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Full-scale characterization of the effects of a bioretention system on water quality and quantity following the replacement of a mixed stormwater and combined sewer system

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ABSTRACT

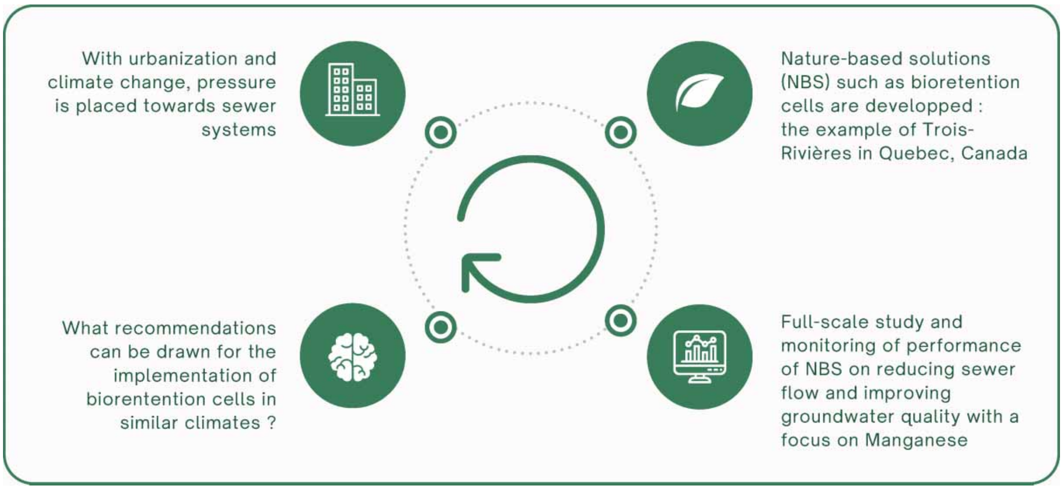
Urbanization is leading to more frequent flooding as cities have more impervious surfaces and runoff exceeds the capacity of combined sewer systems. In heavy rainfall, contaminated excess water is discharged into the natural environment, damaging ecosystems and threatening drinking water sources. To address these challenges aggravated by climate change, urban blue-green water management systems, such as bioretention cells, are increasingly being adopted. Bioretention cells use substrate and plants adapted to the climate to manage rainwater. They form shallow depressions, allowing infiltration, storage, and gradual evacuation of runoff. In 2018, the City of Trois-Rivières (Québec, Canada) installed 54 bioretention cells along a residential street, several of which were equipped with access points to monitor performance. Groundwater quality was monitored through the installation of piezometers to detect potential contamination. This large-scale project aimed to improve stormwater quality and reduce sewer flows. The studied bioretention cells reduced the flow and generally improved water quality entering the sewer system, as well as the quality of stormwater, with some exceptions. Higher outflow concentrations were observed for contaminants such as manganese and nitrate. The results of this initiative provide useful recommendations for similar projects for urban climate change adaptation.

Key words: best management practices (BMP), bioretention cells, blue-green infrastructure (BGI), climate change adaptation, stormwater quality, urban water management

HIGHLIGHTS

- Influent and effluent water quality and quantity were measured in full-scale bioretention cells.
- Bioretention cells reduced sewer flow.
- The advantages of a bioretention cell for improving stormwater quality were showcased.
- Groundwater quality and quantity were assessed for impacts on groundwater drinking water sources.
- Recommendations were given for the implementation of improved similar projects in a cold climate.

GRAPHICAL ABSTRACT



INTRODUCTION

In urban areas, impervious surfaces create a greater volume of runoff and, combined with anthropogenic activities, increase the environmental vulnerability of communities (Paul & Meyer 2001; Erickson *et al.* 2013). Combined sewer systems, draining both wastewater and stormwater, have limited capacity. During heavy rainfall or snowmelt, excess water overflows and discharges untreated runoff into receiving waters, causing significant environmental impacts, including harm to aquatic species (Autixier 2012). Studies have shown that even small increases in the urban impervious surface area can lead to substantial ecological changes in watersheds. For example, intolerant bacterial taxa tend to disappear when more than 12% of a watershed is urbanized (Simonin *et al.* 2019), while an impervious surface threshold as low as 2% has been found to affect aquatic macroinvertebrate populations in streams (King & Baker 2010).

Climate change is multiplying extreme weather events. In northern regions, the intensity of climate change is and will continue to be high. Across Quebec, predictions suggest that the frequency of heavy rain days will increase, alongside modifications in precipitation characteristics such as duration, seasonality, frequency, the magnitude of extremes, and the degree of interannual variability (Leveque *et al.* 2021). This puts additional pressure on urban sewer systems, making it essential to reduce stormwater volumes and protect aquatic ecosystems.

A growing awareness of urban water issues has led to the gradual introduction of various sustainable stormwater management practices (Field & Tafuri 2006). These practices aim to control problems associated with runoff volumes and quality, control peak flows to limit the erosion of receiving watercourses, and manage groundwater recharge (Ville de Trois-Rivières 2013). Terminologies like blue-green infrastructure (BGI), best management practices, and sustainable urban drainage systems (SUDS) have emerged to facilitate communication among researchers globally (Fletcher *et al.* 2015).

A bioretention cell is a vertical-flow SUDS that consists of a shallow depression filled with selected substrate and vegetation adapted to local climatic conditions, maximizing the peak runoff control, detention, treatment, and infiltration of surface water runoff (Hunt *et al.* 2012). In addition to managing surface water runoff, bioretention cells provide aesthetic and safety benefits (calmer traffic, safer intersections, and wider sidewalks). Although few studies have directly measured the impacts of green stormwater infrastructure on active mobility, bioretention cells are one of the few for which outcomes have specifically been measured (Lemieux *et al.* 2023). The integration of bioretention cells has also been associated with the creation of more aesthetically pleasing environments, with more greenery. A 2019 study conducted in the United States surveyed 497 laypersons and 117 designers, highlighting a distinct preference for landscapes featuring green stormwater infrastructure (Suppakittpaisarn *et al.* 2019). However, it also identified how the messiness of green stormwater infrastructure directly impacted the preference. Furthermore, this pleasant environment can be directly linked to the reduction of thermic islands (Santamouris 2014), which have also been shown to degrade distributed drinking water quality (Absalan *et al.* 2024).

Bioretention systems are relatively recent BGI, with the first examples dating back to the 1990s in Prince George County, Maryland (Roy-Poirier *et al.* 2010). These systems have been the subject of several studies; however, their performance in cold climates remains poorly understood due to the radically different conditions they experience during the winter and summer seasons. Notably, it has been demonstrated that road maintenance salts have both negative effects (reduction of heavy metal uptake by plants) and positive impacts on contaminant removal (e.g. total suspended solid removal) (Géhéniau *et al.* 2014). However, their effects on vegetation and microbial communities have yet to be fully understood (Kratky *et al.* 2017). In addition, the impact of large-scale implementation of bioretention cells on sewershed hydrology has mostly been explored via modeling simulations (Meng *et al.* 2014; Wang *et al.* 2019; Gougeon *et al.* 2023). There is a need to investigate the full-scale effects of these BGI on the reduction of stormwater flows and water quality, especially in cold climates.

One major concern is the potential release of heavy metals into groundwater from the runoff managed in the bioretention cells or other stormwater infiltration solutions. It is especially important to protect groundwater when it is vulnerable to potential contamination coming with stormwater infiltration. In general, stormwater infiltration is generally not allowed in areas with high groundwater levels or extreme soil infiltration rates, as these conditions can either prevent filtration or lead to clogging. In Trois-Rivières, the local aquifer is used for drinking water, but the bioretention systems on Saint-Maurice Street pose no direct risk, as they are outside the city's intake zones. However, with the global push to implement SUDS in response to climate change, it is important to assess their effects on groundwater recharge, sewer overflow reduction, and unintended groundwater contamination. Bioretention systems generally achieve over 95% removal of total metals. However, the removal efficiency for dissolved metals can vary (Kratky *et al.* 2017). Several studies have focused specifically on the release of metals by bioretention systems (Muthanna *et al.* 2007; Paus *et al.* 2014; Søberg *et al.* 2017). In some cases, such as Trois-Rivières, heavy metal concerns arise not from stormwater runoff but from naturally high concentrations in the subsoil, particularly manganese. Due to the health risks for bottle-fed infants, Quebec will enforce a maximum allowable concentration of 0.12 mgMn/L for manganese in drinking water by June 2024 (Government of Quebec 2023), in addition to the previously established aesthetic objective of 0.02 mgMn/L. Given its relevance to drinking water, there is a need to further study manganese in relation to other stormwater contaminants in bioretention cell systems. Manganese in groundwater is not a problem unique to Quebec, and to our knowledge, no study has specifically examined manganese and the potential interactions between dissolved organic matter (potentially coming from SUDS) and subsoil manganese.

The goal of this project was to select a site for a full-scale study of the impact of bioretention cells as an approach to climate change adaptation, considering their potential impacts on hydrology and water quality. This study sought to demonstrate the extent to which the implementation of bioretention cells reduces sewer flow and improves (or impairs) the quality of runoff and drainage water, with a focus on manganese. The specific objectives were to: (1) install a monitoring system to measure flowrates into and out of the cells, (2) model the bioretention cells to assess their effectiveness in reducing overall runoff volumes and peak flows at a local and sewershed scale, (3) measure the removal of contaminants in runoff through the bioretention cells, (4) assess the impact of bioretention cells on groundwater quality, including iron and manganese, that are relevant for groundwater sources of drinking water, and (5) provide recommendations for the full-scale implementation of bioretention cells in cold climates considering their impact on sewershed-scale hydrology.

METHODS

Study-site description

The chosen study site was in the City of Trois-Rivières, Québec, Canada. A wide residential street requiring new water and sewer infrastructure was identified for the construction of a series of bioretention cells to assess their performance for the improvement of stormwater quality and the reduction of stormflows. The site was selected because of its width, providing sufficient space, and the combined sewers needed replacement and were separated into storm and sanitary sewers. Given that the city uses both surface water and groundwater as drinking water supply sources, a site was chosen outside the capture zone of their wells to assess their potential impact, should this approach be considered to improve groundwater quantity.

In recent years, the City of Trois-Rivières, located at the mouth of the Saint-Maurice River in Québec, has faced a series of extreme weather events causing power outages, sewage overflows, and costly infrastructure degradation. Recognizing the need for climate change adaptation, the city developed a climate adaptation plan in

2013 (Ville de Trois-Rivières 2013), highlighting risks to its infrastructure. To reduce these vulnerabilities, the municipality aims to implement sustainable urban planning. In 2015, the city launched the *Grand Projet de la Rue Saint-Maurice*, involving the installation of 54 bioretention cells along one of its predominantly residential streets. Although water quality data are available for a subset of the bioretention cells and a parallel project examined plant growth (Dagenais *et al.* 2018; Beral *et al.* 2023a, b), one representative cell was studied in greater detail: the bioretention cell n°4 (BR4) is located at 425 St Maurice Street, Trois-Rivières, QC G8V 1G7, Canada. The aim was to assess its performance at a local scale with sewer monitoring, and the extrapolation of results was made through modeling and simulation.

The organization of BR4 involves several key elements in managing stormwater. A detailed representation is shown in Figure 1, with additional photos in Figure S2 (Supplementary Material). The bioretention area measures 4 m in width and 16 m in length. To protect the vegetation in the bioretention cells during road clearing operations, the sidewalk was placed between them and the street. The runoff water then reaches the inflow well located beneath the sidewalk. This basin acts as a sedimentation pit, providing solids' pre-treatment to prevent clogging of the bioretention cell. This pre-treatment has been recommended for cold climate countries using abrasive on the road in winter. In this study, it has a depth of 1.3 m, which is considered oversized compared to the typical depth of 0.3 m for this type of installation (e.g. The City of Calgary 2016). If the runoff water volume is sufficient, it flows to the bioretention cell. However, in case of an extreme rain event, an overflow redirects excess water from the sedimentation pit to the storm sewer, preventing overloading of the bioretention cell. The water entering the cell passes through the mulch and the planted substrate. Plant selection was based on criteria such as their ability to survive drought and floods and exposure to de-icing salts (Beral *et al.* 2023a). Scientific monitoring of the plants was carried out in BR4. Bioretention cells can be built according to the site conditions, aims and regulations, either as infiltrating to the sub-soil or with a waterproof liner (the main aim

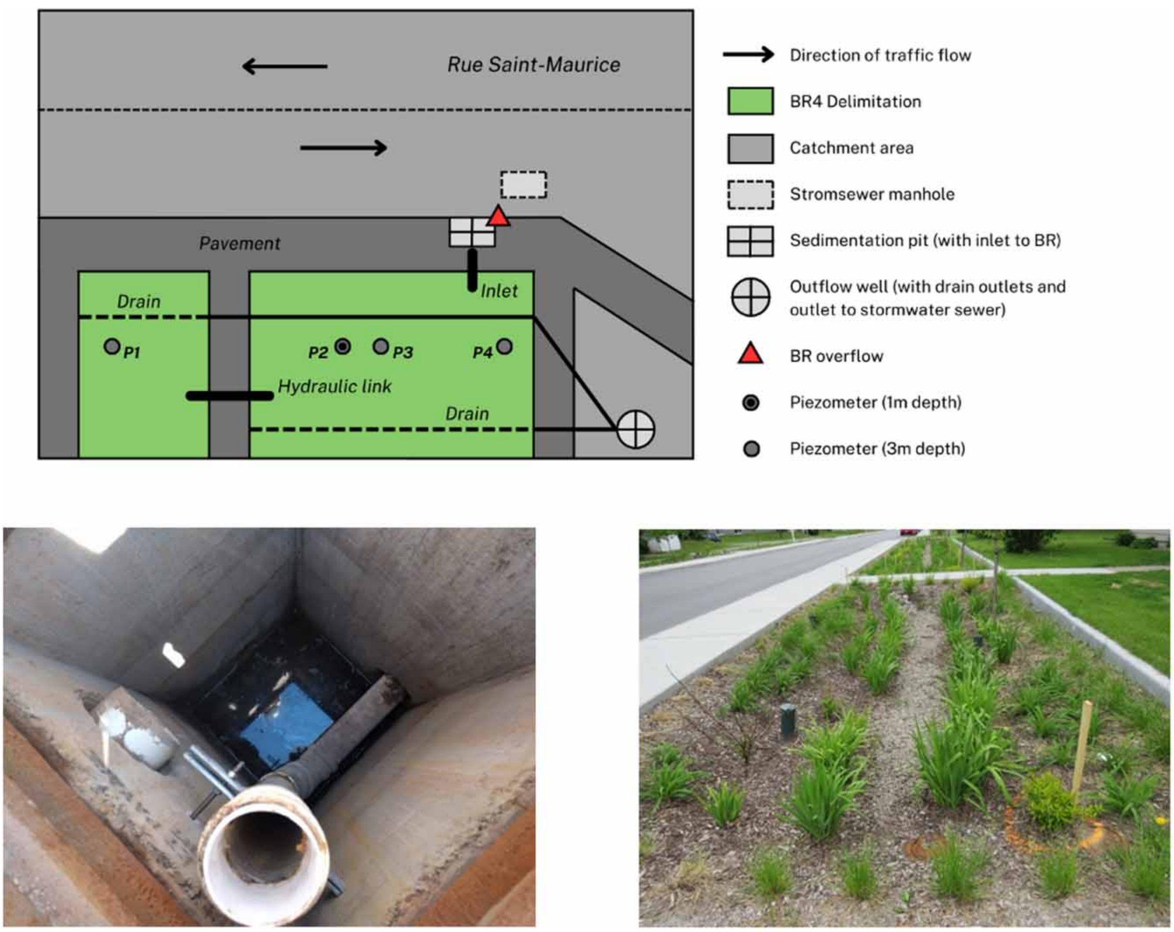


Figure 1 | Plan view representation of BR4, photo of inlet sump and bioretention (April 2019).

being peak flow control and treatment). After filtration within the bioretention cell, the water reaches a layer of sand, where the drainage pipe redirects the excess water to the outflow well. The bioretention cells on Saint-Maurice Street are built without a waterproof membrane. After filtration within the bioretention cell, the water reaches a layer of sand before being exfiltrated underground. The BR4 was built with a drain in this sand layer, allowing for sample collection for scientific monitoring purposes. This drain redirects the excess water to the storm sewer.

Storm Water Management Model modelling

The hydrological model Storm Water Management Model (SWMM) version 5.1.014 was used to simulate precipitation-induced runoff. The SWMM is a dynamic simulation model for urban/suburban precipitation and runoff, which is widely used by researchers and water resource professionals (Rossman & Huber 2015). The objective was to assess the effectiveness of all bioretention cells located along Saint-Maurice Street (see Figure 2) in terms of reducing runoff flows and volumes. This model considers various parameters such as retention capacity, infiltration, and evapotranspiration of runoff. A comparative analysis was conducted between the results obtained from the model with bioretention cells and the model without them to estimate their performance in reducing overall runoff volumes and peak flows.

The SWMM was segmented into 88 sub-basins, with an average surface area of 2.05 ha. This division was carried out by engineers from the City of Trois-Rivières. The model consists of 68 connection points (nodes) and 72 sections (links). The nodes represent the sewer basins in the area, while the links correspond to the pipes. The characteristics of these elements, such as pipe lengths, diameters and maximum depth of nodes, were established by the City of Trois-Rivières. An initial modeling phase was carried out for all these sub-basins of a total area of 111.7 ha. In a second phase, adjustments were made to the model to create a specific local version, encompassing Saint-Maurice Street exclusively. This local system considers only those sub-basins directly connected to Saint-Maurice Street, which represents an area of 16.6 ha.

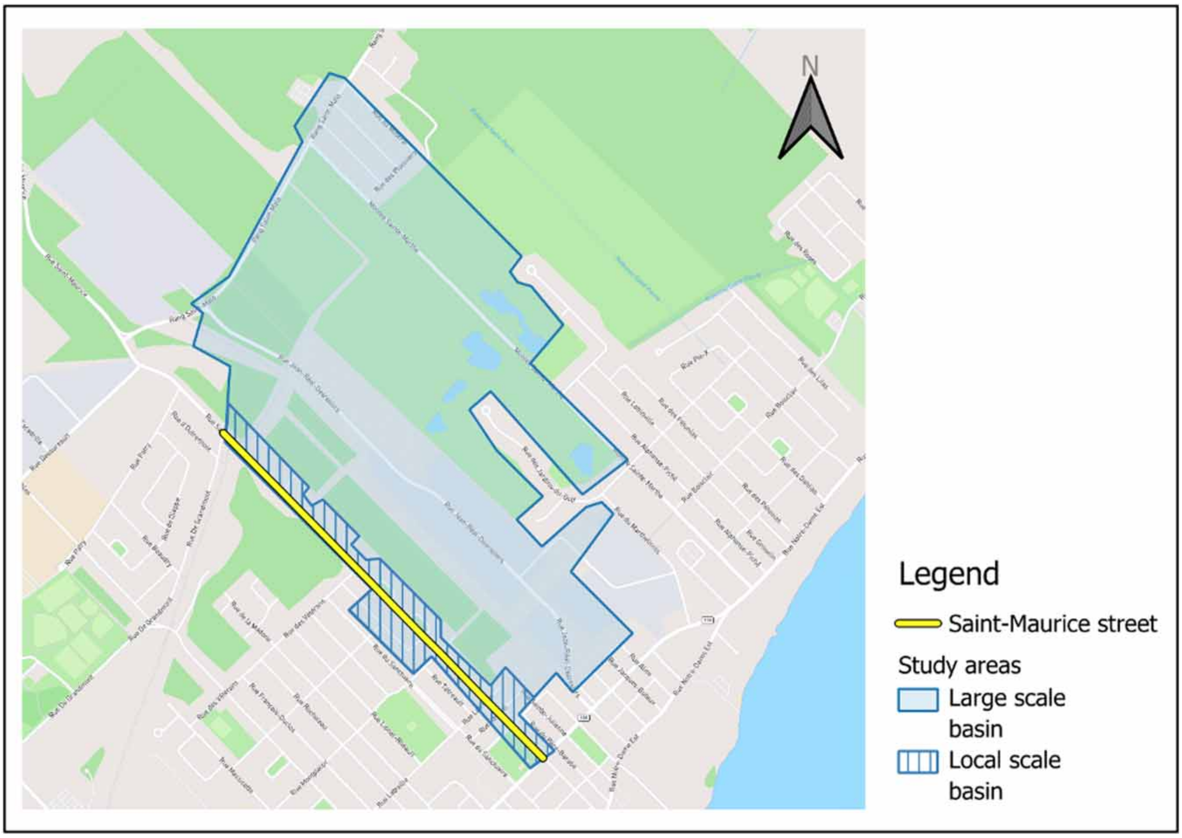


Figure 2 | Map of study areas for the SWMM.

For these simulations, rain events were selected between May and December 2020 based on rainfall data obtained from the nearest meteorological station operated by the City of Trois-Rivières. The selection of events was based on the duration and intensity of rainfall. These events were thunderstorms, representing the longest and most intense occurrences during this 2020 period. Four rainfall events from 2020 were chosen for the present study: the first event (July 19, 2020) was short and intense; the second (July 27, 2020) and the third (August 4, 2020) were, respectively, of medium and long duration, while the last event (August 11, 2020) was a short thunderstorm. Precipitation depths ranged from 13.2 to 91.3 mm, corresponding to return periods of less than 1 in 2 years to 1 in 20 years (Audet *et al.* 2012).

The bioretention cells were added to the SWMM using the software's 'Low Impact Development' (LID) feature, which proposes various types of green infrastructure to be included in the modeling. Four different simulations on separate rainfall events were carried out to calibrate the LID parameters. The parameters tested were determined from the values suggested in the SWMM manual as well as the scientific literature (Autixier *et al.* 2014a, b; Joshi *et al.* 2021; Wang *et al.* 2021). To assess the suitability of this calibration, simulated data were compared with measurements taken using a flow probe installed in 2019 by the City of Trois-Rivières in a sewer pipe downstream of Saint-Maurice Street. To evaluate this calibration, the normalized root mean square error method was used. Further details are provided in the referenced work (Bouattour 2021).

Hydrological monitoring

The installation of the monitoring instrumentation to know both inflow and outflow rates was completed on March 24th, 2021. Both the inlet and outlet of the BR4 were equipped with 'V-Notch' weir boxes. The boxes were made of stainless steel with an angle of 45° for the inlet, while, in 'HDPE' polymer and an angle of 24°, they were used at the outlet. In the sedimentation pit, the water levels were measured every minute by a Solinst Levelogger Edge M10 water pressure sensor adjusted for atmospheric pressure by a Solinst Barologger Edge atmospheric pressure sensor (Solinst 2023a, b). To enable water to reach the bioretention system's area, the weir box must fill up to the level of the pipe conveying the water to bioretention. Furthermore, the inflow basin also has an overflow system connected to the sewer. This instrumentation system was calibrated at the Hydraulic Laboratory of Polytechnique prior to installation (Doucet 2022). In the outflow well, the water level in the 'V-Notch' weir was measured every minute using an ultrasonic transducer Siemens XPS-5 connected to an ultrasonic controller Siemens Sistrans LUT400. To mitigate turbulence or water movement that might disrupt level readings, the outlet box was divided into two compartments, connected by an opening at the bottom of the separator. Since the 'V-Notch' weir was regularly submerged, the water level of the entire well was also measured using a water pressure probe, which was adjusted for atmospheric pressure with a Solinst Levelogger Edge M10 and a Solinst Barologger Edge sensor (Solinst 2023a, b). The setup was calibrated at the CREDEAU Laboratory of Polytechnique for both situations of free flow and submergence of the weir box (Doucet 2022).

The groundwater level was continuously measured in three piezometers (P-1, P-3, and P-4, Figure 1) using Solinst Levelogger probes. Water table level values were adjusted using the atmospheric pressure value measured in the outlet well. Due to technical issues related to the memory capacity limitations of the equipment used, data were not collected continuously throughout the measurement campaign. The measurements taken are organized into a series of data at different intervals between 2021 and 2022. Since the Piezometer P-1 showed strong agreement with the initial expectations and corroborated other observations made regarding the outflow rate, it was selected as the reference for calibrating the data from Piezometers P-3 and P-4. The calibration process began by calculating the initial differences (deltas) between P-1 and the P-3/P-4 data series from their first measurements. Specifically, the deltas were determined by comparing P-1's measurements to those of P-3 and P-4 at the same time points. These differences were then subtracted from the respective measurements of P-3 and P-4 data, effectively adjusting their initial data to match the reference regarding P-1. This adjustment ensured that any discrepancies between P-1 and the other piezometers were corrected, thereby standardizing the data across all instruments.

Water quality monitoring

Four complete sampling events at the inlet and outlet of the bioretention in 2021 and one sampling in 2022 were conducted. The details of each sampled rainfall event are provided in Table 1. Other attempts were made during the study period, but they proved unsuccessful due to a too-small quantity of water entering the catch basin ahead of the entrance of the bioretention. On occasion, debris at the catch basin's entrance resulted in stormwater

Table 1 | Sampled event characterization by the type of event, average intensity, accumulation, and the depth of rainfall

Date	Type of event	Average intensity (mm/h)	Accumulation (mm)	Duration (h)
26-03-2021	Rain on snow	3.3	46	14
08-06-2021	Storm	24	392	16.25
26-06-2021	Rain	2.4	20	8.1
24-09-2021	Rain	2.3	23	10
19-03-2022	Rain on snow	1.3	13	10

bypassing the catch basin's entrance. In these cases, the water did not reach the level of the weir box and did not flow into the bioretention cells.

The method used to sample water quality at the inlet of the bioretention cell was based on the automated collection of sequential grab samples (Ma *et al.* 2009). At the beginning of the event, discrete samples were taken every 5 min, and this interval gradually increased to 1 h between samplings. This approach estimates an event-averaged concentration without the need for an automatic flow-weighted sampler. The same method was used at the outlet, with the only difference being that they were done over 24 h or more. The sampling interval can be defined as 'first-flush enhanced', meaning that it is configured to collect discrete samples every 30 min during the first half of the sampling period and then every hour for the second half of the 24-h duration. This allowed for the collection of rainfall samples at the outlet throughout the entire drainage period of the bioretention system, which had a longer duration than water entering the bioretention cell.

Regarding groundwater, discrete samples were collected from the three piezometers on multiple occasions during the measurement campaign. In total, five sampling campaigns were conducted over the study period, with two sampling events corresponding to that of the inlet and outlet sampling. The groundwater sampling methodology follows the *Guide d'échantillonnage à des fins d'analyses environnementales (Sampling Guide for Environmental Analysis)* (MDDEP 2011). Prior to each sampling, piezometers were purged to obtain representative groundwater samples. The piezometers were purged slowly until stabilization of pH, dissolved O_2, electrical conductivity, and temperature to avoid disruption of the water in the column that could lead to errors in the data. A peristaltic pump was used to extract water from the piezometers. However, sampling in winter proved to be challenging due to frozen water, resulting in a limited number of winter samples.

The analysis of all the samples collected was divided between the laboratories at Polytechnique Montreal and the Interuniversity Research Group in Limnology and Aquatic Environment (GRIL) at the University of Montreal. The samples were transported and kept on ice. The following analyses were performed: ammonium (NH_4^+), dissolved organic carbon (COD), nitrate (NO_3^-), total nitrogen (TN), total phosphorus (TP), phosphate (PO_4^{3-}), sodium (Na^+), chloride (Cl^-), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^+), chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb).

Data analysis

The data were collected using the R (RCore Team 2023; RStudio Team 2023). The characterization of pollutant loads during a rainfall event is done using the event mean concentration (EMC) (McCarthy 2009). It is calculated as the total mass of the pollutant divided by the total runoff volume over an event:

$$\text{EMC} = \frac{\int C(t)Q(t)dt}{\int Q(t)dt}$$

Here, $C(t)$ and $Q(t)$ are time variables, respectively, for concentration and flowrate. In our study, flowrates were continuously measured using the instrumentation detailed in the sections above, whereas pollutant concentrations were dependent on sampling intervals. Thus, the EMC was calculated as a weighted average:

$$\text{EMC} = \frac{V_i}{\sum_i V_i} \cdot c_i = w_i \cdot c_i$$

The results of the groundwater samples obtained from the three piezometers were averaged for each sampled event, resulting in a single average value for the groundwater during each event. Since the piezometers are located at distinct points within BR4 (at the center and both ends), the average of the concentrations measured at these three locations was considered an adequate representation of the entire section of the groundwater that interacts with the bioretention cell.

RESULTS AND DISCUSSION

SWMM and drainage basin-scale hydrology

While previous research has largely relied on modeling simulations to assess the impact of bioretention cells on sewershed hydrology (see the Introduction section), our study offers a fresh perspective by directly measuring the accumulation and release of contaminants in bioretention cells. Our objective is to evaluate the real-world effectiveness of bioretention systems in reducing contaminants at the scale of an urban watershed, with a specific focus on their performance in a cold Quebec climate. This approach is particularly timely, given the evolving nature of this field and the scarcity of real-world data on bioretention systems in such climates. By examining the adaptation of bioretention systems in Trois-Rivières, our research has provided valuable insights into their practical application and performance in managing stormwater runoff in cold-weather conditions.

Indeed, at the large scale of the drainage basin, the implementation of bioretention cells does not appear to have any noticeable effectiveness. A comparison of the simulations with and without bioretention cells shows runoff volume reduction percentages of less than 1% for the four simulated events. Similar results were observed by Chen *et al.* (2019) in the Darst Sewershed area in Peoria, Illinois, where runoff volume reduction ranged from 0.18 to 2.8%. This finding can be explained by the limited area occupied by bioretention cells in relation to the drainage basin's size (1.9 versus 111.7 ha, respectively). In fact, there is a relationship of proportionality between bioretention cell efficiency and the percentage of the surface area covered by the cells (Autixier 2012; Autixier *et al.* 2014a). In the current study's case, the 54 cells along Saint-Maurice Street are not sufficient to generate enough impact on the entire area examined. Furthermore, a small creek has been channeled into the stormwater drainage network and provides an important constant flow.

However, at the local scale of Saint-Maurice Street, the comparison of simulations with and without bioretention cells shows a greater impact of bioretention on runoff volume, as seen in Figure 3. The average results are shown in Table 2. Modeled events show peak flow reductions of between 30 and 34.5% and runoff volume reductions of between 30 and 39%. Here, the effectiveness of bioretention cells is far more remarkable. Peak flows were significantly attenuated, with an average reduction of 33% for the four events studied, while runoff volumes were reduced by an average of 36%. These findings are in line with previous scientific work (Autixier *et al.* 2014a), which showed a decrease in flow volume ranging from 13 to 62% (Géhéniau *et al.* 2014) and demonstrated an average of 59.7% retention rate for warm seasons.

The objectives of climate change adaptation measures generally involve investigating ways to mitigate surge events. In this context, several studies have shown that bioretention cells are capable of reducing the number, frequency, and volume of sewer overflows and thus contribute to reducing their impacts on receiving environments (Autixier *et al.* 2014a). The design of resilient systems for urban hydrology under climate change with an anticipated increase of intensity and duration of precipitation events will require the characterization of the distribution of future flowrates and an investigation of peak flow and volume reductions as a function of bioretention implementation scenarios.

In our study, the sewer network in this area was a separate sewer system prior to the construction of the project (apart from a 300 m section that was combined). The City of Trois-Rivières opted to overhaul the entire sewer system in the area into a separate system, meaning these flowrates no longer contribute to combined sewer overflows. However, modeling results suggest that the addition of bioretention cells, without separating the sewers and removing the flow of the sewered creek, would not be sufficient to reduce overflows without a large increase in the surface area of bioretention cells throughout the drainage basin. This insight highlights the necessity of comprehensive multicriteria decision analyses to guide urban planning and policy decisions. By comparing the costs, benefits and co-benefits of bioretention cells with those of the other combined sewer overflow reduction strategies, stakeholders can gain valuable insights into the most effective and economically viable solutions.

A detailed economic analysis can reveal the relative cost-effectiveness of implementing a fully separated sewer system versus expanding the bioretention cell network. Such comparisons are essential to consider as many combined sewers have not reached the end of their useful life, and green stormwater infrastructure potentially offers a solution for preventing urban flooding at a local level. Furthermore, as cities integrate life-cycle analyses into their

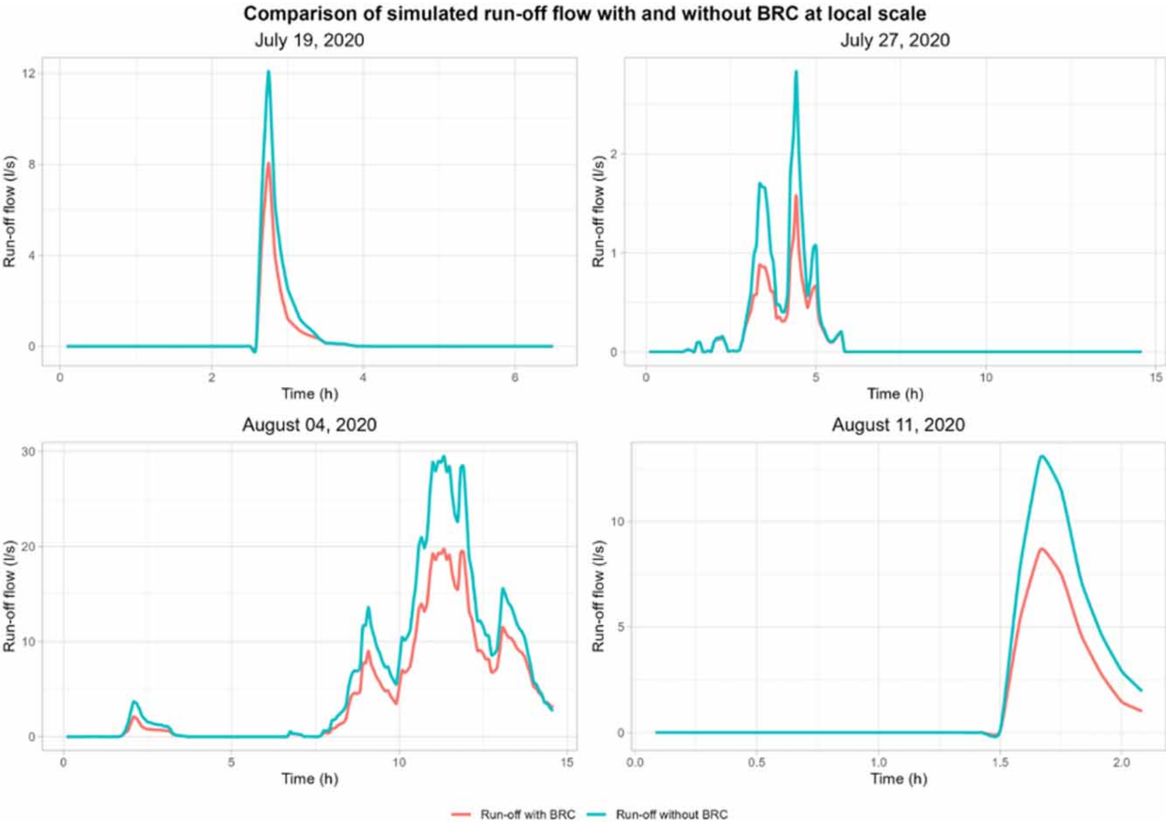


Figure 3 | Comparison between simulated flow with and without BRCs at the local scale (July 19th, 2020; July 27th, 2020; August 4th, 2020; August 11th, 2020).

Table 2 | Percentages of runoff volume reduction and peak flow reduction by bioretention cells for the four events modeled on the SWMM at the drainage system scale and the local system scale

Event	Drainage basin scale (111.7 ha) Average runoff volume reduction (%)	Local basin scale (16.6 ha) Average runoff volume reduction (%)	Local basin scale (16.6 ha) Average peak flow reduction (%)
19-07-2020	0.91	37	33.4
27-07-2020	0.63	39	34.5
04-08-2020	0.70	30	30
11-08-2020	0.35	37	33.5

infrastructure decision-making to mitigate overall emissions, data are needed on how much peak flow and contaminant release can be achieved with the addition of green stormwater infrastructure. Detailed modeling of the evolution of bioretention cell performance over time, considering factors such as clogging and vegetation growth, could also provide valuable data concerning the limits of bioretention cells in cold climates and their long-term effectiveness.

Bioretention cell hydrology

Groundwater

The water table depth exhibited seasonal variations, peaking in winter and early spring before declining in summer. Depths ranged from 0.8 to 1.4 m between February and April and from 1.1 to 1.7 m from June to October (Figure 4). The recorded elevated water table levels suggest periods when groundwater likely exceeded the level of the BR4 drains, which are situated at a depth of 1.40 m. This suggests potential interactions between groundwater and the water filtered by the bioretention cell, which may b collected by the drain during sampling periods. At these identified periods, it will be essential to consider groundwater in interpreting water flow and quality data collected at the bioretention cell outlet.

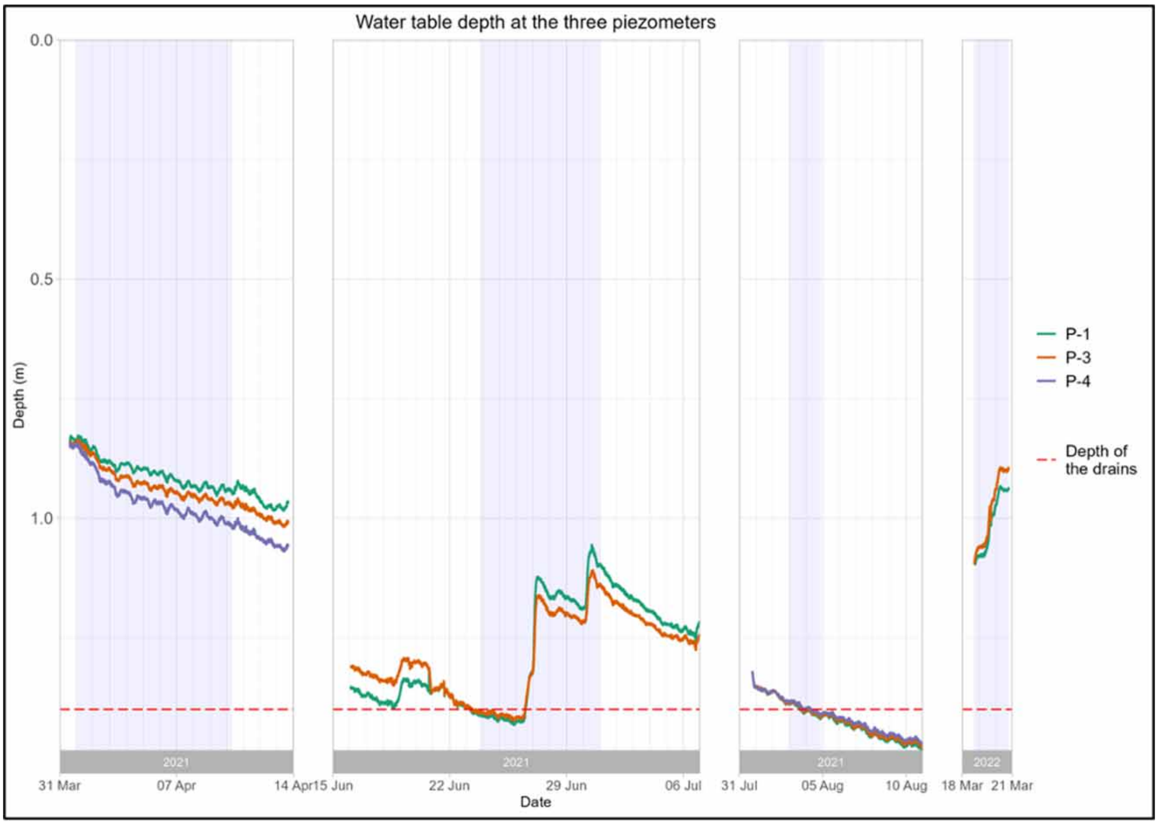


Figure 4 | Groundwater depth within piezometers 1, 3, and 4.

Depth data identified two intervals during which there were no interactions between the groundwater and the filtered water: June 23 to June 26, 2021 and August 04 to October 09, 2021. The observed continuous flow in the bioretention system's outlet well, even when the water table is assumed to be below the drains, suggests that the water table may have been above the drains during certain intervals that were previously identified as having no interactions between the groundwater and the filtered water. Such intervals were identified twice: the first extended from June 23 to June 26, 2021, and the second covered a few hours on August 04, 2021.

Regarding the first interval, the water table depth varied between 1.39 and 1.43 m. Since the drains have a depth of 1.40 m, the water table was 3 cm below the drains at its lowest level. However, given the challenges encountered during data processing, this difference was considered negligible compared to errors related to data calibration. As for the second interval, the groundwater depth curves indicated that during August 2021, the groundwater level was decreasing. However, this second interval corresponded to the period around which the water table would have passed below the drains. Uncertainty remains about the exact moment when the shift of the water table on either side of the drains could have occurred. For these two intervals, conclusions drawn from flow data were, therefore, retained like those derived from groundwater depth data.

Water inlet

For four of the events sampled, the water level was sufficient to reach that of the weir box. We are therefore able to obtain the flowrate at the bioretention inlet. In contrast, for the March 19, 2022 event, the water level did not reach that of the weir box due to low rainfall, consequently impeding both the flowrate and EMC measurement. Rainfall depth measurements were obtained from the nearest meteorological station operated by the City of Trois-Rivières, located 1.3 km from the site, and from the Environment Canada's station located at a distance of 12.5 km (see Figure S1, Supplementary Material). As shown in Figure 5, there is a slight delay between the onset of rainfall and the recorded inflow into the inlet well. This delay could be due to spatial variability of rainfall and rainfall measurements.

The four other events exhibited sufficient runoff to supply the bioretention cell after filling the sedimentation pit. For the events of March 26th, 2021, June 8th, 2021, and June 26th, 2021, we note that the level inside the inlet

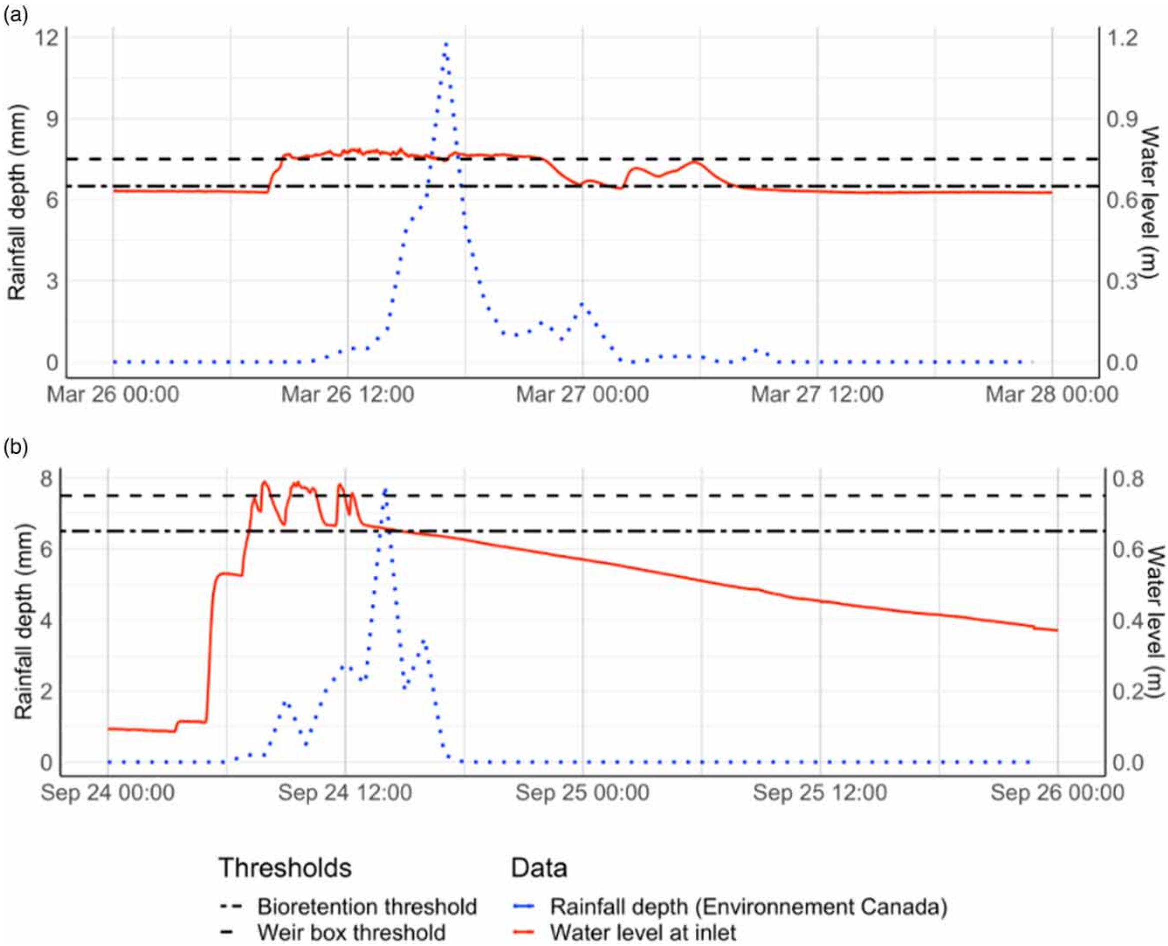


Figure 5 | Inlet water level and rainfall on (a) March 26th, 2021 and (b) September 24th, 2021.

sump before the onset of rain and after the event is high. The water level in the inlet sump after the end of the event decreases very slowly. In comparison, during the September 24th, 2021 event, the level in the sump was initially low and quickly returned to this level after the sampled event. This observation indicates the inlet sump is not watertight and allows runoff water to infiltrate into the ground and groundwater to infiltrate into the sump. During the thaw period (March–April), the catchment of runoff water by the sump, combined with low temperatures and a high water table, seems to maintain a high level in the inlet sump. During this period and until the end of July, the bioretention system can be called upon more frequently, as the margin between the base level in the sump and the discharge threshold to the bioretention system decreases slightly. This compares with the dry period (August–October) when the water table is lower. During this period, the bioretention system is hardly used at all, as the level in the sump is kept too low. Therefore, only major rainfall events can bring sufficient runoff to the inlet to allow the level to reach the weir threshold.

The four other events exhibited sufficient runoff to supply the bioretention cell after filling the sedimentation pit. The events of March 26th, 2021, June 8th, 2021, and June 26th, 2021 presented similar results, and the plot for March 26th, 2021 is observed (Figure 5(a)). For these three events, the water level inside the sedimentation pit was high prior to the start of rainfall and remained high after the sampled event ended. The water level in the pit decreases slowly following events. In comparison, during the event on September 24th, 2021 (Figure 5(b)), the water level in the pit was low and returned to this level after the sampled event. This observation confirms that the pit is not watertight and that this design has a major impact on the performance of the bioretention cell, as it allows runoff water to infiltrate into the ground but also allows groundwater to infiltrate into the pit.

Considering the observed levels of groundwater on site, we can conclude that the conditions during the thaw period (March–April), along with the collection of runoff water by the pit, combined with low temperatures and a high groundwater level, maintained a relatively high water level in the pit. Thus, during this high water table period until the end of July, the bioretention cell received water more frequently in contrast to the drier period (August–October) when the groundwater level is lower, and the pit must fill before water enters the bioretention cell. During the drier period when the groundwater table decreases, the bioretention cell is only minimally used. Only major rainfall events can provide sufficient runoff at the inlet to allow the water level to reach the weir's threshold.

During the four events that generated enough stormflow to fill the sedimentation pit up to the weir, a variation in the water level between the two threshold lines of the bioretention cell and the weir was observed. For instance, in the event of March 26th, 2021, the water level rose until it reached the weir's level and then stabilized above this line. This indicates that the water filled the box and entered the bioretention cell through the dedicated pipe. Then, as the rainfall event continues, precipitation gradually decreases, as does runoff, and we observe that the level in the pit decreases rapidly once it falls below the weir's threshold, stabilizing at the threshold of the pipe leading to the bioretention cell. This observation indicates that the weir box was not completely watertight, despite the sealant used for water loss prevention, and that the water in the pit can exit through other points. However, this loss from the measurement system is negligible compared to the flow entering through the 'V-Notch' weir.

Water outlet

Among the five monitored outflow events between 2021 and 2022, two remained below the detection threshold (24-09-2021 and 19-03-2022) and two exceeded the measurement capacity (26-03-2021 and 08-06-2021). For the June 26th, 2021 event, the water levels reached the level of the outlet 'V-Notch' weir, and a continuous outflow from the bioretention cell was measured (Figure 6). The continuous base outflow, event peak flow, and the following gradual reduction characterizing the drainage period were measured.

It is interesting to note that no accumulation of water was observed in the bioretention cell area over the study. For all events, the bioretention system was able to accept and infiltrate the water input, including an extreme event of 392 mm of rain that flooded parts of the City of Trois-Rivières on June 08, 2021. The outflow during this event was such that it exceeded the measurement capacity noted by the plateau on the curve during the V-notch flooding, even though the equipment was designed for submergence situations. The second event during which the outflow exceeded the measurement capacity occurred during the thaw and was due to heavy rain in addition to the snowmelt (26-03-2021). Additionally, while rainfall occurred on June 26th, the peak flow at the outlet was observed on June 27th. This delay is due to the time required for the water to travel through the bioretention cell and reach the outlet, resulting in peak flow measurements being recorded on the day following the rainfall event.

For the event on September 24th, 2021, we were unable to obtain a flowrate measurement due to excessively low water levels in the outlet well. It can be noted that with the water input from the event, the level gradually increased until September 26; however, according to the recorded data, this level never reached the weir. This issue is only visible in the event sampled during the dry season when the water table is lower, and the soil's infiltration potential is higher. Therefore, to obtain a flowrate measurement at the outlet of the bioretention cell, the presence of a base flow is necessary for the water level to reach the 'V-notch' threshold.

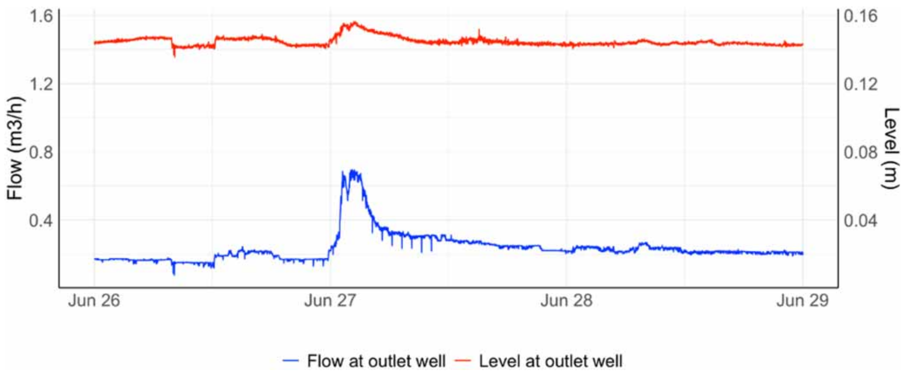


Figure 6 | Hydrograph at the outlet basin for the event sampled on June 26th, 2021.

To summarize, similarly to the inlet of the bioretention system, a base flow was required to allow the drainage flow reading. The research team also faced data collection issues with the ultrasonic transducer. However, it is important to note that no water accumulation was observed on the bioretention cell over the entire study period. The bioretention cell was effective in draining the collected runoff water.

Water quality

Overview

Over the five sampled events between 2021 and 2022, two gave complete results (inflow and outflow) to analyze water quality: March 26th, 2021 and June 26th, 2021. Over these two events, we observed a release of nitrogen, particularly in the form of nitrates. It is also notable that the NO_3^- release was more important during the thaw period. Indeed, during the rainfall on June 26th, the release observed for nitrates is lower, and for TN and NH_4^+, there is removal. In a bioretention system, the release of nitrogen would be attributed to the decomposition of nitrogen-rich organic matter by microorganisms in the soil (Li & Davis 2014). This observation is typical of new bioretention cells, as there was compost in the installed substrate, but the NO_3^- in the substrate tends to decrease with time (Dagenais *et al.* 2022). Also, as the plants are in dormancy in the winter, they do not absorb as much NO_3^-.

The process of ammonium removal or nitrification is slowed down by cold temperatures (Ding *et al.* 2019). NO_3^- removal relies on vegetation presence, which is more active during the summer and may not absorb as much ammonium as observed on June 26th, 2021.

For the two sampled events, we noted an emission of COD. This phenomenon is attributed to the breakdown of organic matter from animals or plants. Various factors may contribute to this increased release, such as the presence of de-icing salts during thaw periods, decreased temperatures, and diminished vegetation coverage (LeFevre *et al.* 2015). However, the concentrations observed for the two events are relatively low in comparison to those found in the natural environment, hence precluding their role in manganese release.

Regarding Cl^- and Na^+ concentrations, removal is observed in March, while release is observed in June. The first event occurs during the thaw period when de-icing salts are still being used. These observations may be due to the time it takes for the salt to be absorbed and then released later (Lawson & Jackson 2021). Analyzing more events would be necessary to conclude these contaminants. However, it can be noted that for the two events in question, the observed concentrations are not a concern and remain below aesthetic quality objectives (Health Canada 2022).

The results also revealed that iron was removed by 96.86% (Table 3), consistent with the literature that indicates iron is typically retained in bioretention systems. This retention could be influenced by several factors. Iron and other metals often absorb strongly organic matter and clay particles in the soil media, a process facilitated by the high surface area and cation exchange capacity of the bioretention substrate (Zhang *et al.* 2023). Additionally, at neutral to alkaline pH levels, many heavy metals precipitate as insoluble hydroxides or carbonates, further enhancing their retention.

Manganese concentration time series

For manganese, Health Canada provides two recommendations: a maximum acceptable concentration (MAC) of 0.12 mg/L and an aesthetic objective of 0.02 mg/L (Health Canada 2022). The technical document from Health Canada related to manganese (Health Canada 2019) reports that some human studies have suggested a potential link between manganese in drinking water and certain neurological effects in children. The effects observed in children align with the neurological effects seen in key animal studies used to establish the MACs. These effects include behavioral disorders, changes in intellectual function, reduced academic performance, short-term memory, and motor dexterity. However, this complex association depends on factors such as age, gender, and nutritional status. The uncertainties related to the methodology used in these epidemiological studies, including the assessment of manganese intake and confounding factors, as well as the variability in results, prevent us from concluding a causal link between these effects and the presence of manganese in drinking water. Nevertheless, numerous animal studies appear to support the biological plausibility of these effects. Notably, the drinking water quality criteria are based on effects observed in rodents exposed to manganese during the first few months of their lives (World Health Organization 2011). Concerning aesthetic considerations, the presence of manganese in drinking water often raises consumer complaints about water color, which is why Health Canada recommends an aesthetic objective.

Table 3 | EMCs and removal percentage for each monitored event (red = release; green = removal)

POLLUTANT	26/03/2021			26/06/2021		
	Inlet (340 samples)	Outlet (480 samples)	Removal rate (%)	Inlet (260 samples)	Outlet (300 samples)	Removal rate (%)
Ammonium NH4 (µg/L)	130,19	233,89	-79,65	442,60	261,49	40,92
Nitrate NO3 (µg/L)	154,47	2865,80	-1755,21	142,24	720,78	-406,74
Total nitrogen NT (µg/L)	499,36	3527,86	-606,47	6354,76	1804,55	71,60
Phosphate PO4 (µg/L)	8,77	2,52	71,33	4,99	10,97	-119,92
Total phosphorus PT (µg/L)	240,33	15,03	93,75	2937,15	102,34	96,52
Dissolved Organic Carbon DOC (mg/L)	4,25	5,41	-27,41	7,91	13,01	-64,56
Chlorides $Cl\ (mg/L)$	209,76	61,83	70,53	16,67	31,65	-18,65
Sodium $Na\ (mg/L)$	182,71	14,55	92,04	31,25	91,22	-191,91
Magnesium $Mg\ (\mu g/L)$	2987,33	1778,72	40,46	15829,86	4702,48	70,29
Calcium $Ca\ (\mu g/L)$	56817,14	22543,99	60,32	161261,26	43134,17	73,25
Potassium $K\ (\mu g/L)$	2099,06	1637,49	21,99	5440,14	4678,75	14,00
Chromium $Cr\ (\mu g/L)$	10,12	0,16	98,41	65,73	1,47	97,76
Manganese $Mn\ (\mu g/L)$	136,28	37,52	72,47	463,23	805,22	-73,83
Iron $Fe\ (\mu g/L)$	6514,56	204,62	96,86	33302,02	6264,22	81,19
Nickel $Ni\ (\mu g/L)$	11,05	0,28	97,47	96,36	2,48	97,42
Copper $Cu\ (\mu g/L)$	21,39	0,86	95,97	171,83	11,18	93,49
Zinc $Zn\ (\mu g/L)$	178,04	2,15	98,79	1120,68	759,44	32,23
Cadmium $Cd\ (\mu g/L)$	0,09	0,00	97,21	0,96	0,06	93,34
Lead $Pb\ (\mu g/L)$	5,55	0,08	98,61	34,53	1,74	94,96

For manganese, we observed removal by the bioretention cell during the event on March 26th, 2021 and a release during the event on June 26th, 2021. The time series illustrated in Figure 7 allows us to see that during the second event, the release is a matter of concern because manganese concentrations are well above the maximum acceptable concentration for drinking water and the prevention criterion for surface waters. During this last event, there is an interaction with the groundwater, meaning that the groundwater would have been captured by the bioretention system's drains due to the high groundwater level. However, while manganese levels in the groundwater surpassed Quebec government criteria, they remained significantly lower than the amounts discharged by the bioretention cell. Likely, the bioretention cell has contributed to the release of this contaminant.

In Québec, many community water systems are supplied by groundwater with high concentrations of manganese that could have neurotoxic effects associated with intellectual impairment of children (Bouchard *et al.* 2011). Manganese in groundwater originates from the soil and sediments. Stormwater can also contain manganese from sources including the wear from vehicles and soil dust (McKenzie *et al.* 2009). Organic matter entering groundwater has been shown to increase the dissolution and mobility of metals such as manganese (Neidhardt *et al.* 2014). Over the study period, the groundwater data appear to show a gradual increase in manganese concentrations in the groundwater, exceeding criterion values. During the study period, the consistent outflow observed during dry periods, coupled with groundwater depth data (piezometers) compared to the bioretention's perforated drain depth, indicated continuous groundwater infiltration into the BR-4 drains. This implies that the groundwater table is positioned above the drain level.

Six comparative samplings identified periods of groundwater–bioretention cell interaction (communication from the Trois-Rivières City). Of these six, four revealed interactions coinciding with observed increased manganese concentrations on June 8, 2021, June 26, 2021, and March 19, 2022 events.

While the hypothesis was based on a limited number of event comparisons, the Mann–Whitney *U* Test and principal component analysis (PCA) were employed on pooled data to compare medians across independent sampling locations and assess potential correlations with other water quality parameters, both with and without groundwater interaction (see Supplementary material, Figures S3 and S4). The Mann–Whitney *U* Test *p*-value of 0.000821, significantly less than the alpha level of 0.05, confirmed a significant difference between groundwater and bioretention inlet manganese medians. Additionally, the PCA supported the clustering of outlet and groundwater samples, particularly in relation to manganese and other heavy metals.

The permeability of the inlet basin or inadequately positioned or designed inlet grates could impact the heavy metals' (Mn and Fe) concentrations in the groundwater. It can result in either inlet clogging, diverting stormwater away from the bioretention cells, or the creation of a hydraulic gradient that drives water toward the

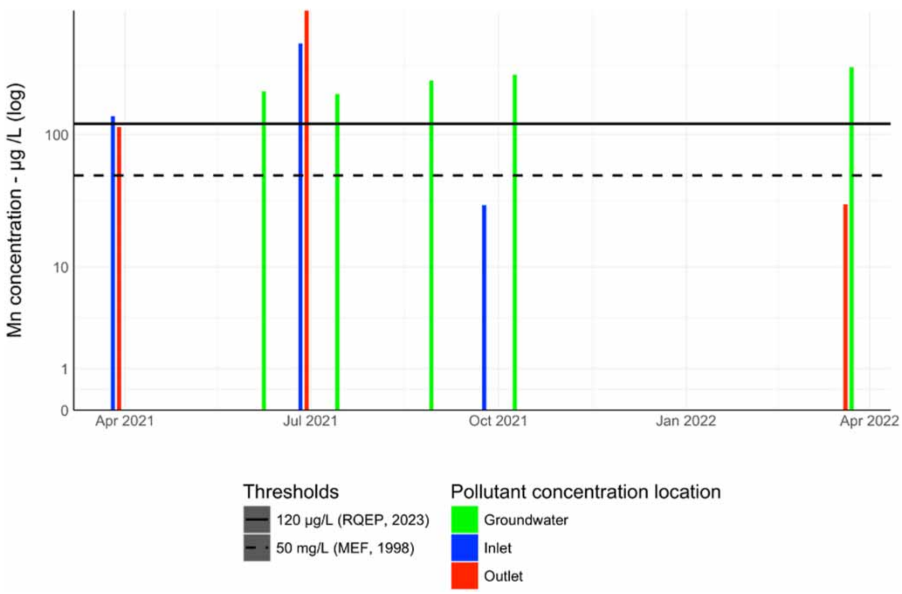


Figure 7 | Time series of manganese concentrations at the inlet and outlet of the bioretention cell (EMC) and in groundwater (mean concentration).

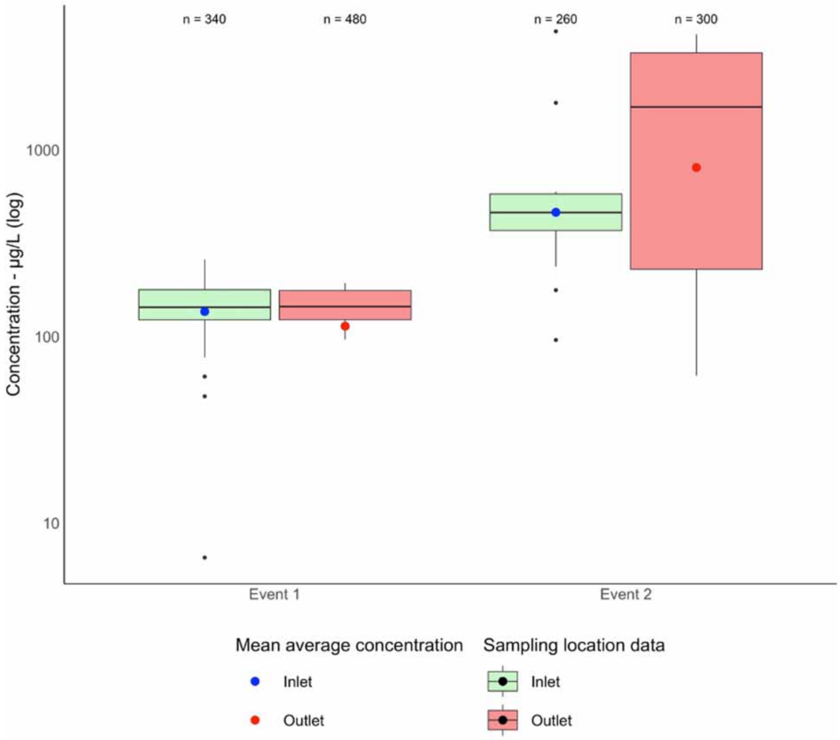


Figure 8 | Variability of the measured manganese concentrations in relation to event mean square concentrations for the two complete sampled events.

groundwater. Similar results or potential effects on groundwater quality associated with infiltrating stormwater have been observed in several studies (Zhang & Chui 2017; Edwards *et al.* 2022; Nazarpour *et al.* 2023).

The distribution of data for both fully sampled events is shown in Figure 8. Firstly, for EV1, the event on March 26th, 2021, we observed little variability between the values, with the median being equal for the inlet and outlet. This reveals consistency among the values, centered around the central value of the median. However, we observed several extreme values at the inlet. This suggests that the observed removal, and hence the performance of the bioretention cell for this event, could have been underestimated. Secondly, for EV2, the event on June 26th, 2021, we observed a large variability between the data at the outlet. The central values of the diagrams are more distant from each other than the values of the EMCs.

For the first event (for which we concluded removal), the difference in median values was not significant. Whereas for the second event (for which we concluded release), the central values of the represented data demonstrate a distinctly more pronounced difference.

It is important to consider the distribution of pollutant concentrations based on runoff volume and flow. In the sampled events, the release of manganese during the second event (EV2) appears to be linked to higher runoff volumes, suggesting that increased flowrates may have remobilized contaminants, including manganese. This pattern suggests that pollutant concentrations, especially during peak flow periods, are influenced by the volume of runoff passing through the system. To better understand the mechanism behind manganese release and retention, a detailed analysis of the relationship between runoff volume and manganese concentrations is necessary. Furthermore, a comprehensive, long-term evaluation of manganese behavior is essential to confirm trends and gain insights into the mechanisms. Additionally, exploring potential modifications to the bioretention cell design or operation could enhance its effectiveness in managing manganese, particularly under varying groundwater conditions and high runoff volumes.

CONCLUSIONS

A full-scale study of bioretention cell effects on local and sewershed hydrology and water quality was conducted. Novel data were generated in support of the protection of cold climate groundwater sources of drinking water, particularly in areas vulnerable to manganese contamination. While considering the challenges and limitations in data collection from the monitoring system, the following conclusions can be drawn:

- Measurements of inflows, outflows and groundwater demonstrated that groundwater was being drained from the system and that not all events had sufficient precipitation to reach the bioretention cells from the inlet basin.
- Most events were captured by the inlet basins that were not sealed and could be a route of groundwater contamination from contaminated runoff.
- Inlet basins should not be oversized to ensure water flow to bioretention cells; they should be designed to avoid the accumulation of debris at their entrance.
- Water table variability and depth must be considered when identifying the most suitable locations for the implementation of bioretention cells. However, even with groundwater drainage, bioretention cells were effective in reducing runoff volumes and peak flows generated from the sector where they were implemented. The reduction of peak flows and volumes is an important consideration for low-lying regions with high water table depth vulnerable to flooding or sewer overflows.
- At a sewershed scale, a sewered creek largely masked the effects of bioretention cells. Efforts to daylight creeks and separate them from combined sewers are options to consider given the large areas of green stormwater infrastructure that would be needed to significantly reduce peak flows at a sewershed level where creeks have been sewered.
- Bioretention cells were effective for reducing most of the measured metals including iron and TP even in cold water. Nitrogen compounds and COD were variably released into the outlet water.
- Manganese is a concern for drinking water and the potential to increase its mobility was observed. Further study is required to observe the long-term trends of manganese in groundwater and in the outlet water from bioretention cells, which is important for communities that rely on groundwater for drinking water.
- Decisions related to contaminants and contaminant removal by green stormwater infrastructure must consider the balance among the various competing needs for aquifer recharge for water supply, urban flood mitigation, reduction of downstream combined sewer overflows and the various uses of the water resource.
- Although cities typically select sites for green stormwater infrastructure implementation based on required upgrades to sewer infrastructure or correction of specific problems, there is a need to improve overall planning to implement the infrastructure where it will provide the greatest benefits relative to costs. Multicriteria decision analysis including life-cycle analysis could provide additional insight.
- Future research should investigate the reduction of peak stormwater flows and volumes in relation to bioretention implementation scenarios for a variety of return periods considering climate change. Critical scenarios should be evaluated to identify potential additional mitigation measures to ensure the resilience of urban stormwater systems and community safety.

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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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