Blue-Green Systems

Blue-Green Systems Vol 5 No 2, 170 doi: 10.2166/bgs.2023.036

Impact of de-icing salt runoff in spring on bioretention efficiency

Henry Beral[a,b,*], Danielle Dagenais[c], Jacques Brisson[a,b] and Margit Kõiv-Vainik[a,b,d]

[a] Complexe des sciences, Département de Sciences biologiques, Faculté des Arts et des Sciences, Université de Montréal, 1375 Avenue Thérèse-Lavoie-Roux, Montréal, QC H2V 0B3, Canada
[b] Institut de Recherche en Biologie Végétale, 4101 Sherbrooke Est, Montréal, QC H1X 2B2, Canada
[c] École d'urbanisme et d'architecture de paysage, Faculté de l'Aménagement, Université de Montréal, 2940, chemin de la Côte-Sainte-Catherine, P.O. Box 6128, Downtown Station, Montréal, QC H3C 3J7, Canada
[d] Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46, Tartu, Tartumaa 50090, Estonia
*Corresponding author. E-mail: henry.beral@umontreal.ca

HB, 0000-0002-2336-1533; DD, 0000-0001-9071-459X; JB, 0000-0003-0046-7551; MK-V, 0000-0003-2340-5134

ABSTRACT

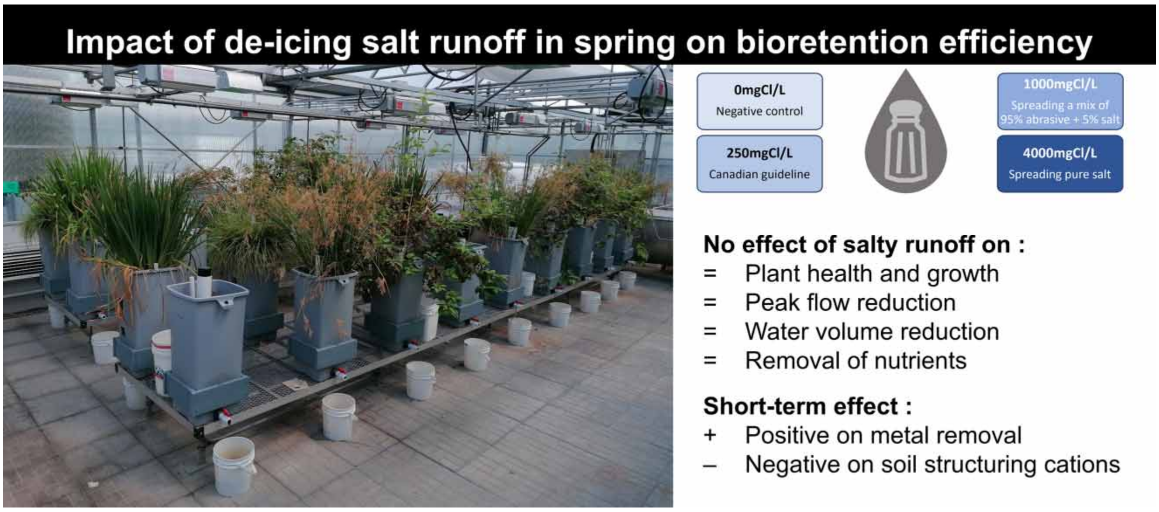
We investigated the effect of de-icing salt in stormwater runoff on bioretention system hydrology and filtration of contaminants. Salt runoffs during the snow melt period were simulated in 20 mesocosms planted with 1 of 3 plant species (*Cornus sericea*, *Juncus effusus* and *Iris versicolor*) or left unplanted, and then watered with semi-synthetic stormwater runoffs supplemented with 4 NaCl concentrations (0, 250, 1,000 or 4,000 mg Cl/L). All bioretention mesocosms, irrespective of treatment, were efficient in reducing water volume, flow and pollution level. There was no phytotoxic effect of NaCl on plants, even at the highest NaCl concentration tested. Water volume reduction and flow rate were influenced by plant species, but salt concentration had no effect. Salt runoffs significantly increased the removal of some metals, such as Cr, Ni, Pb and Zn, but had no effect on nutrient removal. Because snowmelt laden with de-icing salt is of short duration and occurs during plant dormancy, plants in bioretention may be less affected by de-icing salt than previously thought, provided that salinity decreases rapidly to normal levels in the soil water. The long-term effects of de-icing salt and general performance of bioretention should be further studied under full-scale conditions.

Key words: biofilter, cold climate, de-icing salt, dormancy, plant species, salinity

HIGHLIGHTS

- Salt runoff did not reduce metal removal after one season.
- High nutrient removal efficiency regardless of salt concentration.
- Salt runoff did not alter the flow and water volume reduction.
- No phytotoxic effect of de-icing salt in stormwater runoff.

GRAPHICAL ABSTRACT



Impact of de-icing salt runoff in spring on bioretention efficiency

No effect of salty runoff on :

= Plant health and growth
= Peak flow reduction
= Water volume reduction
= Removal of nutrients

Short-term effect :

\+ Positive on metal removal
– Negative on soil structuring cations

1. INTRODUCTION

Urban stormwater is laden with pollutants, such as heavy metals, nutrients, herbicides, polycyclic aromatic hydrocarbons, and various organic compounds (Eriksson *et al.* 2004; Valtanen *et al.* 2014). These contaminants threaten the natural environment as urban stormwater is often discharged into waterways without prior treatment. Blue-green infrastructures such as bioretention cells (BR) are increasingly used to address this issue (Fletcher *et al.* 2015). BR has been shown to effectively manage and treat stormwater runoff through mechanical, chemical and biological processes (Kratky *et al.* 2017).

Although seasonal differences have been shown to have an impact on the effectiveness of BR (Roseen *et al.* 2009; Paus *et al.* 2016; Beral *et al.* 2023), in winter, plants are dormant, microbial activity is reduced and the physical properties of the water and soil change due to low temperatures, all of which could potentially hinder BR performance (Muthanna *et al.* 2007; Blecken *et al.* 2011; Søberg *et al.* 2014; Géhéniau *et al.* 2015). Moreover, in many cold regions, large amounts of de-icing salts and/or abrasives may be spread on roads and sidewalks to ensure safety. For instance, Canada annually uses over five million tonnes of de-icer, the most common being sodium chloride (NaCl) (Environment and Climate Change Canada 2022). Spreading de-icing salt generates salty runoffs when the snow melts (Ramakrishna & Viraraghavan 2005), especially during initial spring warming or the first rainy precipitation of the season (Snodgrass *et al.* 2017; Taka *et al.* 2017; Burgis *et al.* 2020; Goor *et al.* 2021). Salty runoffs could decrease BR effectiveness through a negative effect on the plants and substrate.

In fact, increased osmotic pressure caused by sodium chloride may induce water stress in living organisms (Hintz & Relyea 2019). In plants, osmotic stress results in reduced water absorption by roots and consequently in root development, leaf area, stomatal conductance and plant size (Liem *et al.* 1985; Munns & Tester 2008; Davis *et al.* 2014). This reduction in plant performance may consequently diminish their contribution to BR efficiency (Read *et al.* 2009; Payne *et al.* 2018; Beral *et al.* 2023). Intracellular Na accumulation can also interfere with cellular machinery and may cause nutritional deficiencies due to competition for other nutrient transporters (Cekstere *et al.* 2010). Excess salt disturbs numerous metabolic pathways, leading to chlorosis, necrosis and even plant death (Endreny *et al.* 2012; Equiza *et al.* 2017; Shelke *et al.* 2019; Prodjinoto *et al.* 2021). Resistance to salt stress varies widely among plant species, which suggests that it should be considered during plant selection for BRs exposed to high salinity (Munns & Tester 2008; Dmuchowski *et al.* 2022). However, it is unclear how spring runoffs laden with de-icing salt would affect plant contribution to BR efficiency, as these salty runoffs, no matter how severe, are of relatively short duration and occur early in spring when the plants are still dormant.

Excess sodium chloride can also alter the physicochemical properties of the soil. Upon NaCl dissociation, the sodium cation competes with micro- and macro-elements on soil cation exchange sites. Once these elements are dislodged, they leach out of the substrate (Paus *et al.* 2014; Géhéniau *et al.* 2015; Søberg *et al.* 2020, 2017). A higher Na percentage at the expense of calcium favours a reduction in clay flocculation and a dispersion of colloids (Ramakrishna & Viraraghavan 2005; Fay & Shi 2012). This results in a more compacted soil structure, leading to lower permeability and hydraulic conductivity in BR (Denich *et al.* 2013). Since chloride is considered more mobile and less reactive (Marsalek 2003), BR might only briefly delay its release (Søberg *et al.* 2014; Burgis *et al.* 2020). Higher salinity may also lead to the remobilization of pollutants previously adsorbed by the substrate, through the release of contaminated colloids (Tromp *et al.* 2012; Kakuturu & Clark 2015; Huber *et al.* 2016), or the creation of dissolved metal-chloride complexes (Marsalek 2003; Reinosdotter & Viklander 2007).

Our study aims to investigate the impact of de-icing salts on BR effectiveness, specifically focusing on (1) the impact of NaCl-laden runoffs on the hydrology and contaminants filtration in BR mesocosms, (2) the persistence of the effect on BR after salt runoffs cease during the vegetation period and (3) the resilience of vegetation exposed to spring de-icing salt runoffs.

2. MATERIAL AND METHODS

The mesocosm-scale experiment was conducted in the 'Phytozone' greenhouse of the Institut de recherche en biologie végétale (IRBV), on the site of the Montreal Botanical Garden, in Canada (45°33′40.5″N 73°34′22.4″W). The temperature in the greenhouse was set to correspond to the outside temperature, except during cold periods, but the minimum was set to 5 °C (±2 °C) to prevent damage to the equipment due to freezing (Figure S1). BR efficiency was determined for 16 mesocosms that were planted with one of three species or left unplanted, then subjected to semi-synthetic runoffs supplemented with four different concentrations of NaCl in a 'Latin square' configuration. The assessment was carried out by monitoring hydrology (reduction in water volume and exfiltration rate) and contaminant concentrations and mass in each compartment of the system (water, plants and substrate). In addition, the resilience of plants to NaCl stress was determined by monitoring their growth and health status.

2.1. Experimental design

2.1.1. Column design

High-density polyethylene and polypropylene plastic containers (3569-88 Untouchable® from Rubbermaid Inc.) were used as mesocosms (Figure 1). Each mesocosm (H78 × L35 × W35 cm) was equipped with a rhizotron (a transparent acrylic tube 7 cm wide and 1 m long), as well as a perforated drainage pipe (1.9 cm diameter) in the substrate drainage layer that was connected to a vertical aeration pipe of the same diameter. The vertical aeration pipe was included to prevent blockages or obstructions within the drainage pipe, and to ensure the uninterrupted functioning of the drainage system throughout the experiment, thereby maintaining efficient water flow and enabling sample collection.

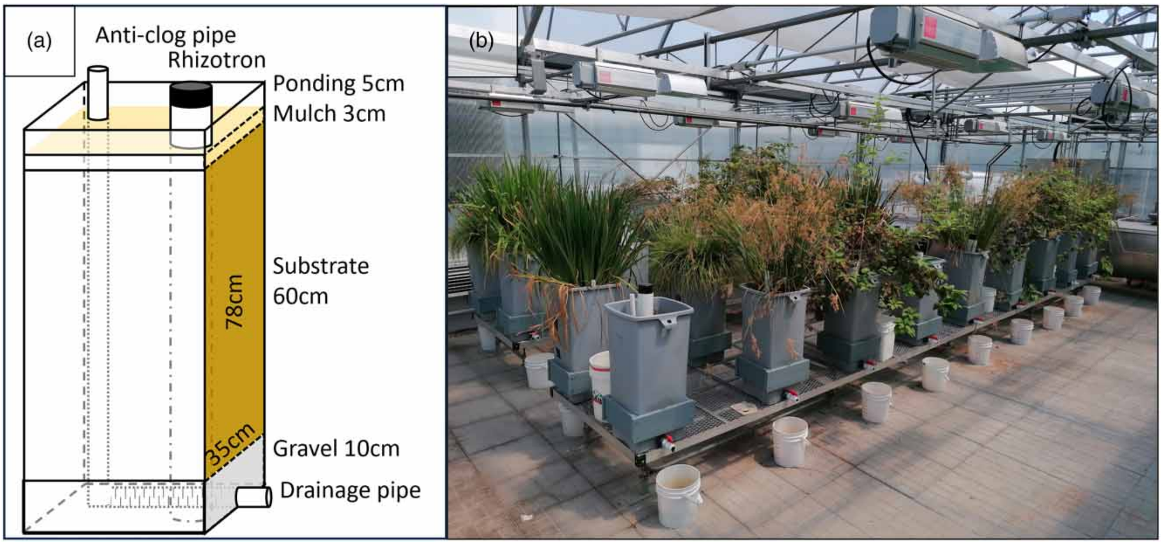


Figure 1 | (a) Schematic of the mesocosm design; (b) Photo of the 16 mesocosms in the IRBV greenhouse, 28 July 2020, Beral H.

2.1.2. Substrate

The bottom 10 cm of the mesocosms were filled with granite gravel as a drainage layer (Ø 5–12 mm; 'Granite gris du nord' from Agrebec Inc.). The main media consisted of 60 cm of commercial sandy loam BR media ('Natureausol' from Savaria Inc.; characteristics summarized in Table S1). On top, 3 cm of mulch (Savaria Inc. fragmented rameal wood) was added (Figure 1). At the time of planting, the mesocosms were treated with the mycorrhizal inoculant ('MykePro Landscape' from Premier Tech Ltd) according to the manufacturer's recommendations. The mycorrhizal inoculants are used with the aim of improving plant health and growth. Their use in municipal plantings is a common practice in Quebec, Canada.

2.1.3. Plant selection and establishment

Among the 16 mesocosms, 4 were unplanted controls and the 12 others were planted with 1 individual of one of the 3 following plant species: *Juncus effusus*, *Cornus sericea* or *Iris versicolor* (hereafter referred to as *Cornus, Juncus and Iris*). These species are among those recommended for BR by the Standards Council of Canada (Standards Council of Canada 2019) and include different biological forms and functional traits (Flora of North America Editorial Committee, eds. 1993). They have also previously been the subject of scientific monitoring in BR studies (Fritioff 2005; Zaimoglu 2006; Najeeb *et al.* 2011, 2009; Nocco *et al.* 2016; Lu *et al.* 2018; Dołęgowska *et al.* 2022; Beral *et al.* 2023).

Tap water was used to gently remove nursery soil from the roots before planting, on 1 June 2018. The plants were then acclimatized in mesocosms irrigated with rainwater for 12 months (from June 2018 to June 2019), followed by a 9-month period of irrigation with semi-synthetic runoff water (see next section), during which monitoring was carried out (Beral *et al.* 2023).

2.1.4. Simulated urban runoff

The semi-synthetic runoff water consisted of rainwater from the greenhouse roof, supplemented with nutrients, trace elements and a carbon source (Table S2; Beral *et al.* 2023). No pathogens or hydrocarbons were used for methodological reasons. Also, no sediment was used, since the removal of total suspended solid (TSS) depends mainly on the particle size of the substrate, and since the medium was the same in all our treatments, no significant difference was expected between treatments. Thus, efforts were focused on pollutants for which plants can potentially play a role in removal.

The urban runoff applied (loading frequency and quantity) simulated that reported in regional climatic data from Environment and Climate Change Canada (2018). Thus, based on a BR area equal to 10% of the collection area (as recommended by Coffman *et al.* 1993; Yang & Chui 2018; Standards Council of Canada 2019), each mesocosm was irrigated with 10 L, three times per week (Monday, Wednesday and Friday) from March to August 2020.

2.1.5. Salinity experiment

We assume that salty runoffs occur mostly during the first few rainy precipitations in early Spring, which accelerate snowmelt and wash out the salts spread during Winter (Williams *et al.* 2000; Goor *et al.* 2021). Thus, to simulate spring road-salt runoff, sodium chloride was added to the semi-synthetic runoff on four occasions, from 12 to 23 March 2020. During the salt runoff period, each mesocosm per species type (three species + one unplanted) received one of four NaCl concentrations. The tested NaCl concentrations were 0 mgCl/L as negative control, 250 mgCl/L – corresponding to Canadian drinking water guidelines (Health Canada 1997), 1,000 mgCl/L – a concentration usually found in runoff from roads spread with a 95/5 sand/salt mixture and previously tested in scientific studies, or 4,000 mgCl/L – a concentration usually found in runoff from roads spread with pure salt (Mayer *et al.* 1999; Denich *et al.* 2013; Paus *et al.* 2014; Géhéniau *et al.* 2015; Taka *et al.* 2017). After the salt runoffs, the mesocosms were irrigated with regular semi-synthetic runoff without de-icing salt until the end of the experiment (25 August 2020).

2.2. Sampling and measurements

Resilience of the vegetation subjected to spring salt runoffs was determined by monitoring plant growth and health. To characterize the impact of spring NaCl runoffs on the hydrology and filtration of contaminants as well as the impact's persistence in time after the salt runoffs, we monitored water loss, exfiltration rate, influent and effluent water quality, as well as substrate properties. The fate of contaminants and plant contribution to the efficiency of BRs subjected to these salt runoffs were determined by following the evolution of the substrate chemical composition, and contaminant uptake in plant tissues.

2.2.1. Plant growth, health and uptake

Plant health and growth were monitored once a month during the growing period. Average leaf area (Equation S1), total leaf area (TLA; one-sided; Equation S2), leaf area index (LAI; Equation S3) and unit ground surface area covered by the plant (Equation S4) were estimated. Health status was assessed as classes (from 5 healthy to 0 dead). At the time of dismantling, the leaves (plus the reproductive parts), stems in the case of the *Cornus* and roots were cut, collected separately and oven-dried at 70 °C to constant weight, to determine their dry biomass weight.

Contaminant concentrations were analysed based on leaf dry material collected from (1) three additional nursery individuals per species at planting time, (2) all 12 individuals of the species included in this experiment at the end of the acclimatization period, (3) a composite sample per species at the end of the first experimental period in 2020, as presented in Beral *et al.* (2023) and (4) all 12 individuals at the end of the experimental growing period following the salt application. The concentrations for N, P, K, Ca, Mg and 15 trace elements were analysed by Environex Inc., an accredited laboratory, using standard methods (see Note S1 for more information). The portion of contaminants taken up by the plants was obtained by multiplying leaf concentration by leaf biomass. Leaf biomass produced was also used as a growth rate indicator.

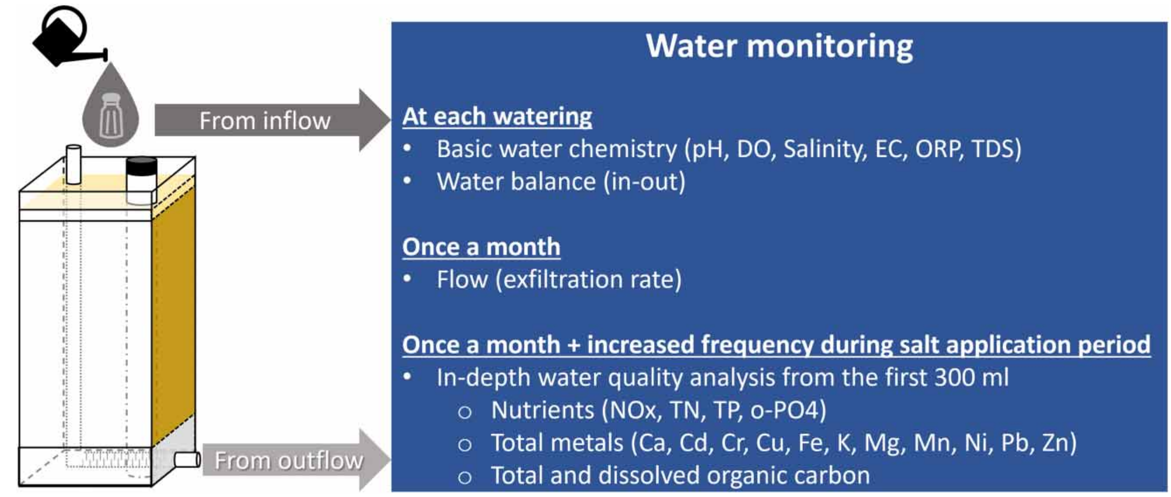
2.2.2. Water loss and exfiltration rate

Water loss through evapotranspiration rate (ET) was measured as mesocosm water balance between two watering events using Equation (1). To determine the exfiltration rate of each mesocosm, released water volume was measured at 10 min–20 min–30 min–1 h–1 h30 min–24 h after watering, once a month during the period of plant growth (see workflow Figure 2). In the following equation, mesocosm water loss through ET, expressed in mm/day, is shown.

$$\mathrm{ET} = \frac{(\text{ influent volume } - \text{ effluent volume }) \ / \ \text{mesocosm area}}{\text{number of days since last watering}} \tag{1}$$

2.2.3. Water quality

At each watering event, the basic physicochemical changes (pH, DO (dissolved oxygen), salinity, EC (electrical conductivity), ORP (oxidation–reduction potential), and TDS (total dissolved solid)) were measured with a multi-parameter probe (HI98194, Hanna Instruments®) both at the inflow and at the outflow. The pollutant concentrations were sampled on the second and fourth salt runoff event days, then twice during the following month and then once a month, for a total of eight samples. For the effluent, only the first 300 mL were collected,



Water monitoring

At each watering
- Basic water chemistry (pH, DO, Salinity, EC, ORP, TDS)
- Water balance (in-out)

Once a month
- Flow (exfiltration rate)

Once a month + increased frequency during salt application period
- In-depth water quality analysis from the first 300 ml
  - Nutrients (NOx, TN, TP, o-PO4)
  - Total metals (Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, Zn)
  - Total and dissolved organic carbon

Figure 2 | Workflow followed to monitor water loss, exfiltration rate and water quality.

which is conservative in terms of pollutant removal, because it is generally the most concentrated (Sansalone & Buchberger 1997; Sansalone & Cristina 2004). A wide range of contaminants were analysed by the Interuniversity Research Group in Limnology – Université de Montréal (GRIL-UDEM) laboratory according to standard methods (Baird *et al.* 2017): NO_x (nitrate (NO_3^-) + nitrite (NO_2^-)), total nitrogen (TN), ammonium (NH_4^+), total phosphorus (TP) and ortho-phosphates (PO_4^{3-}); total metals (Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, Zn), total organic carbon (TOC) and dissolved organic carbon (DOC). For DOC, NO_x and PO_4^{3-}, the analyses were performed after a 0.45 μm filtration using a polyethersulfone (PES) membrane. Multiplying the pollutant concentrations (g/L) analysed by the monthly average water volume (L per event) allowed us to calculate the contaminant mass (grams per mesocosm per event). Trace element concentrations below the detection limit (BDL) were set equal to these limits for data analysis to avoid overestimating trace element removal.

2.2.4. Substrate composition

Samples were taken within horizontal soil cores (diameter 3.8 cm and length 15 cm) before salt runoffs (28 February 2020) and at the time of dismantling (25 August 2020), in each mesocosm, at −10 and −30 cm from the soil surface. The holes made in February were refilled with the original substrate previously autoclaved and then sealed again. Substrate chemical composition was analysed for N, P, K, Ca, Mg and 14 trace elements (see Note S1 for more information) by Environex Inc. Sodium adsorption ratio (SAR) was calculated with Equation S5 following the Regional Salinity Laboratory (Regional Salinity Laboratory (U.S.) 1954).

2.2.5. Data analyses

Linear mixed-effect models (LMMs) were used to compare hydrological performance (ET and exfiltration rate), water quality changes (contaminant mass removal), plant growth (average leaf area, leaf number, TLA, LAI, plant volume, biomass), NaCl concentrations, interaction and time for repeated measures data (see example of the results for water quality parameters in Table 1). The individual mesocosm effect was added to the model as a random factor. All models were checked for normality and homogeneity of variance by visual inspection of residuals against fitted values (*Q*–*Q* plots). Variables that did not meet normality or heterogeneity assumptions

Table 1 | ANOVA *p*-value for the linear mixed model for the main factors: NaCl, species and dates with two- and three-way interactions, when significantly or near-significantly affecting the removal efficiency of water contaminants

	Main factors			**Two-way interaction**			**Three-way interaction**
	NaCl	**Species**	**Date**	**NaCl*species**	**NaCl*date**	**Species*date**	**NaCl*species*date**
Na	0.011		0.02				
Mn						0.002	0.008
TP			0.003		0.031	3.8×10^{-06}	0.006
PO_4		$<2.2 \times 10^{-16}$	0.006			1.3×10^{-06}	
TN		0.053			0.002	6.4×10^{-10}	2.1×10^{-06}
NO_3		3.2×10^{-04}			2.2×10^{-05}	5.2×10^{-09}	5.0×10^{-10}
NH_4		0.028				0.001	
Ca			4.1×10^{-09}		2.4×10^{-05}		
Mg			9.6×10^{-10}		2.0×10^{-04}		
Cr		0.051	0.058		7.4×10^{-04}	2.0×10^{-04}	
Ni			0.005		0.007	0.002	
Pb		0.036	0.009		0.002	0.041	
Zn					2.6×10^{-04}	0.012	
Cu		0.083			0.051		
Cd		0.018	8.2×10^{-12}				
Fe			4.6×10^{-05}				
K			1.1×10^{-07}			0.005	
TOC		0.087					
DOC			0.023				

were modified using the appropriate transformation (square root) when judged necessary. An ANOVA was performed as a measure of variance analysis on the different LMMs focusing on the effect of NaCl concentration, the interaction of NaCl with time or species and the triple interaction. When interactions were statistically significant ($\alpha = 0.05$), full LMMs were then partitioned per species or per date (or per month for parameters with more than 10 repetitions). Then, if the difference between NaCl concentrations was significant, a pairwise comparison *post hoc* Tukey's HSD test with a significance threshold set to $p = 0.05$ was run. Statistical analyses were performed using R software (ver. 4.1.2).

3. RESULTS

3.1. Plant growth, health and contaminant uptake

Overall, regardless of the de-icing salt concentration applied during runoffs, plants showed no growth defects, deficiencies or signs of NaCl-related stress after they emerged from dormancy. Also, no major changes in contaminant concentration in plant tissues due to de-icing salt were observed. The contribution of plants to contaminant removal was mainly limited to macronutrients, which were absorbed and then translocated to aerial parts. For the other trace elements, absorption by plants proved to be of minimal importance, especially since, when absorbed, these elements remain mainly in the root system.

Even though the ANOVA results showed that NaCl concentration significantly influenced the number of leaves per individual, and the interaction of NaCl with dates influenced plant volume, the results of *post hoc* tests were always above the significance threshold. There was no significant effect of NaCl, or an interaction effect involving NaCl, on LAI, TLA, average leaf area or leaf, stem or root dry biomass (Table S3). Phytosanitary status remained at the maximum (healthier class) during the entire experiment. Na increased in roots and leaves at higher NaCl-concentrated runoffs (Tables S4 and S5). No other major change in contaminant concentrations in plant tissues related to de-icing salt was observed.

We found that plants were able to absorb enough primary (N, P, K) and secondary (Ca, Mg) macronutrients to maintain tissue concentrations close to those measured initially when they left the nursery, regardless of the concentration of salt applied during runoffs (Tables S4 and S5). By absorbing into their tissues at least 37% of the primary macronutrient mass introduced into the system by the semi-synthetic runoff (Table S6), all species were able to contribute to the runoff filtration. Plants contributed to a lesser extent to the filtration of secondary macronutrients, with absorption levels representing 2–30% of the mass provided by the semi-synthetic runoff. The concentration of micronutrients (Mn, Zn, Fe) was lower than initially in the leaves, as well as in the roots for Mn, whereas it increased in the roots for Fe. That said, as for the secondary macronutrients, plants played a secondary role in filtration, with variable efficiency depending on the species. On the other hand, plants played no detectable or only a minor role in metals uptake, since concentrations of most metals (Cr, Cu, Ni, Pb) were low or below detection limits in leaves and roots.

3.2. Evapotranspiration

All treatments considered, over the duration of the experiment, the ET rate rose on average from 0.4 to 2.8 mm/day. During the NaCl runoff period and until the end of that month (March), when the plants were still in dormancy, the average ET rate was low (0.5 mm/day) and varied little. Afterwards, the ET rate was significantly influenced by plant species in interaction with dates, with no effect of NaCl concentration. At the peak of the growing season (June), *Juncus* presented an average ET of 4.0 mm/day, *Cornus* 3.2 mm/day, *Iris* 2.6 mm/day, with Unplanted far behind at only 1.0 mm/day (Figure 3).

3.3. Exfiltration rate

Similarly, no significant effects of salt or interactions with salt were found for effluent flow rate. The seasonal average exfiltration rate was around 10 L/h for all salt concentrations applied during the runoffs (Figure 4). A significant difference was observed between plant species, following the trend Unplanted > *Iris* > *Juncus* ≥ *Cornus*, with an initial (and maximal) exfiltration rate of 21.0, 7.4, 2.8 and 2.3 L/h, respectively. The exfiltration rate was rapid, peaking at approximately 10 min after watering, and then decreasing to close to zero after 3 h (Figure 4).

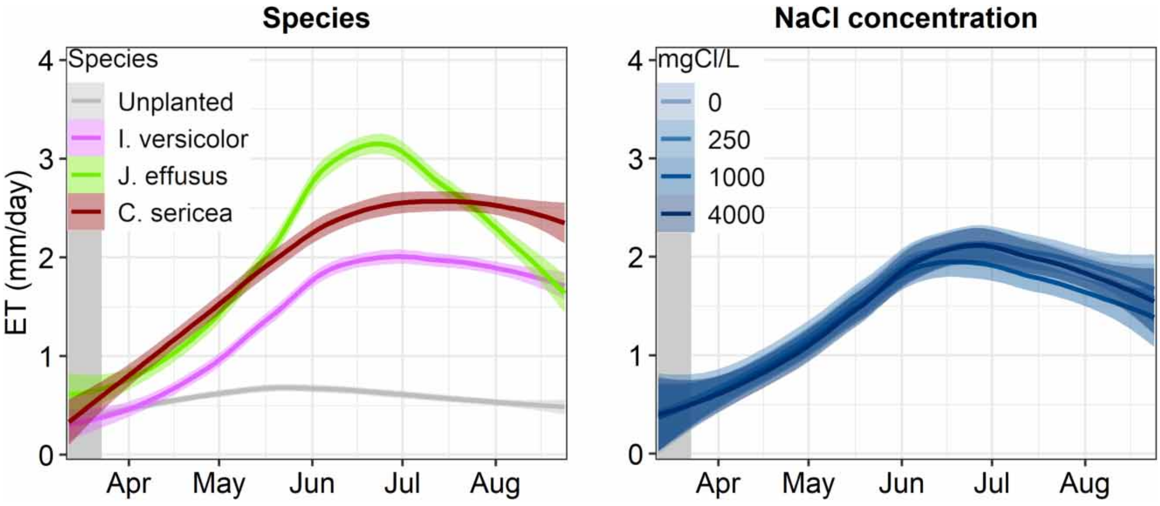


Figure 3 | Local polynomial regression fitting curves ('loess' method used in R geom_smooth function) and confidence interval (set at 0.95) around the smooth line, of the evapotranspiration (ET) rate according to the species planted (left) or to the NaCl concentration (right) in runoffs during spring (indicated by the vertical grey band) as a function of time.

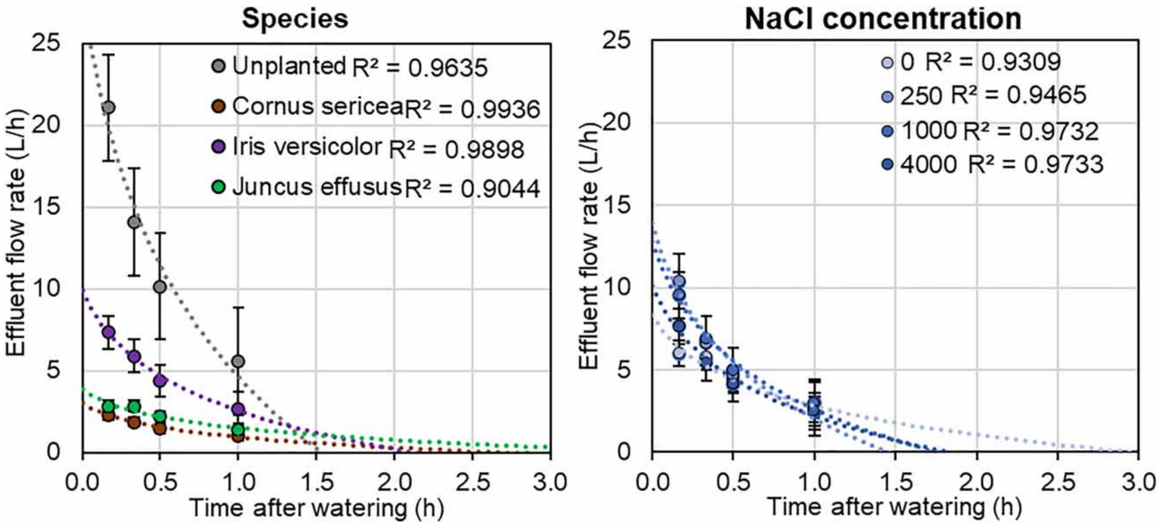


Figure 4 | Mesocosms runoff exfiltration rates per time after watering during the growing season and standard error ($n = 16$), on average per species (left) or NaCl concentration in spring runoff (right). Projection of logarithmic curves and R^2, displayed on the measured points for each species and salt concentration.

3.4. Runoff quality

Overall, the BR maintained a high mass removal efficiency for most trace elements and nutrients regardless of salinity during the whole experiment (Tables S7 and S8). Removal of Cr, Mn, Ni, Pb and Zn was very high, with an average efficiency of at least 82%. For Cu and Fe, removal was slightly less effective, with respectively 66 and 43%. Na and the main soil-structuring cations (Ca, Mg) were released, on average, during the experimental period.

3.4.1. Plant effect

As expected, the presence of plants significantly influenced the removal of nutrients and, to a lesser extent, that of metals. This contribution varied with time (see the significant elements for the species*dates interaction in Table 1). Removal of nutrients (TP, PO_4, TN, NO_3, NH_4, K) was consistently higher in planted mesocosms than in unplanted ones (Tables S7 and S8). Indeed, we found a TP, PO_4, TN, NO_3, NH_4 and K removal efficiency on average per species of at least 88, 95, 72, 74, 94, and 72%, respectively, while unplanted mesocosms removed only 52, 71, 12, −142, 86, and 0%, respectively. This plant effect was not affected by spring salt runoffs at the tested concentrations since in the statistical analysis, the interactions of plants (species) with salt (NaCl) and time (Date) were never statistically significant (see NaCl*species or NaCl*date*species in Table 1).

3.4.2. NaCl effect

There was no significant effect of salt runoffs alone (i.e., without interaction) on the removal of any contaminants except for Na (Table 1). However, there were effects of salt runoffs in interaction with date for several pollutants. There was a significant increase in release of soil-structuring cations (Ca, Mg), due to NaCl runoffs (Figure 5). The higher the NaCl concentration, the greater the release. This effect persisted for almost 1 month after the salt runoffs at the highest concentration (Figure 5). A slight rebound attenuated over time was observed in the following months, as shown by the sigmoid shape of the curves.

If we exclude the control curve (no salt), removal efficiency for several metals presented a trend consistent with the salt gradient applied, i.e., the higher the salt concentration, the greater the removal. The effect was short-term or even limited to the period of salt runoffs'. The mass removal of Cr and Ni was significantly lower at 250 mgCl/L than at the other NaCl concentrations during the runoffs, while the effect persisted until 2 weeks after the runoffs for Pb and Zn (Figure 5). Cu showed a similar trend, although often slightly above the significance threshold. The curves of the control group (no salt) for these metals (Figure 5, Cu not shown) show a reduced removal rate between mid-April and the beginning of July. Sampling or measurement errors in May (see outliers in Figure 5) and the fact that no sampling was done in June could account for these results. Cd, Fe, K and Mn mass removal showed no significant effect of salinity, with or without interactions.

For the removal of macronutrients TP, TN, NO_3 and Mn, the full LMM ANOVA shows a significant effect of NaCl with date (Table 1). However, testing the effect of salt for each date using an ANOVA or a *post hoc*, no significant effect was identified.

As expected, effluent EC, salinity and TDS increased significantly and ORP decreased with spring salt runoffs of increasing salinity (Figure 5). This effect persisted until the end of July, i.e., 4.5 months after the end of the salt runoffs (1.5 months for ORP, i.e., end of April). Temperature, pH and DO were not impacted by NaCl runoffs.

3.5. Substrate changes

Overall, there were no major changes in the concentrations of substrate contaminants, except for SAR, and nitrate in planted mesocosms (Table S1).

Between 'before the salt runoffs' and 'dismantling', the spring salt runoffs increased the concentration of Na in the substrate, while that of Ca and Mg remained stable, resulting in an increase in SAR. For mesocosms treated with the most concentrated NaCl runoffs, the SAR averaged 2, compared to unsalted ones, with a SAR of only 1. Regardless of the species, planted mesocosms lowered the average NO_x concentration below the detection limit (BDL), whereas unplanted mesocosms did not. Compared to values before the runoffs, cation exchange capacity increased slightly, regardless of the NaCl concentration of runoffs, and without significant changes in pH.

4. DISCUSSION

All plant species tested were unaffected by the salt runoffs applied during their dormancy, regardless of the salt concentration. Also, spring salt runoffs had no effect on the hydrology of the BRs, or therefore on water volume or peak flow reduction. Conversely, spring salt runoffs impacted the filtration of many contaminants, increasing metals retention and releasing soil-structuring cations for a relatively short period of time after the salt runoffs ceased. The more concentrated in NaCl the runoffs were, the more intense and persistent these effects became.

4.1. Plant resilience

Very high salinity in BR has been shown to have a negative impact on plant performance and survival during the growing season and consequently on their contribution to BR efficiency (Szota *et al.* 2015). In our experiment, we observed no phytotoxic effect of NaCl, such as growth defects, deficiencies or NaCl-related stress on plants, even at the highest NaCl concentration (4,000 mgCl/L) tested. Plant resistance to a given salinity level generally depends on the duration of its exposure and its stage of growth (Hessini *et al.* 2015). Mesocosms were exposed to salt runoffs for only relatively short periods of time during plants' dormant period, in order to mimic spring

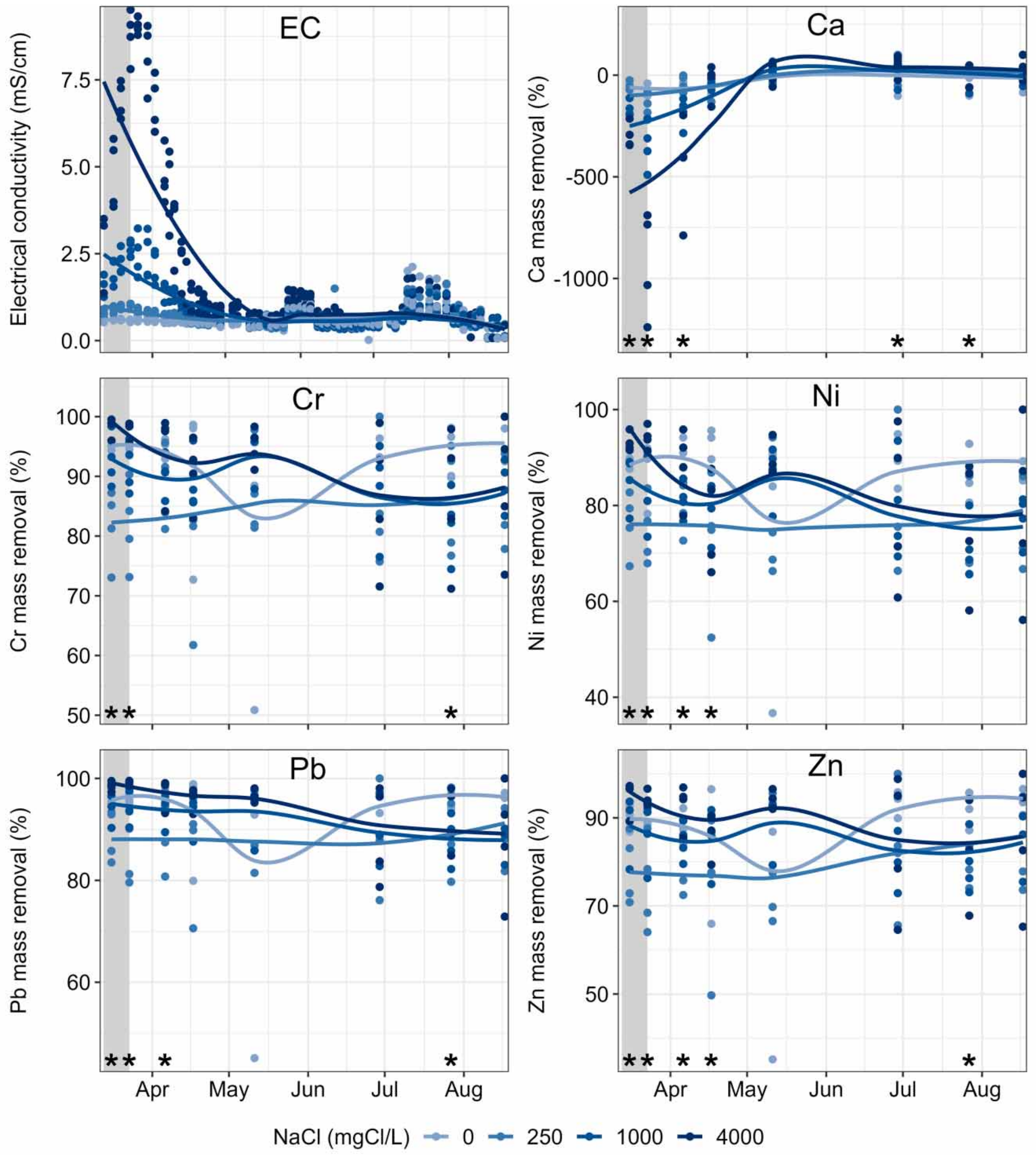


Figure 5 | Mass changes (%) and regression curve of different water parameters as a function of NaCl concentration (blue gradient) in runoff during spring (marked by the vertical grey band). Each point represents a measurement on a salt replica (i.e., eight samples per date). The symbol * on graphs indicates significant differences (set at $p < 0.05$) between NaCl treatments on a specific date.

de-icing salt runoff under real conditions (Williams *et al.* 2000). It is thus likely that the potential deleterious effects of spring NaCl runoffs were limited, due to negligible plant water uptake during dormancy.

A spring salty runoff of short duration could have had a negative impact if it had resulted in a sustained increase in soil water salinity. However, in our experiment, the level of salinity in the effluent dropped rapidly after the salt runoffs ceased, suggesting that salt concentration in the substrate interstitial water returned close to normal soon after, in the growing season. Baraza & Hasenmueller (2021) also observed a rapid drop in salinity following spring salt runoff when monitoring the salinity in the pore water of roadside soil. Similarly, high salinity was found to be of short duration in surface water or groundwater downstream of a watershed with or without modern stormwater management practices (Snodgrass *et al.* 2017). The duration of high salinity levels may depend on soil granulometry, composition and drainage (Ramakrishna & Viraraghavan 2005). In BR, the moderate to high exfiltration rate maintained to avoid stagnant water likely facilitates the evacuation of salt after exposure.

Thus, our results suggest that, under a cold climate, spring salty runoffs caused by road salt may not represent a high threat for plants in BR with a substrate that has a high draining quality. In real conditions, the 3 years of monitoring of these same plant species, selected for their resistance to the urban environment, planted within bioretention in the city of Trois-Rivieres (Canada), did not show any damage related to salt runoffs (Dagenais *et al.* 2022). The long-term effect under real-life conditions remains to be evaluated, but Géhéniau *et al.* (2015) documented no negative effect on vegetation in a BR system operating for 5 years in a parking lot in Montreal (Canada) that was subjected to repeated winter NaCl spraying and snowmelt events. However, in BR, as in the rest of the urban environment, plant tolerance to road salt varies between species, as shown in a recent study in Norway by Laukli *et al.* (2022). Salt tolerance should remain an important criterion for plant selection for use in BR systems in cold environments (Standards Council of Canada 2019). However, long-term monitoring of BR would also help avoid the potential long-term effects of road salt (Willmert *et al.* 2018).

It must be noted that our experiment focused only on the effect of salt in runoff, without considering the direct effect of saline spray on exposed plant parts in winter and spring. Equiza *et al.* (2017) found that species with parts rising above the snow cover, notably evergreens, presented damage likely attributable to salinity. Plant selection for BR in locations that could be subjected to salty spray should thus consider their vulnerability to direct exposure (Laukli *et al.* 2022; Caplan *et al.* 2023). Also, in our experiment, plants were watered regularly after the spring salt runoffs. Watering in spring is considered a strategy to alleviate the negative effects of road salt (Łuczak *et al.* 2021), which can be aggravated by other environmental factors such as drought or high soil pH (Calvo-Polanco *et al.* 2014; Equiza *et al.* 2017).

4.2. Water volume and peak flow reduction

Overall, all BRs successfully reduced water volume and flow. Mimicking spring salt runoffs did not have a significant impact on these hydrological parameters. With an ET rate of 0.4–2.8 mm/day, our results were close to those of experiments without de-icing salt in runoff conducted by Beral *et al.* (2023) and Wadzuk *et al.* (2015), who reported 0.1–1.6 or 1.0–6.1 mm/day, respectively. Plants are the main drivers of ET, and since salt had no effect on them, it is not surprising that we found no salt effect on ET rate either.

Complete exfiltration of effluent in less than 3 h was very rapid compared to that reported in other studies (Khan *et al.* 2012; Yuan *et al.* 2017) and far shorter than the maximum of 48 h recommended by the Standard Council of Canada (Standards Council of Canada 2019). Denich *et al.* (2013) showed lower permeability caused by the spring salt runoffs. It is possible that our serial NaCl runoffs mimicking a single spring season were insufficient to generate a change in the properties of the substrate, which contained little clay. While the effluents released more soil-structuring cations with higher salt concentrations, the final concentrations of these cations in the substrate remained more or less similar, irrespective of the NaCl concentration applied. It is possible that the amount of Ca leached was negligible compared to total Ca in the substrate, so that no effect on soil structure, or therefore on water flow, was noticeable within the time frame of the experiment. This result is similar to those of Burgis *et al.* (2020) who did not observe a cumulative effect of Ca release due to salt over the years. On the other hand, Denich *et al.* (2013) observed a change in the exfiltration rate in their experiment combining salt treatment with cold temperatures (freeze-thaw). Spraakman and Drake (Ding *et al.* 2019; Spraakman & Drake 2021) observed an infiltration capacity remaining above the recommended minimum of 25 mm/h even after several years. Therefore, our results support their hypothesis that the increase they found in infiltration rate was more related to the freeze-thaw cycle than to de-icing salt.

4.3. Water quality improvement

Overall, despite a relatively rapid runoff infiltration rate, all of our systems removed a high level of harmful contaminants (measured from the first flushes). However, we observed an effect of salinity on the removal of soil-structuring cations and some metals. In general, the higher the salt concentration, the greater and longer the effect.

As expected, higher EC, salinity and Na concentration in the effluent following spring salt runoffs were correlated with the NaCl level applied. The NaCl effluent concentration quickly returned to the basal level. These results do not suggest any NaCl accumulation in the substrate. This is consistent with findings by Shetty *et al.* (2020), who, after around 300 days, found Cl concentration at the basal level. Also as expected, soil-structuring cations were released in higher quantity, since they are known to be dislodged from the soil by NaCl in order to maintain electrical neutrality (Bäckström *et al.* 2004).

Søberg *et al.* (2017) did not observe salt-related release of metals in their BR experiment, but several authors have documented a metals remobilization in roadside soils attributable to salts (Amrhein *et al.* 1992; Bäckström *et al.* 2004). In contrast, in our experiment, salt runoffs significantly increased the removal of some metals (Cr, Ni, Pb, Zn and possibly Cu). It may be that dislodging Ca and Mg by Na leads to renewed competition among cations for exchange sites, allowing greater metal fixation. Organic matter could also bind metals through complexation mechanisms (Amrhein *et al.* 1992), but analysis of the substrate showed no increase in organic matter during the experiment. If we compare 'before salt runoffs ' with the control group (0 mgCl/L of NaCl applied) from the substrate, we observe a decrease in SAR. It is possible that the increase in SAR during the periods of NaCl application was compensated by the supply of Ca and Mg over the remainder of the year, preventing the accumulation of Na. This is consistent with the results of an experiment by Denich *et al.* (2013), in which, after mimicking 15 years of salt spreading, they observed no soil destructuration either.

Improved removal of metals at higher salt concentrations contradicts the results of BR experiments by Paus *et al.* (2014) and Costello *et al.* (2020), who found metal leaching at a salt concentration of 1,500 mg Cl/L NaCl, in a 7-year-old BR. Since our mesocosms were relatively young (9 months of runoff application prior to the salt experiment), it is possible that the metal concentrations in the substrate were still low enough to allow the binding of metal (Hunt *et al.* 2012). A mulch layer on top of the BR can increase adsorption and accumulation capacity (Kratky *et al.* 2017).

Treating stormwater by plant uptake can represent 5–10% of total metal removal (Muthanna *et al.* 2007; Read *et al.* 2008), 2–37% of the total P removal and 35–79% of the total N removal (Beral *et al.* 2023). In our experiment, the contribution of plants to the removal of contaminants was mainly limited to macronutrients. In addition, after being absorbed, trace elements mainly remained in the root system and would therefore be difficult to harvest for effective removal, while macronutrients were translocated to aerial parts. This pattern of absorption did not change with salt runoffs. As for volume reduction, it is likely that the potential deleterious effects of NaCl were limited due to negligible uptake by plants during dormancy.

5. CONCLUSIONS

The effectiveness of BR subject to road salt has been questioned. Our study suggests that, at the concentrations of NaCl usually found in runoff water, negative effects are limited and should not be an obstacle to implementing a BR system under cold climatic conditions. However, the possible impact of the sprays on exposed plant parts in winter and early spring was not considered in our experiment. The rapid leaching of NaCl from our BR system appears to have prevented its negative effects on plants from manifesting. Longer-term studies should be conducted to confirm that there is no harmful level of Na accumulation over time in the BR substrate. Although rapid leaching of salinity may be beneficial to plants in BR, this also means that such systems are relatively ineffective in preventing de-icing salt outflow to storm sewers or infiltration in the ground, which could eventually contaminate groundwater or water courses.

ACKNOWLEDGEMENTS

The authors would like to thank Patrick Boivin for technical assistance. Thanks also to Rolando Trejo-Perez, Camille Giguere and Gwladys Jourdan for field work assistance, and to Karen Grislis for helpful comments on a previous draft of the manuscript.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology: H. B., D. D., J. B., M. K. -V.; Data collection and analyses: H. B.; Original draft: H. B.; Review and editing: H. B., D. D., J. B., M. K. -V.; Supervision: D. D., J. B., M. K. -V.

All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was funded by the NSERC [grant no. CRDPJ-513260-17] and the Estonian Research Council [grant no. PUT1125].

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Amrhein, C., Strong, J. E. & Mosher, P. A. 1992 Effect of deicing salts on metal and organic matter mobilization in roadside soils. *Environmental Science & Technology* **26**, 703–709. https://doi.org/10.1021/es00028a006.

Bäckström, M., Karlsson, S., Bäckman, L., Folkeson, L. & Lind, B. 2004 Mobilisation of heavy metals by deicing salts in a roadside environment. *Water Research* **38**, 720–732. https://doi.org/10.1016/j.watres.2003.11.006.

Baird, R. B., Eaton, A. D., Rice, E. W. & Bridgewater, L. L. & American Public Health Association, American Water Works Association, Water Environment Federation 2017 *Standard Methods for the Examination of Water and Wastewater*, 23rd edn. American Public Health Association, Washington, DC.

Baraza, T. & Hasenmueller, E. A. 2021 Road salt retention and transport through vadose zone soils to shallow groundwater. *Science of the Total Environment* **755**, 142240. https://doi.org/10.1016/j.scitotenv.2020.142240.

Beral, H., Dagenais, D., Brisson, J. & Kõiv-Vainik, M. 2023 Plant species contribution to bioretention performance under a temperate climate. *Science of the Total Environment* **858**, 160122. https://doi.org/10.1016/j.scitotenv.2022.160122.

Blecken, G.-T., Marsalek, J. & Viklander, M. 2011 Laboratory study of stormwater biofiltration in low temperatures: Total and dissolved metal removals and fates. *Water Air and Soil Pollution* **219**, 303–317. https://doi.org/10.1007/s11270-010-0708-2.

Burgis, C. R., Hayes, G. M., Henderson, D. A., Zhang, W. & Smith, J. A. 2020 Green stormwater infrastructure redirects deicing salt from surface water to groundwater. *Science of the Total Environment* **729**, 138736. https://doi.org/10.1016/j.scitotenv.2020.138736.

Calvo-Polanco, M., Alejandra Equiza, M., Señorans, J. & Zwiazek, J. J. 2014 Responses of rat root (*Acorus americanus* Raf.) plants to salinity and pH conditions. *Journal of Environmental Quality* **43**, 578–586. https://doi.org/10.2134/jeq2013.07.0266.

Caplan, J. S., Salisbury, A. B., McKenzie, E. R. & Eisenman, S. W. 2023 Deicing salt imperils plants in roadside bioretention basins. https://doi.org/10.2139/ssrn.4388269.

Cekstere, G., Osvalde, A., Nikodemus, O., 2010 Influence of de-icing salt on k supply and street trees ecological status in Riga, Latvia. In: *Highway and Urban Environment, Alliance for Global Sustainability Bookseries* (Rauch, S., Morrison, G. M. & Monzón, A., eds). Springer Netherlands, Dordrecht, pp. 337–345. https://doi.org/10.1007/978-90-481-3043-6_36.

Coffman, L., Green, R., Clar, M. & Bitter, S. 1993 Design considerations associated with bioretention practices. In: *Presented at the Water Resources Planning and Management and Urban Water Resources*, pp. 130–133.

Costello, D. M., Hartung, E. W., Stoll, J. T. & Jefferson, A. J. 2020 Bioretention cell age and construction style influence stormwater pollutant dynamics. *Science of the Total Environment* **712**, 135597. https://doi.org/10.1016/j.scitotenv.2019.135597.

Dagenais, D., Doner, S. & Brisson, J. 2022 Performances des infrastructures vertes de gestion des eaux pluviales (IVGEP) pour la réduction du ruissellement urbain et pour la protection des sources d'eau potable en climat actuel et futur [WWW Document]. Rapport de recherche. Montréal. Ouranos. 86 p. Available from: https://www.ouranos.ca/sites/default/files/2022-07/proj-201419-ebati-dorner-rapportfinal.pdf (accessed 2 February 23).

Davis, L., Sumner, M., Stasolla, C. & Renault, S. 2014 Salinity-induced changes in the root development of a northern woody species, *Cornus sericea*. *Botany* **92**, 597–606. https://doi.org/10.1139/cjb-2013-0272.

Denich, C., Bradford, A. & Drake, J. 2013 Bioretention: Assessing effects of winter salt and aggregate application on plant health, media clogging and effluent quality. *Water Quality Research Journal of Canada* **48**, 387–399. https://doi.org/10.2166/wqrjc.2013.065.

Ding, B., Rezanezhad, F., Gharedaghloo, B., Van Cappellen, P. & Passeport, E. 2019 Bioretention cells under cold climate conditions: Effects of freezing and thawing on water infiltration, soil structure, and nutrient removal. *Science of The Total Environment* **649**, 749–759. https://doi.org/10.1016/j.scitotenv.2018.08.366.

Dmuchowski, W., Brągoszewska, P., Gozdowski, D., Baczewska-Dąbrowska, A. H., Chojnacki, T., Jozwiak, A., Swiezewska, E., Suwara, I. & Gworek, B. 2022 Strategies of urban trees for mitigating salt stress: A case study of eight plant species. *Trees* **36**, 899–914. https://doi.org/10.1007/s00468-020-02044-0.

Dołęgowska, S., Gałuszka, A., Migaszewski, Z. M. & Krzciuk, K. 2022 Bioavailability of selected trace and rare earth elements to *Juncus effusus* L.: The potential role of de-icing chlorides in the roadside environment. *Plant Soil* **472**, 641–658. https://doi.org/10.1007/s11104-021-05278-0.

Endreny, T., Burke, D. J., Burchhardt, K. M., Fabian, M. W. & Kretzer, A. M. 2012 Bioretention column study of bacteria community response to salt-enriched artificial stormwater. *Journal of Environmental Quality* **41**, 1951–1959. https://doi.org/10.2134/jeq2012.0082.

Environment and Climate Change Canada 2018 *Historical Climate Data [WWW Document]*. Available from: https://climate.weather.gc.ca/index_e.html (accessed 10 July 2018).

Environment and Climate Change Canada 2022 *Code of Practice: Road Salts Environmental Management [WWW Document]*. Available from: https://www.canada.ca/en/environment-climate-change/services/pollutants/road-salts/code-practice-environmental-management.html (accessed 26 July 2022).

Equiza, M. A., Calvo-Polanco, M., Cirelli, D., Señorans, J., Wartenbe, M., Saunders, C. & Zwiazek, J. J. 2017 Long-term impact of road salt (NaCl) on soil and urban trees in Edmonton, Canada. *Urban Forestry & Urban Greening* **21**, 16–28. https://doi.org/10.1016/j.ufug.2016.11.003.

Eriksson, E., Baun, A., Mikkelsen, P. S. & Ledin, A. 2004 *Selected Stormwater Priority Pollutants (SSPP) – Introduction and Database*.

Fay, L. & Shi, X. 2012 Environmental impacts of chemicals for snow and Ice control: State of the knowledge. *Water Air and Soil Pollution* **223**, 2751–2770. https://doi.org/10.1007/s11270-011-1064-6.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. 2015 SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal* **12**, 525–542. https://doi.org/10.1080/1573062X.2014.916314.

Flora of North America Editorial Committee 1993 *Flora of North America North of Mexico [WWW Document]*. Available from: http://beta.floranorthamerica.org (accessed 24 February 2021).

Fritioff, Å. 2005 *Metal Accumulation by Plants: Evaluation of the Use of Plants in Stormwater Treatment*. Department of Botany, Stockholm University, Stockholm.

Géhéniau, N., Fuamba, M., Mahaut, V., Gendron, M. R. & Dugué, M. 2015 Monitoring of a rain garden in cold climate: Case study of a parking lot near Montréal. *Journal of Irrigation and Drainage Engineering* **141**, 04014073. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000836.

Goor, J., Cantelon, J., Smart, C. C. & Robinson, C. E. 2021 Seasonal performance of field bioretention systems in retaining phosphorus in a cold climate: Influence of prolonged road salt application. *Science of the Total Environment* **778**, 146069. https://doi.org/10.1016/j.scitotenv.2021.146069.

Health Canada 1997 *Guidelines for Canadian Drinking Water Quality: Guideline Technical Document – Sodium [WWW Document]. aem*. Available from: https://www.canada.ca/en/health-canada/services/publications/healthy-living/guidelines-canadian-drinking-water-quality-guideline-technical-document-sodium.html (accessed 19 November 2020).

Hessini, K., Ferchichi, S., Ben Youssef, S., Werner, K. H., Cruz, C. & Gandour, M. 2015 How does salinity duration affect growth and productivity of cultivated barley? *Agronomy Journal* **107**, 174–180. https://doi.org/10.2134/agronj14.0281.

Hintz, W. D. & Relyea, R. A. 2019 A review of the species, community, and ecosystem impacts of road salt salinisation in fresh waters. *Freshwater Biology* **64**, 1081–1097. https://doi.org/10.1111/fwb.13286.

Huber, M., Hilbig, H., Badenberg, S. C., Fassnacht, J., Drewes, J. E. & Helmreich, B. 2016 Heavy metal removal mechanisms of sorptive filter materials for road runoff treatment and remobilization under de-icing salt applications. *Water Research* **102**, 453–463. https://doi.org/10.1016/j.watres.2016.06.063.

Hunt, W. F., Davis, A. P. & Traver, R. G. 2012 Meeting hydrologic and water quality goals through targeted bioretention design. *Journal of Environmental Engineering* **138**, 698–707. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000504.

Kakuturu, S. P. & Clark, S. E. 2015 Effects of deicing salts on the clogging of stormwater filter media and on the media chemistry. *Journal of Environmental Engineering* **141**, 04015020. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000927.

Khan, U. T., Valeo, C., Chu, A. & van Duin, B. 2012 Bioretention cell efficacy in cold climates: Part 1 — hydrologic performance. *Canadian Journal of Civil Engineering* **39**, 1210–1221. https://doi.org/10.1139/l2012-110.

Kratky, H., Li, Z., Chen, Y., Wang, C., Li, X. & Yu, T. 2017 A critical literature review of bioretention research for stormwater management in cold climate and future research recommendations. *Frontiers of Environmental Science & Engineering* **11**. https://doi.org/10.1007/s11783-017-0982-y.

Laukli, K., Gamborg, M., Haraldsen, T. K. & Vike, E. 2022 Soil and plant selection for rain gardens along streets and roads in cold climates: Simulated cyclic flooding and real-scale studies of five herbaceous perennial species. *Urban Forestry & Urban Greening* **68**, 127477. https://doi.org/10.1016/j.ufug.2022.127477.

Liem, A. S. N., Hendriks, A., Kraal, H. & Loenen, M. 1985 Effects of de-icing salt on roadside grasses and herbs. *Plant Soil* **84**, 299–310. https://doi.org/10.1007/BF02275470.

Lu, D., Huang, Q., Deng, C. & Zheng, Y. 2018 Phytoremediation of copper pollution by eight aquatic plants. *Polish Journal of Environmental Studies* **27**, 175–181. https://doi.org/10.15244/pjoes/73990.

Łuczak, K., Czerniawska-Kusza, I., Rosik-Dulewska, C. & Kusza, G. 2021 Effect of NaCl road salt on the ionic composition of soils and *Aesculus hippocastanum* L. foliage and leaf damage intensity. *Scientific Reports* **11**, 5309. https://doi.org/10.1038/s41598-021-84541-x.

Marsalek, J. 2003 Road salts in urban stormwater: An emerging issue in stormwater management in cold climates. *Water Science and Technology* **48**, 61–70. https://doi.org/10.2166/wst.2003.0493.

Mayer, T., Snodgrass, W. J. & Morin, D. 1999 Spatial characterization of the occurrence of road salts and their environmental concentrations as chlorides in Canadian surface waters and benthic sediments. *Water Quality Research Journal* **34**, 545–574. https://doi.org/10.2166/wqrj.1999.028.

Munns, R. & Tester, M. 2008 Mechanisms of salinity tolerance. *Annual Review of Plant Biology* **59**, 651–681. https://doi.org/10.1146/annurev.arplant.59.032607.092911.

Muthanna, T. M., Viklander, M., Gjesdahl, N. & Thorolfsson, S. T. 2007 Heavy metal removal in cold climate bioretention. *Water Air and Soil Pollution* **183**, 391–402. https://doi.org/10.1007/s11270-007-9387-z.

Najeeb, U., Xu, L., Ali, S., Jilani, G., Gong, H. J., Shen, W. Q. & Zhou, W. J. 2009 Citric acid enhances the phytoextraction of manganese and plant growth by alleviating the ultrastructural damages in *Juncus effusus* L. *Journal of Hazardous Materials* **170**, 1156–1163. https://doi.org/10.1016/j.jhazmat.2009.05.084.

Najeeb, U., Jilani, G., Ali, S., Sarwar, M., Xu, L. & Zhou, W. 2011 Insights into cadmium induced physiological and ultra-structural disorders in *Juncus effusus* L. and its remediation through exogenous citric acid. *Journal of Hazardous Materials* **186**, 565–574. https://doi.org/10.1016/j.jhazmat.2010.11.037.

Nocco, M. A., Rouse, S. E. & Balster, N. J. 2016 Vegetation type alters water and nitrogen budgets in a controlled, replicated experiment on residential-sized rain gardens planted with prairie, shrub, and turfgrass. *Urban Ecosystems* **19**, 1665–1691. https://doi.org/10.1007/s11252-016-0568-7.

Paus, K. H., Morgan, J., Gulliver, J. S., Leiknes, T. & Hozalski, R. M. 2014 Effects of temperature and NaCl on toxic metal retention in bioretention media. *Journal of Environmental Engineering* **140**, 04014034. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000847.

Paus, K. H., Muthanna, T. M. & Braskerud, B. C. 2016 The hydrological performance of bioretention cells in regions with cold climates: Seasonal variation and implications for design. *Hydrology Research* **47**, 291–304. https://doi.org/10.2166/nh.2015.084.

Payne, E. G. I., Pham, T., Deletic, A., Hatt, B. E., Cook, P. L. M. & Fletcher, T. D. 2018 Which species? A decision-support tool to guide plant selection in stormwater biofilters. *Advances in Water Resources* **113**, 86–99. https://doi.org/10.1016/j.advwatres.2017.12.022.

Prodjinoto, H., Irakoze, W., Gandonou, C., Lepoint, G. & Lutts, S. 2021 Discriminating the impact of Na+ and Cl− in the deleterious effects of salt stress on the African rice species (*Oryza glaberrima* Steud.). *Plant Growth Regulation* **94**, 201–219. https://doi.org/10.1007/s10725-021-00709-5.

Ramakrishna, D. M. & Viraraghavan, T. 2005 Environmental impact of chemical deicers – a review. *Water Air and Soil Pollution* **166**, 49–63. https://doi.org/10.1007/s11270-005-8265-9.

Read, J., Wevill, T., Fletcher, T. & Deletic, A. 2008 Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research* **42**, 893–902. https://doi.org/10.1016/j.watres.2007.08.036.

Read, J., Fletcher, T. D., Wevill, T. & Deletic, A. 2009 Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *International Journal of Phytoremediation* **12**, 34–53. https://doi.org/10.1080/15226510902767114.

Regional Salinity Laboratory (U.S.) 1954 *Diagnosis and Improvement of Saline and Alkali Soils*. Agriculture Handbook/United States Department of Agriculture ; No. 60. U.S. Dept. of Agriculture, Washington, DC.

Reinosdotter, K. & Viklander, M. 2007 Road salt influence on pollutant releases from melting urban snow. *Water Quality Research Journal* **42**, 153–161. https://doi.org/10.2166/wqrj.2007.019.

Roseen, R. M., Ballestero, T. P., Houle, J. J., Avellaneda, P., Briggs, J., Fowler, G. & Wildey, R. 2009 Seasonal performance variations for storm-water management systems in cold climate conditions. *Journal of Environmental Engineering* **135**, 128–137. https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(128).

Sansalone, J. & Buchberger, S. 1997 Partitioning and first flush of metals in urban roadway storm water. *Journal of Environmental Engineering* **123**, 134–143. https://doi.org/10.1061/(ASCE)0733-9372(1997)123:2(134).

Sansalone, J. J. & Cristina, C. M. 2004 First flush concepts for suspended and dissolved solids in small impervious watersheds. *Journal of Environmental Engineering* **130**, 1301–1314. https://doi.org/10.1061/(ASCE)0733-9372(2004)130:11(1301).

Shelke, D., Nikalje, G., Nikam, T., Maheshwari, P., Punita, D., Rao, K., Kavi Kishor, P. & Suprasanna, P. 2019 Chloride (Cl −) uptake, transport, and regulation in plant salt tolerance. In: *Molecular Plant Abiotic Stress*. John Wiley & Sons, Ltd, pp. 241–268. https://doi.org/10.1002/9781119463665.ch13.

Shetty, N. H., Mailloux, B. J., McGillis, W. R. & Culligan, P. J. 2020 Observations of the seasonal buildup and washout of salts in urban bioswale soil. *Science of the Total Environment* **722**, 137834. https://doi.org/10.1016/j.scitotenv.2020.137834.

Snodgrass, J. W., Moore, J., Lev, S. M., Casey, R. E., Ownby, D. R., Flora, R. F. & Izzo, G. 2017 Influence of modern stormwater management practices on transport of road salt to surface waters. *Environmental Science & Technology* **51**, 4165–4172. https://doi.org/10.1021/acs.est.6b03107.

Søberg, L. C., Viklander, M. & Blecken, G.-T. 2014 The influence of temperature and salt on metal and sediment removal in stormwater biofilters. *Water Science and Technology* **69**, 2295–2304. https://doi.org/10.2166/wst.2014.161.

Søberg, L. C., Viklander, M. & Blecken, G.-T. 2017 Do salt and low temperature impair metal treatment in stormwater bioretention cells with or without a submerged zone? *Science of the Total Environment* **579**, 1588–1599. https://doi.org/10.1016/j.scitotenv.2016.11.179.

Søberg, L. C., Al-Rubaei, A. M., Viklander, M. & Blecken, G.-T. 2020 Phosphorus and TSS removal by stormwater bioretention: Effects of temperature, salt, and a submerged zone and their interactions. *Water, Air, & Soil Pollution* **231**, 270. https://doi.org/10.1007/s11270-020-04646-3.

Spraakman, S. & Drake, J. A. P. 2021 Hydrologic and soil properties of mature bioretention cells in Ontario, Canada. *Water Science and Technology* **84**, 3541–3560. https://doi.org/10.2166/wst.2021.464.

Standards Council of Canada 2019 Conception des systèmes de biorétention (National standard of Canada No. CSA W200:18).

Szota, C., Farrell, C., Livesley, S. J. & Fletcher, T. D. 2015 Salt tolerant plants increase nitrogen removal from biofiltration systems affected by saline stormwater. *Water Research* **83**, 195–204. https://doi.org/10.1016/j.watres.2015.06.024.

Taka, M., Kokkonen, T., Kuoppamäki, K., Niemi, T., Sillanpää, N., Valtanen, M., Warsta, L. & Setälä, H. 2017 Spatio-temporal patterns of major ions in urban stormwater under cold climate. *Hydrological Processes* **31**, 1564–1577. https://doi.org/10.1002/hyp.11126.

Tromp, K., Lima, A. T., Barendregt, A. & Verhoeven, J. T. A. 2012 Retention of heavy metals and poly-aromatic hydrocarbons from road water in a constructed wetland and the effect of de-icing. *Journal of Hazardous Materials* **203–204**, 290–298. https://doi.org/10.1016/j.jhazmat.2011.12.024.

Valtanen, M., Sillanpää, N. & Setälä, H. 2014 The effects of urbanization on runoff pollutant concentrations, loadings and their seasonal patterns under cold climate. *Water, Air, & Soil Pollution* **225**, 1977. https://doi.org/10.1007/s11270-014-1977-y.

Wadzuk, B. M., Hickman, J. M. & Traver, R. G. 2015 Understanding the role of evapotranspiration in bioretention: Mesocosm study. *Journal of Sustainable Water in the Built Environment* **1**, 04014002. https://doi.org/10.1061/JSWBAY.0000794.

Williams, D. D., Williams, N. E. & Cao, Y. 2000 Road salt contamination of groundwater in a major metropolitan area and development of a biological index to monitor its impact. *Water Research* **34**, 127–138. https://doi.org/10.1016/S0043-1354(99)00129-3.

Willmert, H. M., Osso, J. D., Twiss, M. R. & Langen, T. A. 2018 Winter road management effects on roadside soil and vegetation along a mountain pass in the Adirondack Park, New York, USA. *Journal of Environmental Management* **225**, 215–223. https://doi.org/10.1016/j.jenvman.2018.07.085.

Yang, Y. & Chui, T. F. M. 2018 Optimizing surface and contributing areas of bioretention cells for stormwater runoff quality and quantity management. *Journal of Environmental Management* **206**, 1090–1103. https://doi.org/10.1016/j.jenvman.2017.11.064.

Yuan, J., Dunnett, N. & Stovin, V. 2017 The influence of vegetation on rain garden hydrological performance. *Urban Water Journal* **14**, 1083–1089. https://doi.org/10.1080/1573062X.2017.1363251.

Zaimoglu, Z. 2006 Treatment of campus wastewater by a pilot-scale constructed wetland utilizing *Typha latifolia*, *Juncus acutus* and *Iris versicolor*. *Journal of Environmental Biology* **27**, 293–298.

First received 19 July 2023; accepted in revised form 15 October 2023. Available online 6 November 2023