cold climates. The study design aimed to represent real, as opposed to laboratory, conditions to the extent possible (e.g. de-icing mix used by the City of Guelph was applied in the study). It was, however, a short-term study extending over two growing seasons and the intervening winter. Accelerated loadings of winter de-icing materials were applied to provide an indication of long term issues, with recognition that bioretention processes, particularly biological processes, are likely to be affected by the high hydraulic and de-icer loadings which were conditions of the study.

The scope of this paper is the assessment of the impact of road de-icers (salt and aggregate) on the infiltration rate of bioretention media, plant health and survivability and on overall system lifespan. It also summarises the observed behaviour of sodium (Na^+) and chloride (Cl^-) ions and the fate of heavy metals and nutrients in bioretention mesocosms exposed to winter road maintenance materials.

METHODOLOGY

Bioretention mesocosms

Ten identical bioretention mesocosms (Figure 1) were constructed following typical bioretention design guidelines (e.g. Claytor & Schueler 1996; PSAT 2002; Windograff 2002; WSDE 2005) using a medium with the characteristics shown in Tables 1 and 2 and plants with salt tolerances as shown in Table 3. The medium was placed within the mesocosms in 10 cm lifts, using consistent methods of fill and compaction.

Synthetic runoff composition and loading

A 95% sand, 5% rock salt residential (low priority) de-icer 'B-sand', provided by the City of Guelph, ON, was used in the formulation of synthetic winter runoff. This solution was manufactured by combining 121.5 g of B-sand with 5 L of de-ionised (DI) water and mixing rapidly to allow for complete dissociation of Na^+ and Cl^- ions. The mass

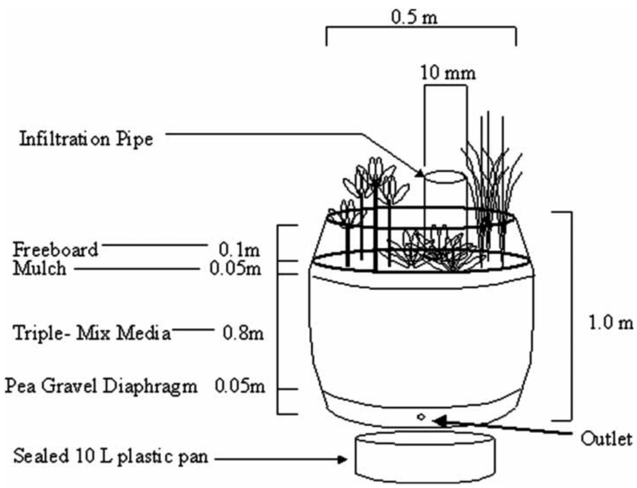

Figure 1 | Outdoor bioretention mesocosm components.

of the 95/5 mixture to be applied to the columns was determined based on the drainage area for which the mesocosms were sized, the assumption that the drainage area consisted of a two lane residential street, and concentrations measured in winter runoff from residential streets in Guelph, Ontario. Measured concentrations of Cl^- ranged from 6 to 952 mg/L and a value near the upper end of the range was selected in an effort to study performance under more extreme conditions. Mixing 121.5 g of the B-sand with 5 L of water yielded concentrations of chloride and sodium in the ranges measured in the field and were consistent with the average chloride concentration of 805 mg/L for urban Toronto snow reported by Howard & Livingstone (2000). Based on analysis of winter hydrology and de-icer application data from the City of Guelph, 10 applications were assumed per year. Further details of the methodology are provided in Denich & Bradford (2008).

The synthetic urban runoff formulation (with heavy metals and nutrients) followed that of Davis *et al.* (2001) to facilitate the comparison of removal rates; removal efficiencies can vary depending on influent concentrations (McNett *et al.* 2011). Actual concentrations in the synthetic runoff formulation are provided in Table 4. Because well water was used in the preparation of samples, nitrate concentrations were considerably higher due to natural background concentrations of 10.6 mg/L in the well water.

Mesocosm dosing, sampling and activities

The mesocosms were constructed outdoors in early summer 2007 to allow for plant establishment prior to testing. The initial infiltration capacity of the media was established for mesocosms 1–10. Mesocosms were moved to an unheated, indoor space during the winter months and synthetic urban runoff equivalent to 2 years' loading (2,430 g of 95/5 mix) was applied to mesocosms 6–10. This loading was delivered in 18 doses of synthetic winter runoff, with at least 24 hours between doses. To eliminate any effects due to absorption by dry soils, mesocosms were pre-wetted with 25 L of clean water and allowed to drain for at least 24 hours. Following dosing, mesocosms 6 and 8–10 were flushed 10 times with 10 L of DI water to track the migration of Na^+ and Cl^- out of the systems. Mesocosm 7 received doses of more concentrated synthetic winter runoff, equivalent to an additional 13 years of loading. The 15-year loading was intended to help characterise bioretention life expectancy in response to long-term sand and salt application. Concentrated stormwater applied over a short period of time is not equivalent to a lower concentration applied over a long period of time. However, in lieu of a

Table 1 | Chemical properties of the bioretention medium

Nutrients		Metals		Other	
Property	Value (mg/kg)	Property	Value (mg/kg)	Property	Value
NH_4-N	159 ± 17	Copper (Cu)	13.5 ± 0.7	Organics	3.9 ± 0.1
Nitrite (NO_2^-)	<1	Lead (Pb)	8.0 ± 0.0	pH	7.4 ± 0.0
Nitrate (NO_3^-)	<1	Zinc (Zn)	56 ± 4.0	CEC (meq/100 g)	21.9 ± 1.2
Organic N	5,491 ± 371	Aluminium (Al)	5,035 ± 21		
TKN	5,650 ± 354	Iron (Fe)	7,215 ± 77		
Total P (TP)	2,235 ± 728				

Table 2 | Physical properties of the bioretention medium

Property	Value
d_{60}	0.6 mm
d_{10}	0.08 mm
Coefficient of uniformity (Cu)	7.5
Organic content	3.94 ± 0.99%

Table 3 | Plants selected for bioretention mesocosms

Botanical name	Common name	Salt tolerance
Epimedium × rubrum	Barren wort	Low-none
Aster novae-angliae 'Red Shades'	Red Shades Aster	High
Rudbeckia hirta	Coneflower	Moderate
Sedum kamtschaticum	Russian Stonecrop	Moderate–high
Panicum virgatum	Switchgrass	High

Table 4 | Synthetic urban runoff composition

Pollutant	Concentration applied (mg/L, except pH)
Heavy Metals	
Copper	0.05
Lead	0.01
Zinc	0.4
Nutrients	
Nitrate	12.7
Ammonia as N	0.48
TKN	16.0
Organic nitrogen	3.9
Phosphorus	0.13
Other	
pH	8.2

long duration study, this method can provide an indication of long-term performance and has been used in other studies (Lucas & Greenway 2008).

The mesocosms were subsequently moved outdoors, allowed to fully thaw, and the infiltration capacity of the bioretention media was re-measured. To evaluate if the winter runoff affected pollutant removal processes, 2-year (mesocosm 8) and 15-year (mesocosm 7) salt-exposed mesocosms, as well as a control mesocosm (mesocosm 1), were dosed with a synthetic urban runoff solution (with heavy metals and nutrients). Effluent samples were collected at 2, 4.5, 8.5 and 24 hours after synthetic urban runoff application and 4 hours after a clean water flush. The inclusion of distributed effluent collection in the testing methodology was intended to demonstrate temporal effects on effluent concentrations, specifically to indicate the timing of the peak effluent concentrations.

Soil samples were collected at the end of the study and analysed for cations and anions. Cores were collected from a control column and at three depths (21, 42 and 63 cm) from a 2-year and 15-year salt-exposed mesocosm. Plant health was also assessed at the end of the study based on plant vigour, colour, necrosis, and overall survival. Table 5 summarises the dosing and activity schedule for each mesocosm.

Laboratory analysis methods and data analysis

Cl^- and Na^+ concentrations were measured during testing using a Thermo Orion meter, Model 250A+ and Na^+ ion-selective (Cole-Parmer) and Cl^- ion-selective (Fischer Scientific) electrodes. Samples collected during synthetic urban runoff dosing were analysed for pH, conductivity and temperature; anions (chloride, sulphate), nutrients (nitrate (NO_3^-), ammonia as N (NH_3-N), organic nitrogen (organic-N), total Kjeldahl nitrogen (TKN), ortho-phosphate (ortho-P) and total phosphorus (TP)); and metals (copper (Cu), lead (Pb) and zinc (Zn)). Nitrite (NO_2^-) results are not reported, as concentrations were consistently below detection limits in all samples analysed. Due to high Na^+ and Cl^- levels in column effluent samples, as a result of exposure to road de-icers, special consideration was given to the analysis of effluent metal concentrations so as to obtain appropriately low detection limits. Metal sample analysis was carried out using procedures adapted from PSWQAT (1995) (EPA 6020A), where suspended particulate resin, consisting of immobilised iminodiacetate on a divinylbenzene polymer, is used to chelate and pre-concentrate metals, followed by analysis using inductively coupled plasma mass spectrometry.

Salt mass balances were completed for each mesocosm. This included estimating initial and final background concentrations within the bioretention media as well as recording input and output concentrations and solution volumes. Masses of nutrients and metals were calculated from measured volumes (L) and concentrations (mg/L) at 2, 4.5,

Table 5 | Dosing and testing activities schedule

		Columns									
		Control					Experimental				
Activity	**Date**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mesocosm construction and planting	Summer 2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Infiltration testing (pre-dosing)	Aug. 2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Testing for background Na^+ and Cl^- levels in mesocosms	Mar. 13–Mar. 27, 2008						✓	✓	✓	✓	✓
Application of 18 doses of synthetic winter runoff (2 year-equivalent)	Mar. 29–Apr. 22, 2008						✓	✓	✓	✓	✓
DI flush (to analyse mobilisation of residual Na^+ and Cl^- post-dosing)	Apr. 23–May 2, 2008						✓		✓	✓	✓
Application of additional 13 year-equivalent winter runoff dose	Apr. 23–May 5, 2008							✓			
Infiltration testing (post-dosing)	June 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Soil coring (to analyse ion interactions and exchange processes within soil)	June 2008	✓					✓	✓		✓	✓
Application of synthetic urban runoff	Aug. 2008	✓						✓	✓		
Plant health analysis	Aug. 2007, Jan./Apr. 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

8.5 and 24 hours after synthetic urban runoff application and 4 hours after clean water flush. Cumulative mass, 24 hours after synthetic urban runoff application and 4 hours after flush, are reported. Cumulative output mass and total input mass were used to calculate removal efficiencies.

RESULTS AND DISCUSSION

Infiltration testing

Prior to application of synthetic runoff, infiltration testing (five trials) indicated that infiltration rates for the media in mesocosms 1–10 ranged from 7 to 73 m/d, averaging 24.8 m/d and closely matching rates reported by Hsieh & Davis (2005b). After a complete winter season, as well as the application of the synthetic winter runoff, the infiltration rate for all mesocosms (1–10) increased (Figure 2). The control mesocosms (no winter runoff application) had the largest increase with infiltration rates averaging 139 m/day. Average infiltration rates from mesocosms dosed with the 2-year equivalent winter runoff loading increased to 77 m/day and the infiltration rate from the mesocosm dosed with the 15-year equivalent loading increased to 28 m/day. Soil volumes increased during freezing of the bioretention mesocosms and did not return to their original level beneath the

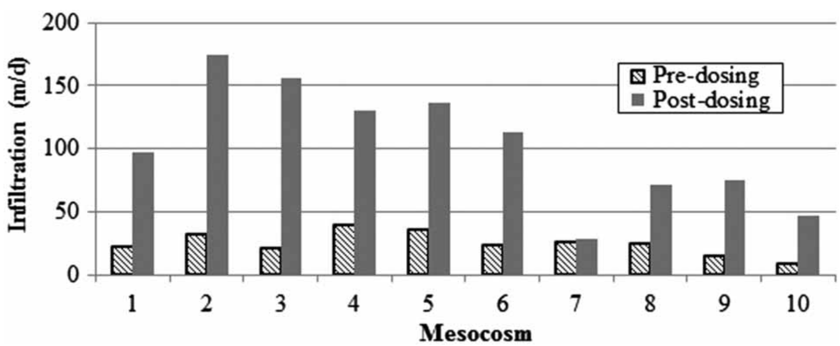

Figure 2 | Infiltration rate comparison pre and post synthetic winter runoff application.

container's top edge after the soil matrix thawed. Increases in permeability of bioretention media have been previously reported by Pitt *et al.* (2004) and Hsieh & Davis (2005a). Increased volume of media with high organic matter content, such as bioretention mixes, has been attributed to freeze-thaw action (Brady & Weil 2002; Pitt *et al.* 2004) which increases interstitial space between soil aggregates, increasing the connected porosity (Hillel 1998) and thus resulting in an increase in infiltration rates.

Mesocosms subjected to a 2-year equivalence of winter runoff loading experienced a slightly smaller increase in infiltration rate when compared to the control columns, suggesting that media clogging due to high suspended solids loading may have partially counteracted the effects of expansion due to freezing. Visual observations following synthetic winter runoff application indicated that considerable surface aggregate and suspended solids (silts and fines) accumulation occurred as a result of mechanical filtration by the mulch layer, although a large portion of the aggregate also migrated beneath the mulch surface.

The permeability of Column 7 (15-year equivalence) exhibited a modest (10%) increase. Observations of Column 7 made at the commencement of testing (soil frozen), confirm the same increase in soil volume observed in other columns; however, subsequent observations revealed a recession of the soil surface to near its original level by the end of the testing period. It is believed that the application of the equivalence of 15 years, versus 2 years, of de-icer, totalling more than 15 kg of de-icing aggregate and over 130 L of liquid synthetic runoff, acted to re-compact and redistribute the bioretention medium, thereby negating any increases in connected porosity or pore size experienced during soil expansion.

Salt mass balance

The Na^+ and Cl^- mass balance results are interpreted in two phases: the mass balance during contaminant exposure using synthetic winter runoff inputs (pre-deionised (DI) water flush), and the mass balance at the end of the DI flush representing rain events following spring snow melt. The collected effluent volume was 88–90 and 91–92% of the input volume, pre-flush and post-flush, respectively. Similar losses in volume were also observed by Davis *et al.* (2003) and can be attributed to evapotranspiration.

Background Na^+ and Cl^- levels in leachate from the soil, mulch and plant matrix varied considerably between individual columns despite a uniform soil medium and installation procedures. Values ranged from 591 to 1,995 mg/L for Na^+ and 79 to 643 mg/L for Cl^-. In June 2008, digested samples of soils not exposed to synthetic winter runoff, were analysed and found to contain 80–90 mgNa^+/kg and 40–50 mgCl^-/kg. By using the volume of soil in each column, the maximum Na^+ and Cl^- mass were estimated to be 22.68 gNa^+/column and 11.34 gCl^-/column and used as upper limits on the source of Na^+ and Cl^- from the bioretention medium.

Input concentrations ranged from 205 to 1,810 mg/L for Na^+ and 382 to 1,275 mg/L for Cl^-. The concentration variability was caused by variable salt aggregate grain size within the de-icer mix (121.5 g of 95/5 sand/salt mix). Results demonstrate a consistent response to the winter runoff and DI flushing. At the conclusion of the 18 synthetic winter runoff doses, mesocosms 6–10 demonstrated a cumulative retention of input Na^+ and Cl^- mass (Table 6). Total input mass was the sum of the contributions from synthetic winter runoff input, aggregate residual and background soil leachate. Cl^- and Na^+ ions were released from all columns during subsequent DI-flushing (Table 6). At the conclusion of the trials, all flushed columns had cumulatively released a higher Na^+ mass than the total input mass. Figure 3 illustrates a representative behaviour of the bioretention medium in response to successive Na^+ and Cl^- loadings.

The lack of agreement between the input mass and the output mass indicates the presence of an additional source of Na^+ not accounted for in the input dose, aggregate residual or the soil background determinations. The large

Table 6 | Na^+ and Cl^- mass balance during the two phases of testing

	Contaminant exposure-pre-flush (% mass retained in soil relative to input)		Post DI-flush (% mass retained in soil relative to input)	
Column	Na^+	Cl^-	Na^+	Cl^-
10	35	68	–45	18
9	19	61	–72%	10
8	6	45	–69	6
7	18	58	–	–
6	9	45	–90	–5

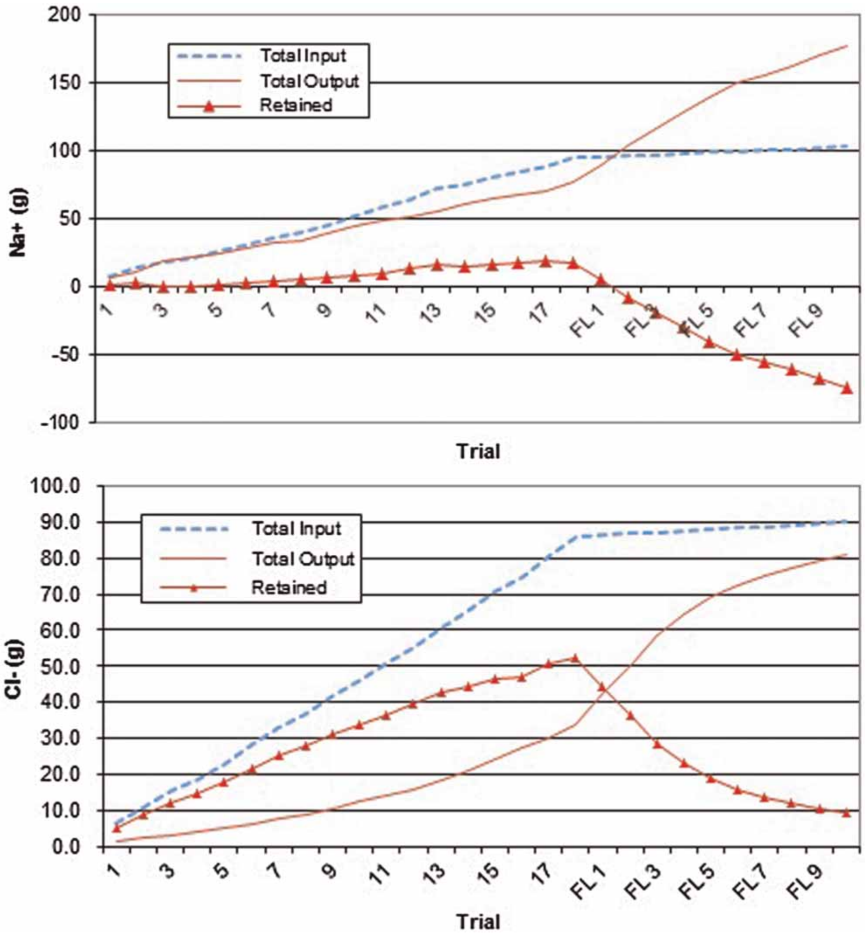

Figure 3 | Representative mesocosm behaviour for mesocosm 9: Na^+ (top), Cl^- (bottom).

discrepancies between measured Na^+ inputs and outputs are attributed to several sources of error in the execution of the experiment. Soil grab samples analysed may not have been representative, resulting in an underestimation of the total Na^+ content within the medium. The variability of Na^+ content within the aggregate used in the synthetic runoff may have not been sufficiently evaluated and the sample used for aggregate ion residual determination may have underestimated Na^+ inputs. Although removal of undissolved salt aggregate was part of the methodology, it is possible that undissolved rock salt which escaped detection may have resulted in the input concentration being underestimated.

The agreement between input Cl^- mass and output Cl^- mass was much closer than in the Na^+ mass balance, with only a –4 to 18.2 g difference. The 10 flushes or 100 L/mesocosm were not sufficient to mobilise all retained Cl^-. In a bioretention system designed for infiltration to native soils, the mobilised Na^+ and Cl^- would be transported to groundwater given appropriate migration time and sufficient infiltrating volume.

In an effort to understand the processes taking place within the soil profile and properly interpret mass balance results, soil coring and analysis was performed after synthetic winter runoff and flush applications (Table 7). Note that Samples A, B and C were taken at 21, 42 and 63 cm below the soil surface, respectively.

Soil coring results demonstrate adsorption processes taking place within the soil profile along the flow path of infiltrated synthetic winter runoff. Base cation (Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+}) levels were higher, relative to the control sample, in Samples A and B, except K^+, which was slightly lower in Sample A. Concentrations of Ca^{2+}, Mg^{2+}, K^+ and Al^{3+} were highest in Sample B and decreased

Table 7 | Summary table for soil coring, post synthetic winter runoff application

Constituent	Control (mg/kg)	Sample A (mg/kg)	Sample B (mg/kg)	Sample C (mg/kg)
Aluminum (Al)	5,035	5,150	5,260	4,470
Calcium (Ca)	17,400	18,800	24,900	15,600
Magnesium (Mg)	4,000	4,270	8,780	3,680
Potassium (K)	805	780	920	750
Sodium (Na)	85	290	360	240
Chloride	45	90	230	170
Other				
TOC	3.4	5.2	4.8	3
pH	7.4	7.28	7.4	7.22

again in Sample C to levels below those in Sample A and the control sample (Table 6). Na^+ levels at all depths (A, B and C) were elevated compared to the control; since the media appears to be a sink rather than a source of Na^+, this analysis could not explain the higher mass of Na^+ measured in the effluent than in the influent as shown in Table 6.

Heavy metals and nutrients

Heavy metals

Overall, the final cumulative mass of Cu, Pb and Zn removed by the bioretention media were very similar for all columns (Table 8), with removal efficiencies of 87–91, 85–86 and 88–91%, respectively. A small (<5%) but steady decline in metal removal efficiency was observed between the start and end of dosing with synthetic urban runoff. During the DI flushing, metals remained captured within the mesocosms and did not become remobilised. The removal efficiencies observed in the salt-exposed and control mesocosms were similar, providing no evidence that the exposure of bioretention medium to the equivalence of 2 and 15 years of de-icing salt and aggregate, affects the removal of heavy metals.

Table 8 | Mass of Cu, Pb and Zn collected and respective removal efficiencies

Metal and specimen		Cumulative collected mass (µg) End	Flush	Removal efficiency (%) End	Flush
Cu	Control	25.0	25.0	88	88
	2-yr	18.8	18.8	91	91
	15-yr	19.2	26.7	91	87
Pb	Control	5.5	7.0	89	85
	2-yr	6.1	6.8	87	86
	15-yr	4.0	6.9	92	86
Zn	Control	101.6	131.3	93	91
	2-yr	127.5	139.8	91	90
	15-yr	108.5	177.1	93	88

Nutrients

Removal was only observed for NO_3^- species of nitrogen. The control, 2- and 15-year salt exposed columns released nitrogen at different rates and times. Removal efficiencies are outlined in Table 9. Effluent NO_3^- mass varied little with collection time compared to other nitrogen species. Removal efficiencies of tested columns ranged from 83 to 88%. This was somewhat surprising since negatively charged NO_3^- ions are not adsorbed by the predominantly negative binding sites and therefore should move freely downward with draining water (Brady & Weil 2002). Nevertheless, similar NO_3^- removal efficiencies to those achieved

Table 9 | Mass of nitrogen species collected and removal efficiencies

Collection time		Cumulative collected mass (mg)		Removal efficiency (%)	
		End	Flush	End	Flush
NO_3^-	Control	7.1	8.8	86	83
	2-yr	7.5	8.7	85	83
	15-yr	5.5	6.3	89	88
NH_4-N	Control	1.4	2.7	–185	–470
	2-yr	1.3	2.9	–162	–509
	15-yr	0.9	1.7	–88	–264
Organic-N	Control	84.6	120.5	–442	–672
	2-yr	44.3	67.8	–184	–334
	15-yr	41.8	64.0	–168	–310
TN	Control	93.1	132	–39	–97
	2-yr	53.1	79.4	21	–19
	15-yr	48.2	72	28	–8
Ortho-P	Control	21.6	35.7	–4,062	–6,770
	2-yr	10.9	20.1	–1,988	–3,772
	15-yr	8.1	14.2	–1,464	–2,638
TP	Control	22.3	37.7	–4,187	–7,141
	2-yr	11.6	20.8	–2,123	–3,908
	15-yr	8.9	16.1	–1,613	–3,001

in this study were published by Hunt *et al*. (2006), who found that two conventionally drained bioretention cells were capable of annual NO_3^- mass removals of 40% (ranging from 13 to 75%) due to the existence of denitrification micro-sites within an unsaturated organic soil. The organic matter within the bioretention media provides the required carbon source for denitrification. The presence of small internal nitrogen-transformation-zones is supported by Parkin (1987) and Dietz & Clausen (2005) who found that conditions that would favour bacterial denitrification did exist within the bioretention media.

The cumulative effluent mass for all other nutrient species was far greater than the influent mass. Nutrients were steadily released from the mesocosms during dosing of synthetic urban runoff and subsequent DI flushing. The majority of nitrogen released was organic-N. Similar increases in NH_4-N have been reported by Hsieh & Davis (2005a, b) and Hunt *et al*. (2006). The increase could be attributed to several processes including the formation of NH_4 due to decomposition of organic matter in the media, the conversion of organic-N originally in the media to NH_4 (Tchobanoglous & Schroeder 1987; Brady & Weil 2002) and the leaching of background NH_4-N naturally found in the medium. The 15-year salt column routinely produced lower levels of both organic-N and NH_3-N as compared to the others.

The analysis of effluent samples revealed that the mass of TP collected was greatly dominated by ortho-P. TP mass leaching increased with collection time and had greatly increased at the end of effluent collection; no removal of ortho-P or TP occurred at any time. The peak mass mobilisation of TP occurred after the columns were flushed with clean water.

Plant health

Plants chosen from the salt tolerant bioretention plant list developed as part of this research were observed throughout each phase of the experiment. The health of the plant (plant vigour, colour, necrosis and survival) and overall plant aesthetics (presence of flower, plant form and shape) were assessed visually. During the establishment phase (June–October 2007) all plant materials were successfully established.

After exposure to the equivalent of 2 years' salt, plant health was re-assessed on May 9, June 12 and August 14, 2008. Observations indicated plant mortality of all *Rudebeckia herta* and *Epimedium ruberium* in all mesocosms less column 8, including those that did not receive synthetic winter runoff. Control plantings of *Epimedium ruberium* (planted in off-site gardens) experienced low winter survival rates and all control plantings of *Rudebeckia herta* experienced 100% plant mortality. Both cultivars of plants are clearly ill suited for the Guelph, ON climate. The remaining plant specimens, *Aster nova angliae 'Red Shades', Sedum kamtschaticum* and *Panicum virgatum* had excellent survival rates with 90% survival of all *Aster and Sedum* specimens and 100% survival of all *Panicum* grasses.

All surviving plants in columns 1–5 (no synthetic runoff application) demonstrated no reduction in total biomass, chlorosis or necrosis. Columns 6 and 8–10 (synthetic winter runoff application), elicited some chlorosis early in re-emergence growth, however it remained for only a short period. Column 10 demonstrated an early decrease in plant vigour; all three surviving plant species were slightly stunted in early May, however by June all plants were growing well and no longer lagged those in other mesocosms.

Plants exposed to high synthetic winter runoff loadings, as part of life span testing (Column 7), did show effects of the elevated salt exposure as expected. *Epimedium* and *Sedum* did not survive the high mass loadings experienced in this mesocosm. Surviving species of *Aster* and *Panicum* displayed severe chlorosis early in their spring re-emergence but like the plants of Columns 6 and 8–10 the effects were short lived. However, plants in Column 7 displayed a significant decrease in vigour, with most plants stunted by as much as 15 cm in height. The decrease in plant vigour was evident in all stages of growth but became less pronounced in subsequent months. The tolerance of *Aster nova angliae 'Red Shades'* and *Panicum virgatum* to the extreme salt exposure in this study suggest good potential for use in bioretention cells receiving runoff from areas subject to application of road salt.

IMPLICATION OF RESULTS

Winter permeability

The modest increase in infiltration rate suggests that the infiltration capacity of the types of soils tested herein should not limit bioretention use in cold climates and should be expected to function well hydraulically during a 15-year design life, however more detailed research is needed. In particular, the determination of how much of the freeze-expansion was a result of the special conditions of the experimental systems should be pursued. Freeze/thaw effects may affect *in situ* bioretention soils, however one would suspect that native settings might reduce or resist expansion effects.

Impacts of road salts

Results from the overall mass balances of Na^+ and Cl^- indicate that movement of these ions through the bioretention media into native sub-soils would occur and the subsequent migration into both groundwater and surface water is likely. Similarly elevated levels of Na^+ and Cl^- in collected effluents were reported by Czerniawska-Kusza *et al.* (2004) who conducted lysimetric analysis of roadside soils exposed to de-icers (NaCl and CaCl) and concluded that salts play a significant role in the pollution of soil and that permeable soils allowed soluble pollutants to penetrate deep layers of the soil profile in urban areas.

It is important to note that due to the nature of salts, neither infiltration techniques (bioretention included) nor other stormwater management practices are effective in the removal of Na^+ and Cl^- from runoff. Therefore the control/reduction of de-icer inputs is a critical approach to surface and groundwater protection. The exposure of bioretention can be limited by locating facilities in areas that receive low annual de-icer loads (typically low priority roads) in combination with implementation of salt management strategies on public and private lands near bioretention facilities. It may be possible to incorporate controls on underdrainage such that infiltration is not promoted during periods when the temporary stores of Cl^- in the media remain high. However, at other times underdrainage may be restricted and infiltration promoted. Although passive operation of stormwater management systems is preferred, such control of underdrains may be a way to balance the need for groundwater recharge with the desire to protect groundwater quality.

Stormwater quality

With respect to nutrients, the forms of particular concern depend upon whether the stormwater passing through the bioretention media will be collected in underdrains and discharged to a surface water system, allowed to infiltrate native soils and recharge groundwater, or a combination of both. The high NO_3^- mass removal (83–88%) observed in this study is encouraging for locations where groundwater recharge is desired. The anoxic conditions required for denitrification were achieved in the bulk media, or 'hot spots' within the bulk media, in this study, but could also be achieved by promoting a saturated zone near the base of a bioretention system, either below a raised underdrain, or at times when underdrainage is restricted as discussed above.

From a surface water perspective, the bioretention system, as designed in this study, had unsatisfactory removal of TN and TP. In addition to concerns with respect to eutrophication of surface water receptors, unionised ammonia is directly toxic to fish (Tchobanoglous & Schroeder 1987). Although the bioretention systems performance did indicate the presence of small internal nitrogen-transformation-zones, there may have been insufficient areas in the bioretention medium with the aerobic conditions required for enhanced nitrification (NH_3–N to NO_3^-). Overall, the medium used in the mesocosms may have been too fine-grained.

The results of this study also clearly point to the need to pay closer attention to the chemical composition of the media. The mechanism responsible for the elevated levels of phosphorous in the mesocosm effluent is likely the leaching (mobilisation) of phosphorous in response to infiltrating water. Specifically, the mobilisation of the phosphorous initially present in the bioretention medium and/or the phosphorous bacterially converted from organic material into ortho-P via decomposition during the three-month interval between media characterisation and the experiments. The capacity of the soils to promote adsorption, and possibly precipitation, of phosphorous is important (Davis *et al.* 2001). Characterisation of the bioretention media used in this study indicate high levels of aluminium (5,035 mg/kg), iron (7,215 mg/kg) and clay and silt content of 8% which could have acted to remove phosphorous. However, this capacity may have been overwhelmed by the large amount of phosphorous leaching from the bioretention media selected. In addition, Davis (2003) and Hsieh & Davis (2005a) suggested dynamic processes (i.e. preferential flow paths) may prevent soils with higher cation exchange capacity (CEC) and cation levels to achieve phosphorous removals. Therefore, the physical and chemical properties of soil may be an inadequate predictor of phosphorous removal/mobilisation.

The mesocosm exposed to the equivalence of 15 years of winter road maintenance materials (aggregate and salt) provided the best overall removal of nitrogen and phosphorous (Tables 4 and 5). It had the lowest nutrient release, followed by the 2-year mesocosm and finally the control, except in the case of ammonia (where 15 years > control > 2 years). The performance of each mesocosm may be related to the volume of water infiltrated through the medium during the application of synthetic winter runoff. The infiltrated water may have leached nutrients from the medium thereby pseudo-ageing the medium. Pitt *et al.* (2004) reported that the leaching of nutrients (nitrate and phosphorous) exhibited by younger media (short ageing time) was much greater than that from older facilities. The relationship between media ageing time and nutrient leaching from bioretention media was also suggested by Culbertson & Hutchinson (2004).

The study confirmed the ability of bioretention facilities to remove heavy metals commonly found in stormwater runoff (Cu, Pb and Zn), and the low risk of heavy metal contamination to surface and groundwater (Pitt *et al.* 2004) posed by effluent from bioretention facilities. However, the potential for increased risks associated with the accumulation of heavy metals in bioretention facilities over longer operational time frames (Davis *et al.* 2003), particularly in areas of road salt application, requires further investigation.

CONCLUSION

Testing on 10 outdoor bioretention mesocosms was undertaken to investigate concerns related to media clogging, plant health, nutrient removal, potential trade-offs between groundwater quality and quantity, and design life. Freeze–thaw action was shown to increase media volume and infiltration rates. The mesocosms most heavily loaded with winter road maintenance materials (aggregate and salt) had the smallest increase of infiltration rate indicating that these materials did impact infiltration capacity. The results demonstrated that although Na^+ and Cl^- ions are temporarily retained within bioretention media, they will ultimately migrate to receiving water systems. Further investigation is needed to better understand the implications and trade-offs associated with wide-scale stormwater infiltration. The plants used in this study, *Aster nova angliae 'Red Shades'* and *Panicum virgatum*, were capable of tolerating the extreme doses of salt-laden stormwater and offer good potential for use in cold climates.

The application of salt-laden synthetic winter runoff did not negatively impact the removal rates of metals. The 15-year mesocosm had removal efficiencies for Cu, Pb, and Zn of 87, 86, and 88%, respectively. However, long-term studies will provide more insight into pollutant removal processes over the entire life of a bioretention system. The mesocosms provided NO_3^- removal, but were incapable of removing NH_4-N and organic-N. Similarly, the mesocosms did not provide any phosphorus removal. The application of synthetic winter runoff did not negatively impact nutrient removal. The high nitrate removal was attributed to unplanned anoxic micro-sites within the bioretention media which created isolated pockets suitable for denitrification. The high levels of other nutrient species is likely the result of leaching of nutrients initially present in the bioretention media or produced through biodegradation of organic matter.

Overall, the results of this study support the use of bioretention as an alternative stormwater management and treatment system in cold climates. For bioretention systems which drain to surface waters, the ability to delay and dilute salt-laden runoff may offer important environmental benefits. Further research is needed to better understand the migration of Cl^- and Na^+ ions within full-sized bioretention cells. Long-term processes, such as the accumulation of metals, leaching from bioretention media and implication to groundwater systems, continue to require additional investigation.

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