Blue-Green Systems

Impact of bioretention cells in cities with a cold climate: modeling snow management based on a case study

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ABSTRACT

The performance of blue-green infrastructures (BGIs) has been well documented in temperate and subtropical climates, but evidence supporting their application in cold climates, especially during snowmelt, is still scarce. To address this gap, the present study proposes a modeling method for simulating the performance of bioretention cells during snowmelt according to different spatial implementation scenarios. We used the Storm Water Management Model (SWMM) of a catchment in a medium-sized city in Quebec, Canada as a case study. Pollutants commonly found in the snow (TSS, Cr, Pb, Zn, Cl⁻) were included in the model using event mean concentrations (EMCs) documented in the literature. Bioretention cells performed best on industrial road sites for the entire snowmelt period. Bioretention cell performance was affected by snow management procedures applied to the roads in residential areas. Not modeling the snow cover build-up and meltdown in the simulation led to higher runoff and bioretention cell performance. Modeling results facilitated the identification of bioretention cell sites that efficiently controlled runoff during snowmelt. Such information is needed to support decision planning for BGIs in cities with cold climate.

Key words: cold climate, green infrastructure, snowmelt modeling, Stormwater Management Model (SWMM), stormwater quality modeling, urban planning

HIGHLIGHTS

- Land use and snow management procedures impact bioretention cell performance.
- Modeled bioretention cells implemented on industrial roads show the best performance for snowmelt runoff.
- Ignoring snow cover build-up and meltdown modeling leads to higher runoff volume and bioretention cell performance.
- Bioretention cell soil freezing should be considered in future blue-green infrastructure modeling under a cold climate.

GRAPHICAL ABSTRACT
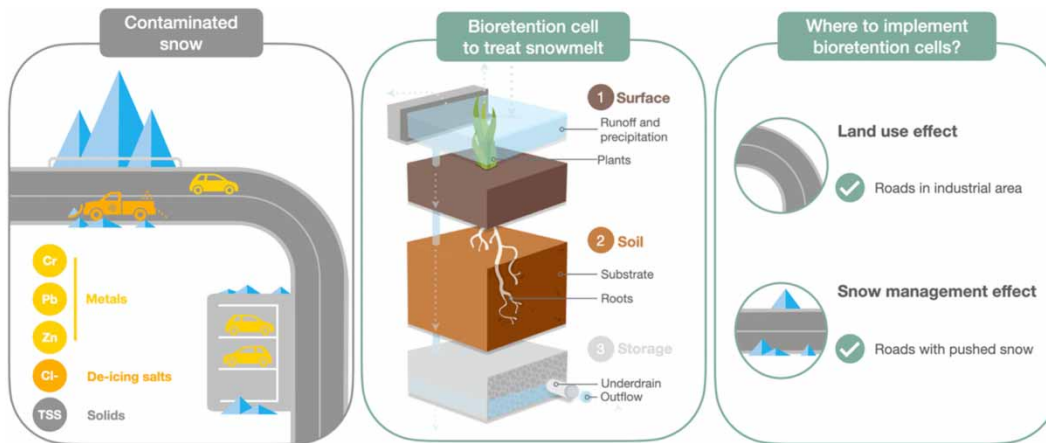
1. INTRODUCTION

Blue-green infrastructures (BGIs) are increasingly promoted and implemented worldwide to alleviate some of the negative impacts of urbanization and climate change. Unlike conventional grey infrastructures, BGIs mimic natural processes reducing runoff volumes and improving runoff quality through improved on-site stormwater infiltration and evaporation. Thus, these nature-based drainage systems have the potential to mitigate pollutants in runoff and increase the resilience of urban drainage systems (Fowdar *et al.* 2021). BGIs are part of low-impact development (LID) practices applied to develop urban land by more effectively taking advantage of vegetated systems. Many studies have highlighted the range of socio-economic and environmental benefits that BGI can provide, such as improving the urban landscape aesthetic, reducing the heat island effect, or supporting biodiversity (Oral *et al.* 2020; Kõiv-Vainik *et al.* 2022).

BGIs application around the world is increasingly being documented, highlighting great variability in performance across different climatic conditions (Kõiv-Vainik *et al.* 2022). This is a barrier to BGI large-scale adoption, especially in countries with a cold climate, such as Canada (Goor *et al.* 2021; Li *et al.* 2021; Kõiv-Vainik *et al.* 2022). Urban areas in cold climates face water quantity and quality management challenges from the accumulation of significant amounts of snow during the winter. The province of Quebec (Canada) receives 275 cm of snow on average each year (Gouvernement du Québec 2022). In urban areas, roadside snowbanks (piles of snow pushed to the side by a snowplow) are exposed to a variety of pollutants, such as deicing agents, abrasives, debris, heavy metals, oil and grease, micro- and nano-plastics from winter road maintenance and corrosion of vehicles and structures (Westerlund & Viklander 2011; Vijayan *et al.* 2019; Wang *et al.* 2021). In Montreal, Quebec, 13,000,000 m^3 of used snow must be treated each year (Vérificateur général 2017). With warmer spring temperatures, these contaminants are transported with the snowmelt water, subsequently affecting surface and groundwater quality, soil, flora and fauna, and infrastructures (Marsalek 2003; Betts *et al.* 2015; Arnott *et al.* 2020).

Bioretention cells, also termed rain gardens or bioinfiltration cells, are considered the most effective storm control measures for managing urban runoff, improving both water quantity and quality, and are the most commonly applied LID practices (Kõiv-Vainik *et al.* 2022). Several studies demonstrated that bioretention cells were able to reduce some pollutants found in contaminated snow. Bioretention cells also appeared less sensitive to cold temperatures and deicing salts compared to other BGIs such as swales or wetlands (Semadeni-Davies 2006; Roseen *et al.* 2009). Bioretention cells can therefore be a valuable solution to reduce the environmental impacts of snowmelt if established on the proper site (Gu *et al.* 2019).

However, urban planning for such infrastructures is usually done on a case-by-case basis, lacking long-term strategy and, in the vast majority, cold climate characteristics such as snow or cold temperatures are not considered, thus resulting in non-optimal positioning (Kuller *et al.* 2017, 2019; Ferrans *et al.* 2022). Modeling can help determine suitable bioretention implementation sites in cities with a cold climate by considering these phenomena and testing different implementation scenarios. The process of urban snowmelting is complex since it varies according to local snowpack characteristics such as snow density, albedo, porosity, or solar

energy absorption. Few hydrologic models are capable of modeling snowmelt in urban areas (Moghadas *et al.* 2018; Hamouz & Muthanna 2019). The open-access and commonly used Storm Water Management Model (SWMM) from the US EPA can integrate data on local meteorological conditions and municipal snow management practices (Rossman 2015) for predicting snowmelt. Given the large contribution of snow to urban hydrology in many regions, it is essential to integrate snow when assessing BGI performances.

To this day, research on bioretention cells in cold climate has mainly been conducted at a system scale, investigating how hydrological and pollutant removal performances were affected by freezing temperatures and snow (Muthanna *et al.* 2007; Géhéniau *et al.* 2015; Ding *et al.* 2019; Li *et al.* 2021). These studies therefore propose to remedy the effects of cold by adapting the design and size of a unit bioretention cell but do not consider large-scale applications. A large part of the literature that predicts BGI impacts at the catchment scale relies on modeling (Autixier *et al.* 2014; Joshi *et al.* 2021) and most studies do not consider cold climate because of the complexity it adds to the model (e.g., snow characteristics, temperature data) (Hamouz & Muthanna 2019). There is a knowledge gap in the assessment of BGI performances considering both large-scale implementation and cold climate challenges.

In this study, we employed SWMM modeling to investigate the impacts of bioretention cells on snowmelt runoff under the conditions of a case study in Quebec with the ultimate aim of better supporting bioretention cell planning in cold climates. The specific objectives were to (i) apply an urban snow hydraulic model, (ii) assess the impact of bioretention cell implementation scenarios on snowmelt quantity and quality, and to (iii) provide recommendations for strategic implementation of bioretention cells in cities with a cold climate.

2. METHODS

2.1. Case study description

We chose a catchment of the city of Trois-Rivières, Quebec, Canada (46.22°N,72.30°W, Figure 1). Trois-Rivières is considered representative of a medium-sized city in Quebec. The studied catchment covers an area of 181 ha. Golf courses and undeveloped parcels covered 65% of the catchment, 14% were residential, 16% were industrial and the snow storage area covered the last 5% of the area (Figure 1(b)). Overall, 23% of the catchment was impervious (roofs contribute 35% and roads/parking lots 65%). Stormwater is drained in a separate sewer system and discharged into the St. Lawrence River through two untreated outfalls (O-1 and O-3).

2.2. Meteorological data

Meteorological data for the studied area were available from the Trois-Rivières airport (YRQ) station (46.21°N,72.40°O, 60.70 m above sea level), located about 15 km from the catchment. To consider the entire snow period (i.e. period during which snow fell and remained on the ground), we obtained hourly temperatures and precipitation, and daily snowfall heights for November–June from 2018 to 2021 from the national weather bureau (Gouvernement du Canada 2022, Table 1). We defined the end of the selected winter period as the end of the melting period at the snow storage site.
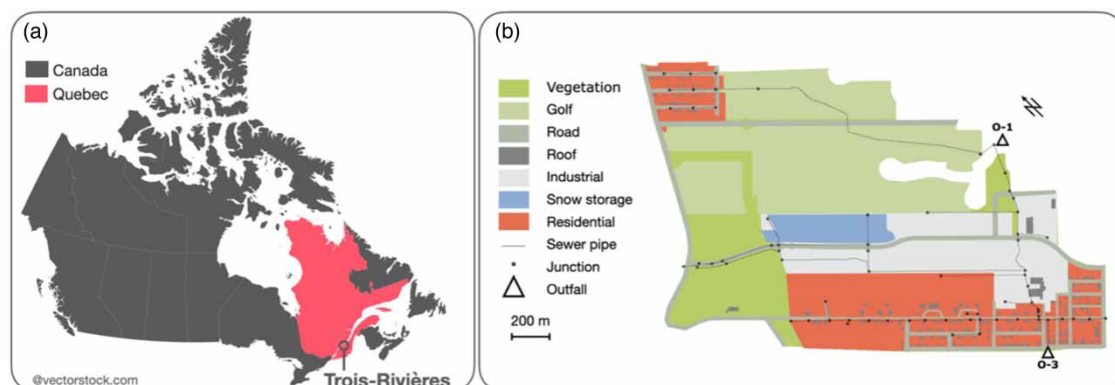

Figure 1 | Locations of Trois-Rivières (a) and the studied catchment (b) with land uses and separate sewer network (b).

Table 1 | Selected winters for modeling

Date [year/month/day]	Precipitation [mm]	T [°C]		Snow depth [cm]	
		Minimum	Average	Maximum	Average
2018/11/01–2019/06/30	453	−31	−1.2	110	56
2019/11/01–2020/05/31	260	−29	−1.6	67	27
2020/11/01–2021/05/31	243	−26	0.0	61	19

We performed SWMM simulations for the three winters and each simulation was run twice: with and without snow modeling. With snow meant that the snow package of SWMM was used, considering the snow form of precipitation and modeling the snow cover build-up and melt down.

2.3. Modeling

Figure 2 shows, as a conceptual diagram, the global method used to model snowmelt runoff quantity and quality in SWWM.

2.3.1. Urban snow model

We performed hydrological-hydraulic and water quality simulations using the open-access Stormwater Management Model (SWMM) 5.1.015 from the United States Environmental Protection Agency (EPA) (Rossman 2015).
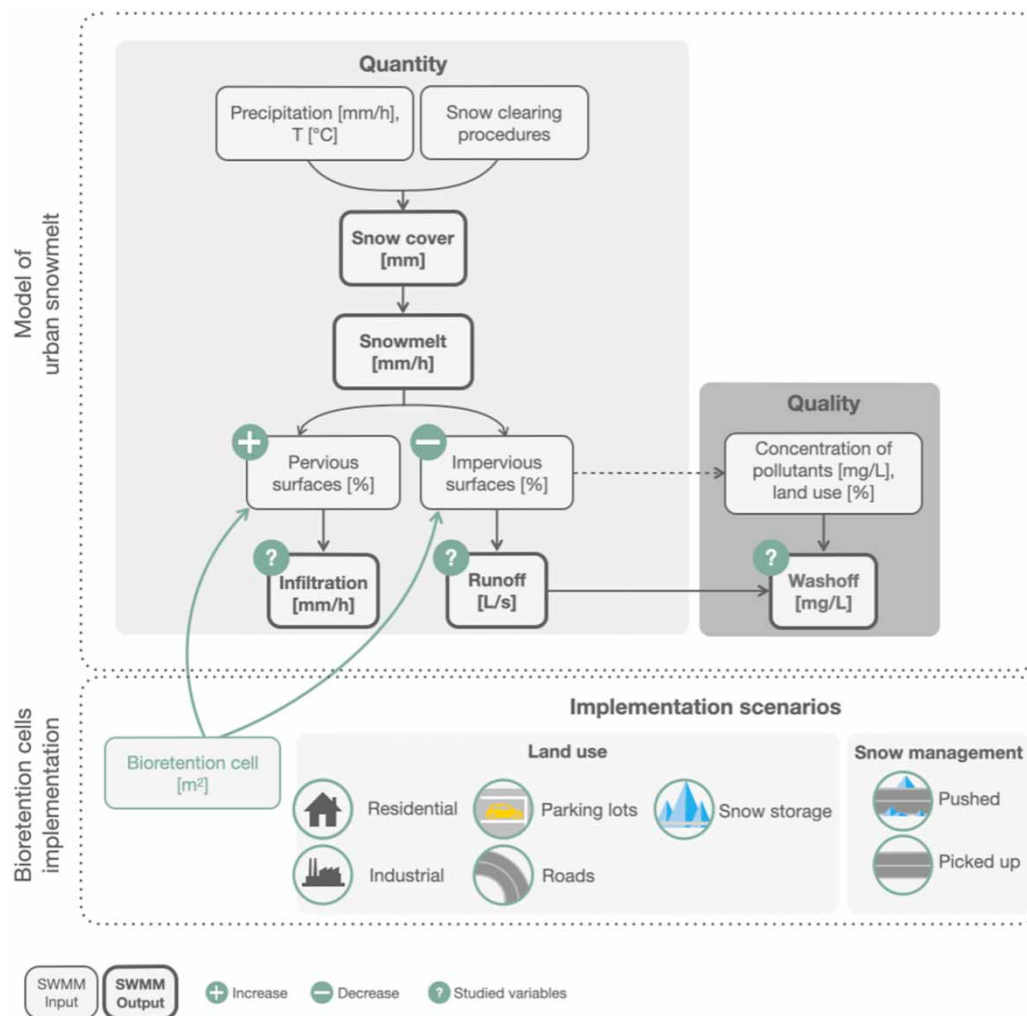
Figure 2 | Conceptual diagram of global SWMM modeling.

We determined the snow properties of the SWMM hydraulic base model of the catchment that are necessary to estimate runoff in areas with seasonal snow cover. The base SWMM model of the studied catchment was provided by the city of Trois-Rivières and calibrated by Bouattour (2021). The base SWMM model was divided into 88 subcatchments. We used the Horton method and dynamic wave routing to simulate infiltration and flow routing in the sewer network, respectively (Rossman 2015). We performed spatial analyses (e.g., calculating roof and roads areas) in ArcGIS 10.6.

2.3.1.1. Snowpack setup: catchment discretization and parameter selection. We used the snowpack editor of SWMM 5.1.015 to simulate snow accumulation and melting over the studied area. Snowpack setup was based on the study by Moghadas *et al.* (2018). To consider the different snow removal procedures in the various parts of the catchment, we created eight snowpack objects according to land use (industrial, residential, natural, and snow storage) and snow quality in relation to snow removal procedures (picked up, pushed, or undisturbed). Undisturbed snow referred to untouched snow, while picked up snow was transported to a storage site and pushed snow was simply pushed to the side of the road by a plow, remaining 'stored' there. The entire road surface was cleared after 3 cm of fresh snow (J. St-Laurent, e-mail communication, 2021), corresponding to a snow water equivalent (SWE) of 6 mm for a snow density of 200 kg/m^3 (Moghadas *et al.* 2018, Table 2). We created two snowpack objects to represent snow over the industrial areas while differentiating between the manufacturing industry (Industrial I) and commercial areas (Industrial II), characterized by different snow management procedures (Table 2). Assuming that snow on roofs was not cleared, 67 and 68% of impervious surface was thus cleared in residential and industrial II areas, respectively, corresponding to the surface proportion of roads and parking lot. In the absence of site-specific information, we made our assumptions about snow storage based on the study of Moghadas *et al.* (2018): 80% of the pushed snow was assumed to be stored on an impermeable surface (roadsides and parking lots) and 20% on a permeable surface (vegetated roadsides and gardens). Natural areas with undisturbed snow were totally permeable and therefore not subject to snow removal (Table 2). Industrial I was the large parking lot of the manufacturing industry with snow cleared and stored *in situ*. We assumed that the snow storage only stores snow collected from the catchment streets, excluding snow collected outside of the study area. We defined eight types of snowpack objects (i.e. eight sets of parameters representing snow clearing and redistribution procedures, Table 2) to represent the snow on 88 subcatchments of the SWMM base model (Figure 3).

We calibrated the separation temperature between snow and rain (SNOTMP) to 0.9 °C (Table 3) by comparing simulated and observed snow depths over three different winters (Supplementary material, Figure S1). To develop a robust and comprehensible model, soil freezing was excluded. Ground frosting is a complex mechanism that requires specific parameters and local data such as snow insulating capacity, soil properties and temperatures, frost depth, etc. (Ala-Aho *et al.* 2021) that vary in time and space and were neither accessible nor supported by SWMM. Moreover, references concerning the effect of frozen soils at the urban catchment scale are lacking (Moghadas *et al.* 2018). A typical snow depletion curve for natural areas was applied for pervious surfaces (Rossman & Huber 2016a). Snow depletion effects for impervious surfaces were excluded, assuming 100% snow coverage remained until snow stored on impervious surfaces melted completely. However, snow

Table 2 | Snowpack SWMM object parameters; average impervious area (Imp.), snow depth for snow clearance in water equivalent (h_{min}), fractions of impervious area snow cleared (Imp. cleared), fraction of cleared snow stored on impervious (F_{imp}) and pervious (F_{per}) surfaces, and fraction of snow collected and stored in snow storage (F_{sub})

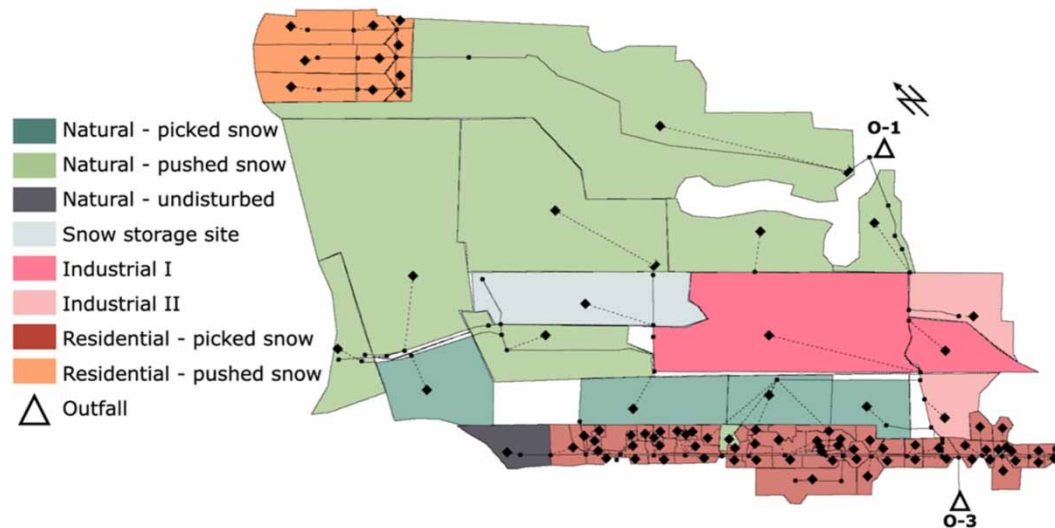| Snowpack	Imp. [%]	h_{min} [mm]	Imp. cleared	F_{imp}	F_{per}	F_{sub}
Industrial I pushed	74.5	6	1	0.80	0.20	0
Industrial II pushed	44.0	6	0.68	0.20	0.80	0
Residential picked up	44.2	6	0.67	0	0	2
Residential pushed	47.5	6	0.67	0.20	0.80	0
Natural picked up	23.0	6	1	0	0	1
Natural pushed	38.4	6	1	0.20	0.80	0
Natural undisturbed	0.0	N/A	0	N/A	N/A	N/A
Snow storage	65.0	N/A	0	N/A	N/A	N/A

Figure 3 | Snowpack objects assigned to each SWMM subcatchment.

Table 3 | Values of hydrological parameters used in the SWMM

Model parameter	Description	Value
SNOTMP [°C]	Rain/snow separation temperature	0.9
T_{base} [°C][a]	Snow melting temperature	0
FWF [%][b]	Fraction free water capacity, snowpack capacity to store liquid water from snowmelt or rain	10
Melt factor [mm/h/°C][b]	Minimum, relocated snow	0.2
	Maximum, relocated snow	0.46
	Minimum, undisturbed snow	0.008
	Maximum, undisturbed snow	0.05

[a]Rossman & Huber 2016a.
[b]Moghadas et al. 2018.

quality impacts on melting rate were considered through DHM coefficients. More details on the snowmelt runoff governing equations are described in the Supplementary material, Section 1.

2.3.1.2. Water quality modeling. The continuous snowmelt quality data needed to feed models are scarce since monitoring is complicated by several factors including: the limited length of the snowmelt period, the effect of low temperatures on battery-dependent measuring devices and the inability to measure water due to the presence of ice. To circumvent these limitations, we used the simplified event mean concentration (EMC) to model water quality, assuming constant concentrations of pollutants in runoff during an event (Rossman & Huber 2016b). EMC values for five pollutants were adapted from average concentrations found in the literature for each land use (Exall *et al.* 2011; Mayer *et al.* 2011; Géhéniau *et al.* 2015, Table 4). Studies conducted during the snowmelt period in Canada were used. Modeling pollutant loads with EMC involves uncertainties, particularly if local calibration and validation data are lacking. However, this is the most

Table 4 | Literature-based EMC for selected pollutants and land uses

Land use	Reference	Location	TSS [mg/L]	Cr [μg/L]	Pb [μg/L]	Zn [μg/L]	Cl⁻ [mg/L]
Road	Mayer *et al.* (2011)	Burlington, Ontario, Canada	145	19	37	609	1,213
Parking lots	Géhéniau *et al.* (2015)	Montreal, Quebec, Canada	37	5	3	34	934
Snow storage	Exall *et al.* (2011)	Richmond Hill, Ontario, Canada	29[a]	11[a]	14[a]	54[a]	2,550

[a]Estimated from a bar diagram.

common method because required parameters for quality simulations are limited (Tuomela *et al.* 2019). We studied total suspended solid (TSS), three heavy metals, namely chromium (Cr), lead (Pb) and zinc (Zn), and chloride ions (Cl$^-$), which are all commonly found in contaminated snow. We assumed that pollutant loads in runoff came from impervious surfaces subjected to traffic and winter maintenance practices (roads and parking lots) and from the snow storage site (Trowbridge *et al.* 2010; Westerlund & Viklander 2011; Moghadas *et al.* 2015, Figure 1).

Deicing operations specific to each land use were considered for defining the values of EMC for Cl$^-$: we used a larger EMC of 1,213 mg/L for roads, compared to an EMC of 934 mg/L for parking lots, to account for the fact that greater quantities of salt are sprayed on roads than on parking lots (Environment Canada 2012). We computed pollutant loads for the melting period from December to the end of March.

2.3.2. Bioretention cell implementation modeling

Bioretention cells consist of several layers: planted surface, substrate, storage, and underdrain. Direct precipitation and runoff from adjacent impervious surfaces are received on the surface. Water can further infiltrate into the soil and percolate to the storage layer composed of gravel. Water exits the system from the surface via evaporation, from the storage layer via further infiltration into the native soil, by the underdrain connected to the sewer or via surface outflow (then redirected to the sewer). Parameters for bioretention cell design and soil characteristics used in this study were calibrated with measurements obtained from an existing bioretention cell system in Trois-Rivières (Bouattour 2021) and are summarized in Table 5.

The soil layer refers to the bioretention media with a sandy loam texture and thickness of 450 mm thick (Table 5). Our choices of a less draining soil and shallow substrate depth were conservative. The storage layer consisted of coarse stone or gravel through which water could either infiltrate into the underlying natural soil at a rate of 1.3 mm/h corresponding to a silty clay soil, or flow out through the underdrain system (Autixier *et al.* 2014; Rossman 2015). Based on a previous study performed in Quebec (Dagenais *et al.* 2014), bioretention implementation scenarios were established on the hypothesis that 10% of impervious surfaces (roads, parking lots, impervious area of snow storage site) would be converted to bioretention cells, making it possible to maintain surface functionality while effectively reducing runoff (MDDEFP 2011). We defined eight (8) implementation scenarios depending on the land use and the type of impervious surface being converted to a bioretention cell. Each scenario considered catchment parts separately, as summarized in Table 6.

We compared the performance of the scenarios based on water quantity (peak runoff, infiltration, and runoff volumes) and quality (pollutant mass loads). For comparison purposes, bioretention cell performance at system scale was calculated: removal of pollutant, runoff volume reduction, and infiltration volume increase were

Table 5 | Summary of bioretention cell characteristics, based on Bouattour (2021)

Layer	Parameter	Value
Surface	Berm height (storage depth) [mm]	75
	Vegetation volume (fraction)	0.05
	Surface roughness (Manning's *n*)	0.1
	Surface slope [%]	0.77
Soil (sandy loam soil)	Thickness [mm]	450
	Porosity (volume fraction)	0.45
	Field capacity (volume fraction)	0.19
	Wilting point (volume fraction)	0.085
	Conductivity [mm/h]	119.4
	Conductivity slope	10
	Suction head [mm]	89
Storage	Thickness [mm]	150
	Void ratio	0.5
	Conductivity (underlying soil) [mm/h]	1.3
	Clogging factor	0
Underdrain	Flow coefficient [mm/h]	2.3
	Flow exponent	0.5
	Offset height [mm]	13

Table 6 | Bioretention cell implementation scenarios

Land use	Impervious surface	Scenario name	Bioretention cell area [m²]
Industrial	Parking lots, roads	*Ind*	19,419 *Total of roads and parking lots (1,318 m² + 18,101 m²)*
	Roads	*R_ind*	1,318
	Parking lots	*P_ind*	18,101
Residential	Roads	*Res*	7,680 *Total of roads picked up and pushed (4,471 m² + 3,209 m²)*
	Roads with picked up snow	*Pi_res*	4,471
	Roads with pushed snow	*Pu_res*	3,209
Snow storage	Snow storage	*SS*	5,589
Industrial, residential	Parking lot, roads	*Ind_Res*	27,099 *Total of industrial and residential (19,419 + 7,680)*

normalized by bioretention area regardless of total converted impervious surface. Based on scenario performance, a hierarchy of sites was then established with respect to maximum pollutant removal and runoff reduction to prioritize implementation sites.

3. RESULTS AND DISCUSSION

3.1. Urban snow simulation results

3.1.1. Overview

The results of winter 2020–2021 illustrate typical results obtained from the urban snow model used in this study. Model inputs and outputs are plotted with respect to time in Figure 4 for the entire winter (left) and a selected runoff event (right).

From November to January, catchment average snow depth fluctuated because the temperature oscillated close to the separation temperature of 0.9 °C (Figure 4(a) and 4(c)). Differences in subcatchment snow depths (Figure 4(d) and 4(e)) show the impact of snow clearing parameters defined for each snowpack (Table 2). Snow depth of the residential land with collected snow was the lowest, as snow was regularly cleared from roads and transferred to the snow storage site, which had the greatest snow depth (Figure 4(e)). Residential land with pushed snow had a greater snow depth and a slower melting rate than the industrial subcatchment, probably due to the undisturbed snow stored on house roofs. This reflects the melt factor assignment choice (Table 3): untouched snow on residential roofs, assumed to be less contaminated and excluding its albedo, melted more slowly than snow relocated from industrial impervious surfaces. These results are consistent with the sensitivity analysis, which highlighted the importance of both the dividing temperature and the melt factor (Supplementary material, Section 4). Figure 4(g) shows that SWMM considered two types of runoffs: snowmelt and rain. Runoff peaked on February 28, between 12:00 and 22:00, corresponding to snowmelt, which began at 11:00. The delay of approximately one hour reflects the time required by the liquid water to fill the free water capacity of the snowpack (Moghadas *et al.* 2018). Snowmelt runoff rates were greatly influenced by air temperature (Figure 4(b) and 4(g)). During dry weather, snowmelt mainly exited the subcatchments as runoff rather than infiltration (Figure 4(i)). Completely permeable natural subcatchments produced no runoff and had the largest infiltration rate of 2.4 mm/h observed during the rainy period. Between February 28 at 22:00 and March 1 at 16:00, the three precipitation events led to three runoff and infiltration peaks (Figure 4(b) and 4(i)). As for runoff, a delay of 1 hour was observed between rainfall onset and the beginning of infiltration (i.e. non-zero infiltration rate). Runoff maximum rates increased with fraction of impervious area: industrial I was the most impervious subcatchment, while residential with collected snow was the most permeable. Opposite trends were observed for infiltration: subcatchments with high runoff rates showed small corresponding infiltration rates.
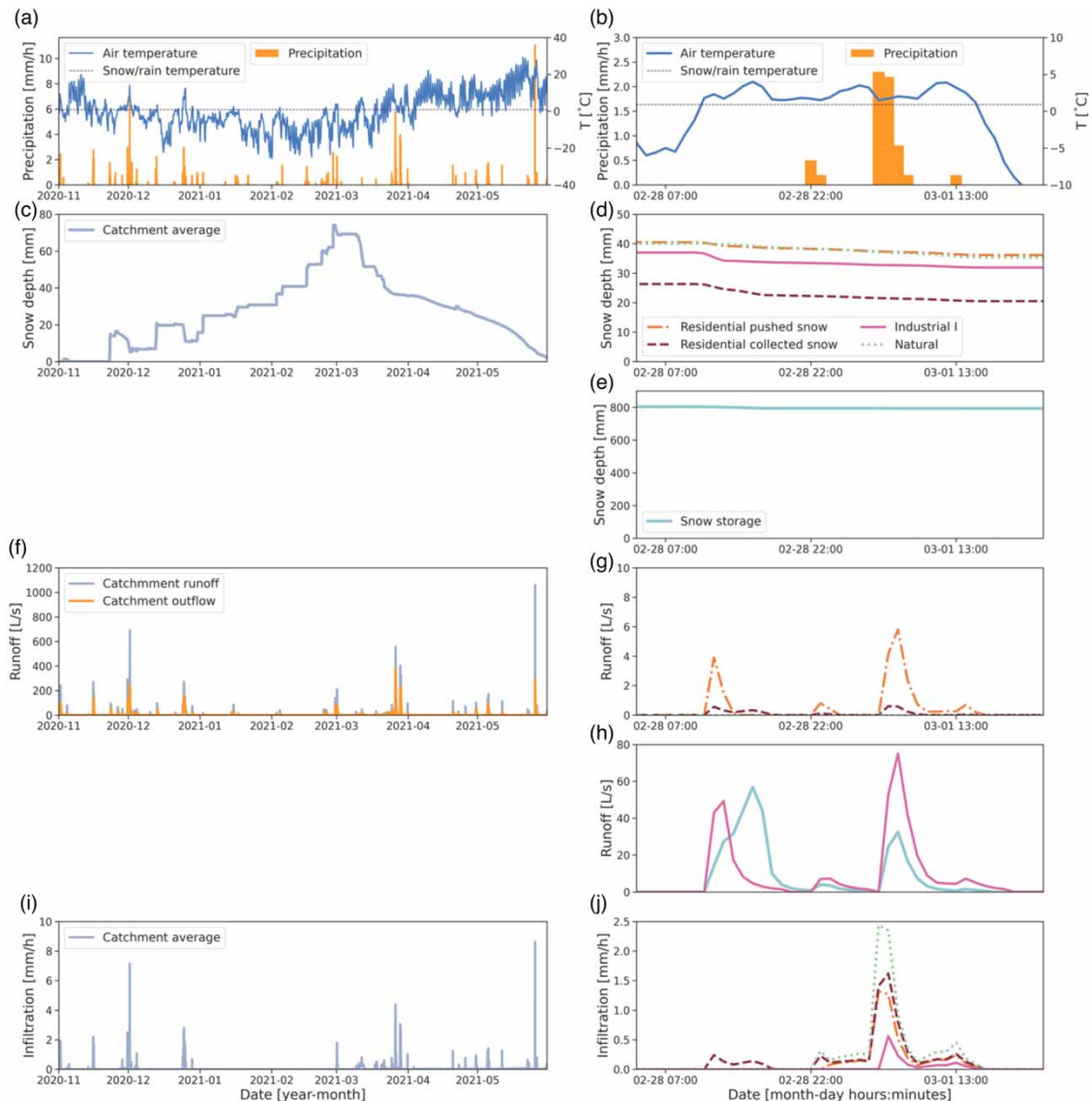
Figure 4 | (a) Urban snowmelt simulation input precipitation; (b) input air temperature; (c) output catchment average snow depth; (d) subcatchments snow depths; (e) snow storage snow depth; (f) catchment runoff and outflow rates; (g, h) subcatchments runoffs; (i) catchment infiltration; (j) subcatchments infiltrations for winter 2020–2021 (left) and a selected event (right).

3.1.2. Effect of snow cover modeling on catchment hydrology

Results of runoff and infiltration volumes, average rates, and total durations according to build-up (December–February) and melt down (March to May) periods are shown in Figure 5.

The snow cover impacted the water mass balance of the catchment, enhancing water infiltration and thus decreasing runoff from impervious surfaces (Figure 5). During snow build-up, both runoff and infiltration average volumes and total duration decreased. Low temperatures observed during these months resulted in frozen water, which inhibited runoff and infiltration because these are hydrological processes that affect liquid water quantity. During snowmelt, modeling snow led to a slightly lower average runoff volume than without, while the corresponding average infiltrated volume was greater. Runoff and infiltration duration during this period largely increased while average corresponding rates tended to decrease. Melting snow thus influenced water release, limiting runoff flowrates but favoring longer events, which promoted water infiltration into soil. These observations are in line with findings by Moghadas et al. (2018), which highlighted the role of snow depth in controlling runoff generation. These results support the importance of considering snow cover when modeling the hydrology of a subcatchment under cold climates for runoff assessment. Without considering snow, runoff tends to be higher
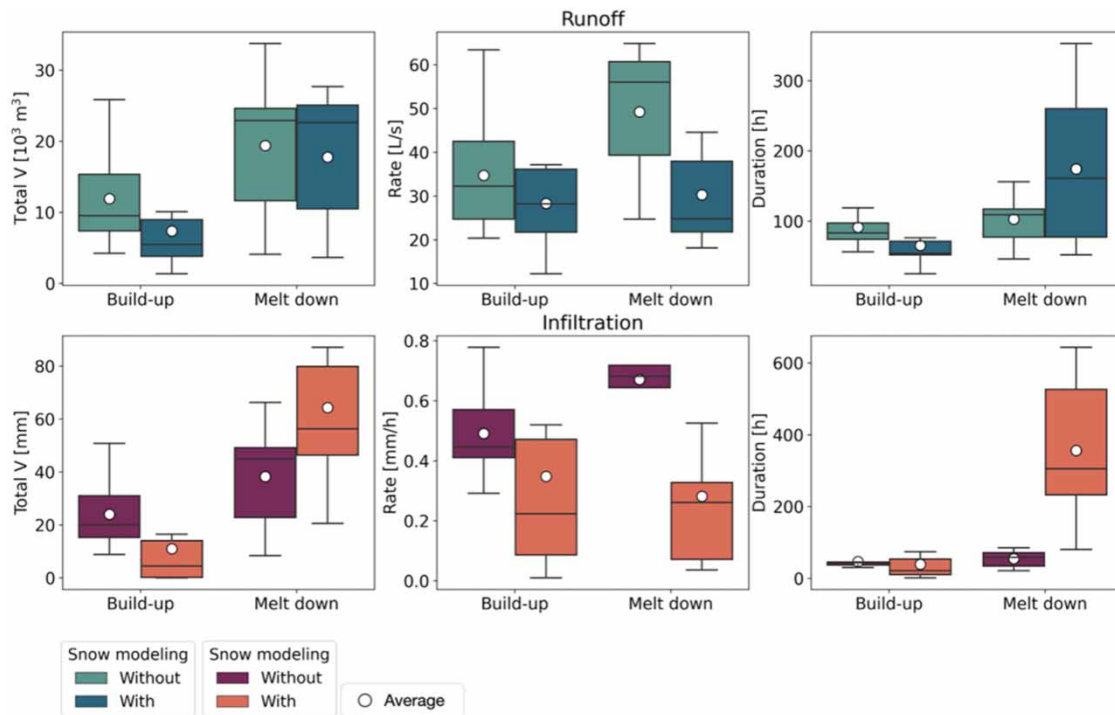
Figure 5 | Runoff (top) and infiltration (bottom) volumes, average rates, and total duration for build-up (December to February) and melt down (March to May) periods, with and without snow modeling, summed for the three winters.

and infiltration lower. Several studies highlighted that soil infiltration capacity can be reduced by freezing–thawing conditions increasing runoff production early in the snowmelt period (He *et al.* 2015; Moghadas *et al.* 2018). However, the insulating effect of the snowpack may reduce the impact of frost on infiltration (Ding *et al.* 2019; Ala-Aho *et al.* 2021; Pineau *et al.* 2021). Water mainly infiltrated through pervious surfaces that were not subjected to snow removal. This suggests that excluding soil freezing from the modeling is a viable hypothesis.

3.2. Scenario performance: the impact of bioretention cells on snowmelt

3.2.1. Catchment scale performance

Figures 6 and 7 show the impact of each scenario on runoff quantity (peak runoff, infiltration, and runoff volumes) and quality (pollutant mass loads), respectively.

Implementation of bioretention cells on both roads and parking lots (scenario denoted *Ind*) of the industrial area decreased average runoff total volume and peak flow (Figure 6(a)). While similar results were obtained when bioretention cells were only deployed on parking lots (*P_ind*), conversion of roads did not significantly impact runoff volume or peak flowrate. All implementation scenarios on industrial land improved infiltration. Bioretention cell implementation on all roads of the residential area (*Res*) decreased average runoff total volume and peak flowrate (Figure 6(b)). Bioretention cell implementation on residential areas where snow was pushed and stored *in situ* (*Pu_res*) was more effective at reducing both maximum runoff volume and flowrate peak compared to roads where snow was picked up (*Pi_res*). Infiltration was not significantly improved by either *Pi_res* or *Pu_res* scenarios individually, but it was improved by the combination of the two (*Res*). Bioretention cells implemented on parking lots (*P_ind*) performed better than those on roads (*R_ind*) for Cl⁻, TSS and Cr, reducing their maximum loads by 45% compared to a reduction of 10% on roads. Runoff from roads carried a higher concentration of pollutants than from parking lots (Table 4). *R_ind* performed slightly better than *P_ind* for Pb and Zn removal. Deployment of bioretention cells on both roads and parking lots (*Ind*) led to the best results, combining positive effects of both scenarios *P_ind* and *R_ind*. However, *Ind* scenario did not perform significantly better than *P_ind* the best of the two scenarios (Figures 6(a) and 7(a)). Similar patterns were observed for all pollutants: bioretention cells deployed on roads where snow was pushed (*Pu_res*) were more efficient at reducing maximum loads for all pollutants (Figure 7(b)). Treatment performance was affected by both land use and snow management (Figures 6 and 7). Parking lots showed better performance for both
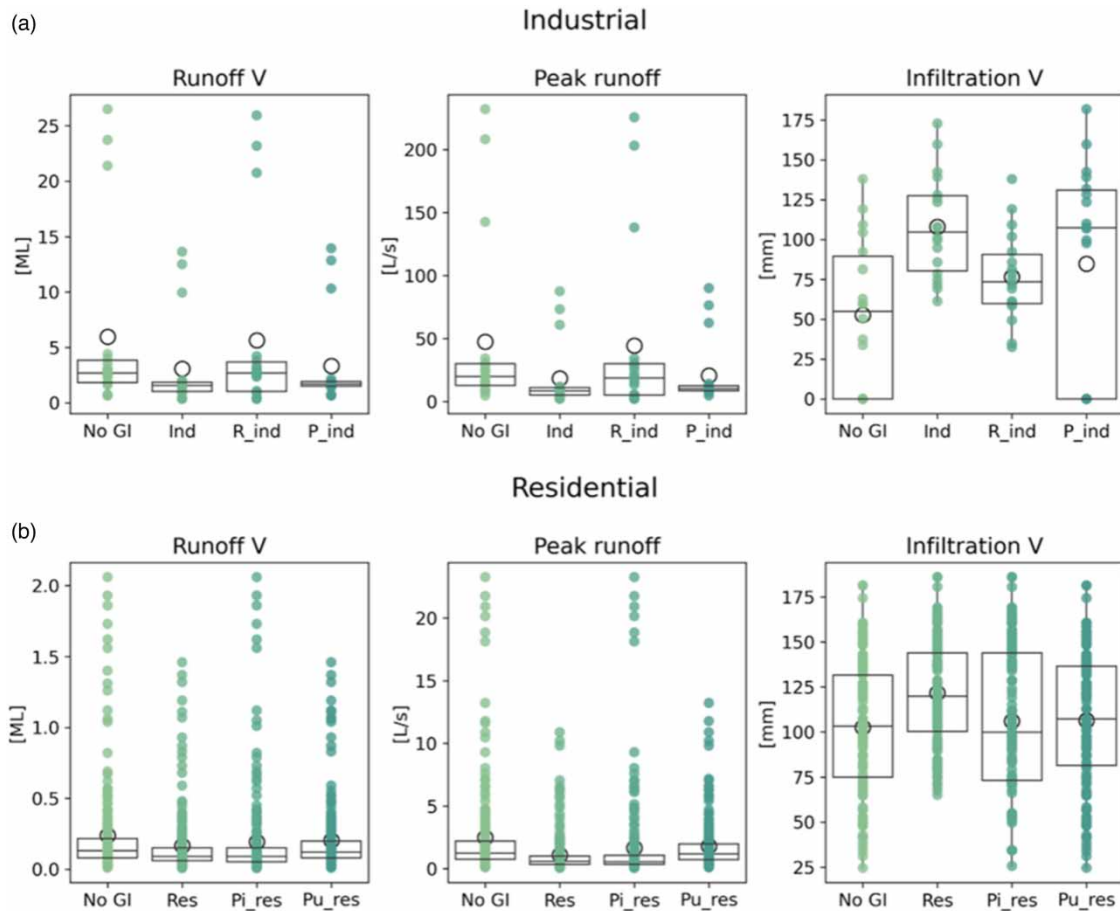
Figure 6 | Peak runoff, infiltration and total runoff volumes summed from the three winters for different scenarios; (a) during snowmelt for industrial and (b) residential land uses (implementation on industrial roads and parking lots (Ind), roads (R_ind), parking lots (P_ind); on residential roads (Res), roads with picked up snow (Pi_res), roads with pushed snow (Pu_res)); note the different scales.

runoff quality and quantity improvement, reducing average runoff volume and peak and Cl⁻, Cr and TSS mass loads, because of the large potential area that can be converted to bioretention. Implementation of bioretention cells on roads where snow was pushed was more effective than picked up in reducing maximum runoff volume, peak flowrate, and pollutant mass loads.

3.2.2. Specific bioretention cell performance

Table 7 summarizes specific bioretention cell qualitative performance (pollutant removal) and quantitative performance (runoff reduction and infiltration increase) with respect to implementation scenarios.

Our results show that the ability of bioretention cells to manage snowmelt runoff was strongly dependent on land use (industrial, residential, snow storage), type of impervious surface (parking lot, road) and snow management procedure (snow picked up vs. pushed). Both qualitative and quantitative performances were best for roads in industrial areas (*R_ind* scenario) (Table 7). However, infiltration improved more for bioretention cells on parking lots. Compared with residential areas, bioretention cell implementation on roads where snow is pushed and stored *in situ* (*Pu_res*) demonstrated slightly better performance for both quantity and quality compared to roads where snow was picked up (*Pi_res*), except for Cr. Bioretention cells implemented on industrial areas performed better than on residential areas for Cl⁻, runoff and infiltration volumes. Similar results were obtained for TSS and Cr. Bioretention cells deployed on residential areas were more effective for Pb and Zn removal, with mass removal of 9 and 146 mg/m² for *Res* and 5 and 79 mg/m² for *Ind*. Implementation on snow storage sites was more effective over all industrial and residential areas (*Ind* and *Res*) for all pollutants. Deployment on industrial areas was more beneficial with respect to water quantity, additionally reducing runoff volume by 104 L/m² and improving infiltration by 34 mm/m² compared to snow storage. When snow is not modeled (Supplementary material, Table S4), specific bioretention cell performance for both quantity and quality was greater.
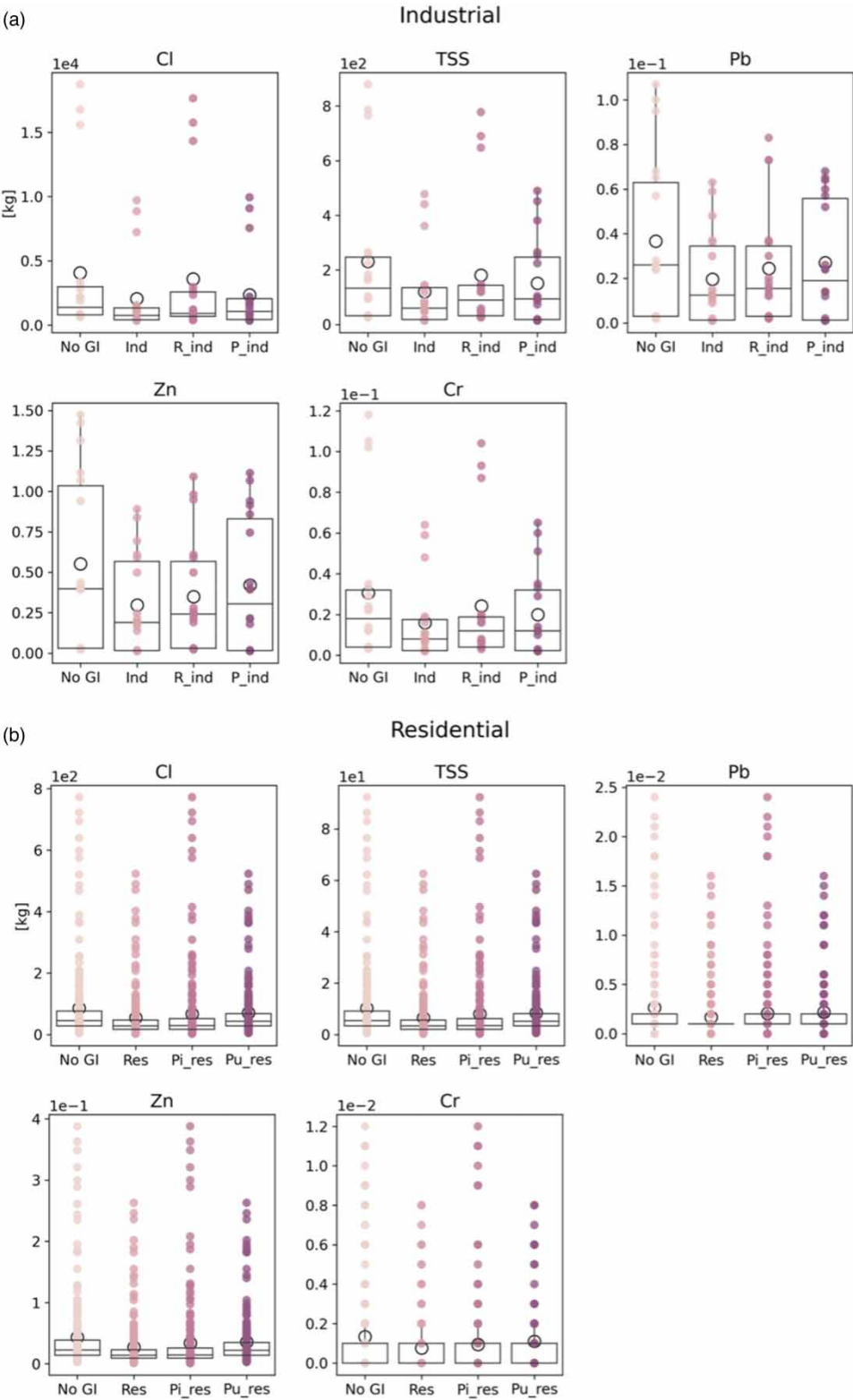
Figure 7 | Pollutant loads summed from the three winters for different scenarios; during snowmelt for (a) industrial and (b) residential land uses; note the different scales.

3.2.3. Model validation and further research needs

Our modeled results were consistent with findings in several field studies conducted in cold climate around the world. For example, a laboratory study showed that the prototype bioretention cell was able to remove up to 145 and 17 mg/m^2 of Zn and Pb per event, respectively (Davis *et al.* 2001), confirming the order of magnitude of the

Table 7 | Specific bioretention cell performance for the reduction of pollutant loads and runoff volume and for increase in infiltration volume averaged over three winters; for different scenarios (implementation on industrial roads and parking lots (Ind), roads (R_ind), parking lots (P_ind); on residential roads (Res), roads with picked up snow (Pi_res), roads with pushed snow (Pu_res))

Scenario	Land use	Pollutant removal					Runoff reduction [L/m²]	Infiltration increase [mm/m²]
		TSS [g/m²]	Cr [mg/m²]	Pb [mg/m²]	Zn [mg/m²]	Cl⁻ [g/m²]		
Ind	Industrial	34	5	5	79	626	891	658
R_ind		230	30	56	918	2,173	1,393	583
P_ind		27	4	3	44	575	871	705
Res	Residential	35	5	9	146	290	667	562
Pi_res		36	7	9	150	299	712	545
Pu_res		40	5	10	167	332	771	678
SS	Snow storage	75	10	19	316	628	787	624
Ind_res	Industrial, Residential	32	4	6	89	509	797	570

specific bioretention cell performance determined through modeling (Table 7). However, EMC simplified modeling made it possible to study the removal of pollutants based on the reduction of the hydraulic loading rate, which led to overestimation of bioretention cell performance due to omission of the effect of frozen soil on infiltration. Muthanna *et al.* (2007) studied a pilot bioretention cell receiving wash water from a tunnel in Norway. The modeled monthly performance levels in this study were found to be similar to those measured by Muthanna *et al.* (2007), e.g., 230 vs. 240 mg/m² for Zn and 14 vs. 3 mg/m² for Pb, modeled and measured respectively. While Zn removal performance was similar, modeled Pb removal was much greater. This may be due to the higher concentration of Pb observed in runoff from roads in Canada (Table 4) compared to Norway or partitioning between dissolved and suspended form of Pb which is not considered by the model. Muthanna *et al.* (2007) also observed that bioretention cell Pb removal performance in summer was 11 mg/m², closer to the 14 mg/m² obtained through modeling in this study. This suggests that neglecting frozen soil from analysis may lead to an overestimation of modeled bioretention performance in winter. Paus *et al.* (2016) also observed that a low soil hydraulic conductivity of 130 mm/h (119.4 mm/h used in the model, Table 5) was impacted by the seasons, with reduced infiltration in March and April. Bioretention cells on parking lots infiltrated up to 45% of the incoming runoff (Supplementary material, Table S5): this result aligns with findings by Paus *et al.* (2016), who measured a ratio of 55%, but is greater than the field results of Géhéniau *et al.* (2015), of 35% during the cold season. Moreover, this method does not take into account the physicochemical interactions within the bioretention cell (pollutant uptake by plant and substrate, metal partitioning, etc.). Data were measured during a rain on snow event in late March 2021 at the inlet of an existing bioretention cell system in Trois-Rivières, located on the side of a road in a residential area. Average Cr, Pb, Zn, and Cl⁻ concentrations were 8, 4.2, 136.5, and 229 mg/L (Dagenais *et al.* 2022), lower than EMC used in this study for roads (based on literature, Table 4). This could be due to the timing of the measurement, as pollutants in snowmelt are less concentrated at the end of the melting period. Alternatively, it could have been a result of the limited traffic observed in residential areas. Moreover, this period corresponded to the COVID-19 pandemic with lockdown restriction, teleworking, school closed, etc. which reduced traffic. This also suggests that an additional type of land use could be added to the model to differentiate roads with lower traffic typical of residential areas. This would allow a more accurate representation of runoff quality from residential areas. Field data would be required to determine more accurate EMC values. Modeling results confirm that bioretention cells significantly reduced Cl⁻ mass loads in effluents, thereby preventing saline shock to the environment. According to our results (73% over 4 months), Cl⁻ reduction from bioretention cells on industrial roads compared well to the 80% reduction values observed by Burgis *et al.* (2020) for a four-lane road over 1 year of monitoring in Virginia, United States. We chose the study of Burgis *et al.* (2020) because salt spreading practices were similar to those of Trois-Rivières, and thus road runoff concentrations entering the bioretention cells were in the same range too (1,745 vs. 1,213 mg/L in our model (Table 4)), which was a necessary condition to allow a relevant comparison. Our results also highlighted that snow management procedures impact bioretention cell performance, with best performance obtained when

the snow was pushed (Figures 6 and 7, Table 7). These results suggest that snow removal practices in cities with a cold climate could be adapted to better take advantage of bioretention cells in winter. Snow could be stored on top of bioretention cells to optimize treatment upon snowmelt. However, more reflections and discussions should be held to properly define a directive on how snow should be managed by the bioretention cells. Although the snow cover insulates the soil, preventing its freezing, the weight of the snowpack could cause soil compaction impairing its hydraulic conductivity (Pineau *et al.* 2021). Additional snow can also delay the warming up of the soil and the development of vegetation, having consequences for the functioning of bioretention cells in early spring (Rixen *et al.* 2022). Moreover, storing very large snow piles on top of the bioretention cells would not allow for the use of pretreatment, which helps to ensure the long-term performance of bioretention cells (William *et al.* 2019). Overall, modeling enabled assessment of bioretention cell performance under snow conditions. The main limitation of this approach lies in the need for more data, to better consider the soil freezing effect and local snowmelt quality. Further observations under these specific conditions are required to validate and improve the model.

3.3. Recommendations for bioretention cell implementation

Implementation site hierarchy to treat snowmelt with respect to two objectives was established as shown in Figure 8.

The following recommendations can be formulated to support bioretention cell implementation in cities with a cold climate. To improve both quantity and quality (Figure 8, objectives A and B) of snowmelt, main roads in industrial areas should be favored for bioretention cell implementation (Table 7). Unit performance of bioretention cells is best when implemented on industrial roads, reducing the largest pollutant mass and runoff volume (Table 7). Implementing bioretention on roads that are an important source of highly polluted runoff (Table 4) greatly impacted the ratio of pervious to impervious surfaces, which led to both an effective reduction of the runoff source and an increase in the removal of runoff and pollutants. After industrial roads, the model suggests that the next largest improvement to stormwater management can be made by installing bioretention cells in industrial parking lots (Figure 8, objective A). Large impervious surfaces, such as parking lots, allow for larger bioretention cells in industrial areas compared to residential areas, which increases reduction of runoff (volume and peak) and pollutant loads (Cl^-, TSS, Cr), and improves infiltration (Figures 6 and 7). Implementation on residential roads with pushed snow improves point source treatment and capitalizes on bioretention cell performance (Table 7). Snowbanks store large volumes of water and thus represent great potential for reducing both maximum runoff (volume and peak flow) and Pb and Zn loads (Figures 6 and 7). Bioretention cells can
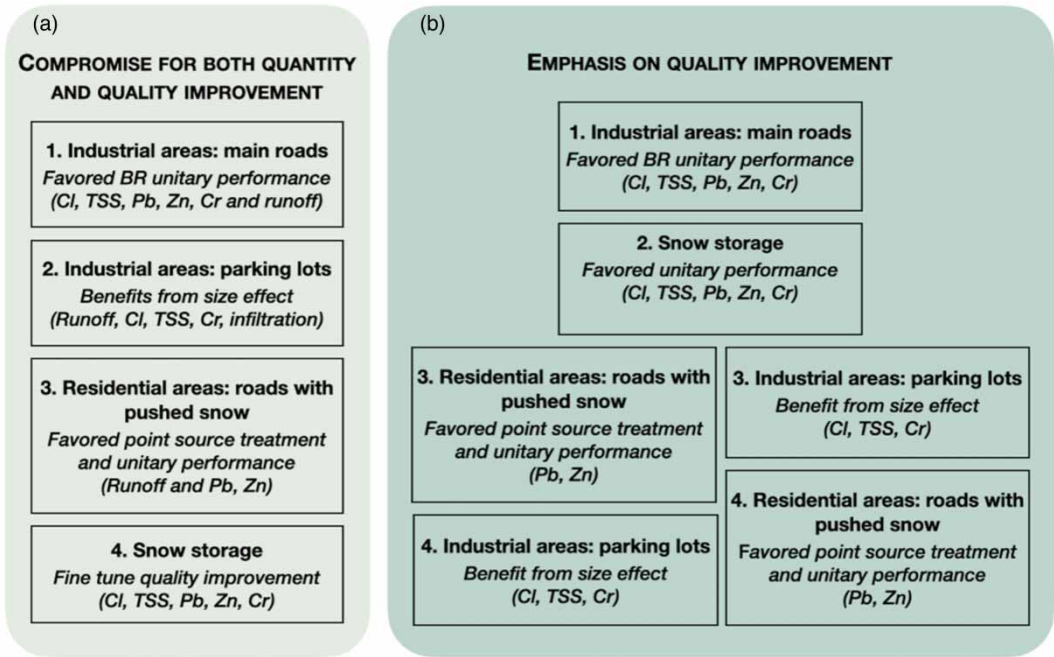

Figure 8 | Recommendations for bioretention cell (BR) implementation priority for treating snowmelt with two objectives.

be implemented around snow storage sites to help mitigate the poor quality of snowmelt. However, runoff from snow storage contains the highest Cl^- concentration (Table 4), which can damage bioretention cells vegetation. Design of bioretention cells could be adapted by choosing salt-tolerant plants for instance (Denich *et al.* 2013). When we consider only water quality improvements, a different implementation priority emerges (Figure 8, objective B). Once installed on industrial roads, bioretention cells can be extended to the snow storage on surrounding land to optimize unitary performance of the bioretention cells (Table 7). However, bioretention cell deployment on highly contaminated areas should be considered with caution, to prevent groundwater contamination due to enhanced infiltration. Finally, at the low end of the priority list, bioretention cells can be implemented on residential roads or on industrial parking lots, depending on the targeted pollutant: removal of Pb and Zn or Cl^-, TSS, and Cr, respectively. Nonetheless, these recommendations consider only the benefits from bioretention cells to manage snowmelt runoff. It is largely acknowledged that bioretention cells can provide a broad range of benefits, which could be considered simultaneously to snowmelt management criteria by combining a range of spatial information into decision-support tools to support more integrated decision making (Kuller *et al.* 2017, 2019).

4. CONCLUSION

The methodology proposed in this study enables snow management to be considered and evaluated in decision making on BGIs siting by using limited input data. Addressing the complex issues related to urban snow management across sites over an urban territory requires that decisions be made to set aside certain components and factors. Nevertheless, results suggest that snow should be systematically modeled in similar case studies to better reflect local conditions and improve the performance of large-scale BGIs implementation in cities with a cold climate. Assessment of several BGI implementation scenarios showed that bioretention cell performance depended on land use and snow management procedures. Modeling served as a preliminary screening tool to help identify preferred sites for implementing BGIs in cold climates. To improve snowmelt quantity and quality, bioretention cells should be implemented in the following order: on industrial roads, industrial parking lots, roads with pushed snow and snow storage surroundings. For a purely qualitative objective, i.e. focusing on improving snowmelt quality, the implementation order should be: (1) industrial roads, (2) snow storage surroundings, and (3) roads with pushed snow or parking lots. This research supports the integration of new criteria in decision-support tools to reflect the challenges and opportunities in BGIs planning in cold regions, which is crucial to support long-term urban water management. Further research and field data collection are required to improve snow modeling and validate prediction of bioretention cell performance. Further investigation to validate design such as plant choices suited to cold climate is also needed.

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.

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