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Analyzing the hydrological behaviour of bioretention cells: insights from field data and SWMM modelling

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Abstract

Bioretention cells (BRCs) are widely implemented in urban areas to manage stormwater runoff and reduce pressure on drainage systems. However, their actual performance often diverges from design expectations due to construction constraints and site-specific conditions. This study compares water retention in 31 BRCs located in Montreal, Canada, as simulated with the Storm Water Management Model (SWMM) and observed through field data collection. BRCs were selected for analysis based on their impervious-to-permeable (I/P) ratio and physical characteristics. The field data comprised water level measurements taken by pressure probes and rainfall data provided by the city, used to analyze the hydrological behaviour of the BRCs during the non-freezing season (May to November). Results for four randomly selected BRCs are presented herein. For one of them, the simulated and observed water retention were close, with a Nash-Sutcliffe efficiency value of 0.74 and a strong positive correlation. For the other three, differences were observed between modelled and observed data, attributed to deviations between design (modelled) and field-built conditions, as confirmed by field visits during rainfall events. These results highlight the need to consider the physical limitations of the BRCs in the field and their construction characteristics, such as elevated inlets or poorly directed street slopes, when assessing their performance.

Highlights

- SWMM helped identify variations between field-built BRCs and their design specifications.
- The I/P ratio, vegetation, and physical characteristics affect BRC retention and infiltration capacity.
- Fieldwork and modelling results showed that BRCs' construction defects limited runoff capture.

Introduction

Bioretention cells (BRCs) are an essential component of sustainable urban drainage systems, commonly employed to manage stormwater by enhancing infiltration, removing pollutants, and reducing peak flows in urban catchments (Bonneau et al., 2021; Nazarpour et al., 2023). Previous studies have shown the importance of incorporating modelling tools, such as SWMM (Rossman & Simon, 2022), to predict the BRCs' hydrological behaviour and their effectiveness under diverse environmental conditions (Bonneau et al., 2021) and construction designs (Sagrelius et al., 2023). Recent investigations have examined the limitations and capabilities of hydrological models in reproducing the water dynamics within BRCs. Comparisons of field data with model outputs have highlighted discrepancies, which, according to the reviewed literature, may arise from modelling assumptions. These assumptions include representing BRCs with rectangular cross-sections (Bond et al., 2021), uncertainties related to model parameters (Tansar et al., 2023), or deviations between constructed features and original design specifications.

SWMM, developed by the US EPA, is one of the most frequently used models for simulating low-impact development (LID) practices (Pons et al., 2023). The LID module simplifies the representation of each BRC by using a layered system to model the various components, including surface storage, soil media, and drainage layer (Bond et al., 2021). This module also enables the integration of BRCs into the broader urban drainage network, allowing more accurate design and implementation of urban runoff control measures. SWMM is often preferred over other models due to its open-source availability and, more recently, the capacity to integrate the SWMM interface with Python, for example, Pyswmm (Mcdonnell et al., 2020), which utilizes SWMM's computational engine. Despite the advancements in modelling capabilities, accurately simulating the hydrologic performance of BRCs remains challenging due to the complex interplay of factors such as soil properties, vegetation type, antecedent moisture conditions, and the spatial variability of rainfall within urban catchments (Lisenbee et al., 2021; Vijayaraghavan et al., 2021).

Various studies have reported inconsistencies between SWMM simulations and observed water levels in BRCs, particularly within the filter media (Bonneau et al., 2021; DeBusk et al., 2011; Fournel et al., 2013). These differences can be attributed to model simplifications, such as the use of a single-permeability approach (i.e., assuming uniform infiltration across soil layers), vegetation (type and density), neglect of preferential flow paths, soil (type, layer thickness, and void ratio), or oversimplified representation of soil-water interactions (e.g., capillarity, air entrapment), which can lead to poor replication of water level dynamics (Fournel et al., 2013; Lisenbee et al., 2021; Tansar et al., 2023). Another significant challenge arises from discrepancies between the construction process and initial design assumptions. Real-world construction often deviates from original design specifications due to unforeseen site conditions, material availability, or practical construction constraints, impacting the overall performance of BRCs (Bond et al., 2021; Sun et al., 2019). Therefore, a comprehensive comparison of SWMM's results against actual field measurements is important to improve modelling accuracy, redefine design practices based on the observed discrepancies between design intentions and construction realities, and support more reliable design practices for stormwater control within urban environments.

The poor agreement between modelled and observed data can highlight the need to better understand BRC infiltration and retention processes under different design configurations and precipitation patterns to optimize their design and application (Li et al., 2021; Sagrelius et al., 2023; Vijayaraghavan et al., 2021). In this context, understanding the extent and sources of discrepancy between simulated and real-world behaviour remains essential to improve predictive reliability.

More specifically, the objectives of this study were to assess the model's effectiveness in reproducing water level dynamics within the surface of the studied BRCs, to evaluate the consistency between design assumptions and field measurements, and to identify potential sources of errors. The outcomes of this study aim to support more accurate and robust bioretention modelling.

Materials and methods

Study area and bioretention cell selection

Out of the 82 BRCs constructed in 2021 and 2022 within the Rosemont-La-Petite-Patrie borough in Montreal, 31 were chosen and equipped with an Onset HOBO U20 BASE-U-4 pressure probe to estimate water levels in the BRCs. These probes were programmed to record data at five-minute intervals and had data storage capacities sufficient for two months of continuous measurements with a typical measurement error of ±0.075% of the full-scale (±0.3 cm water depth). Details on the probe installation are provided in a later section (see Instrumentation and field data collection).

In collaboration with the city, two criteria were used to select the BRCs for field measurements. The first criterion was based on their impervious drainage area to permeable surface area (I/P) ratio, while the second focused on the physical characteristics of the BRCs, including the number of entry points (cell inlets), drainage type (presence/absence of an overflow sump), and type of entrance (presence/absence of sediment trap). To ensure a diverse dataset, the BRCs with the highest I/P ratios and different physical characteristics highlighted above were prioritized. The I/P ratio was used to identify the BRCs that receive the highest runoff volume, resulting in a greater retention depth. In this paper, the results for a subset of four BRCs (see Figure 1) are presented as an initial evaluation.

The BRCs were located to capture stormwater runoff from adjacent impervious surfaces such as roads and sidewalks, thereby decreasing the load on the municipal drainage system. Each BRC consists of a surface ponding area, including perennial plant species adapted to the Quebec climate, which can survive the winter without requiring annual replacement, plus an engineered soil layer. However, the proportion of vegetation fluctuates with seasonal changes, impacting the hydrological performance of BRCs throughout the growing season.

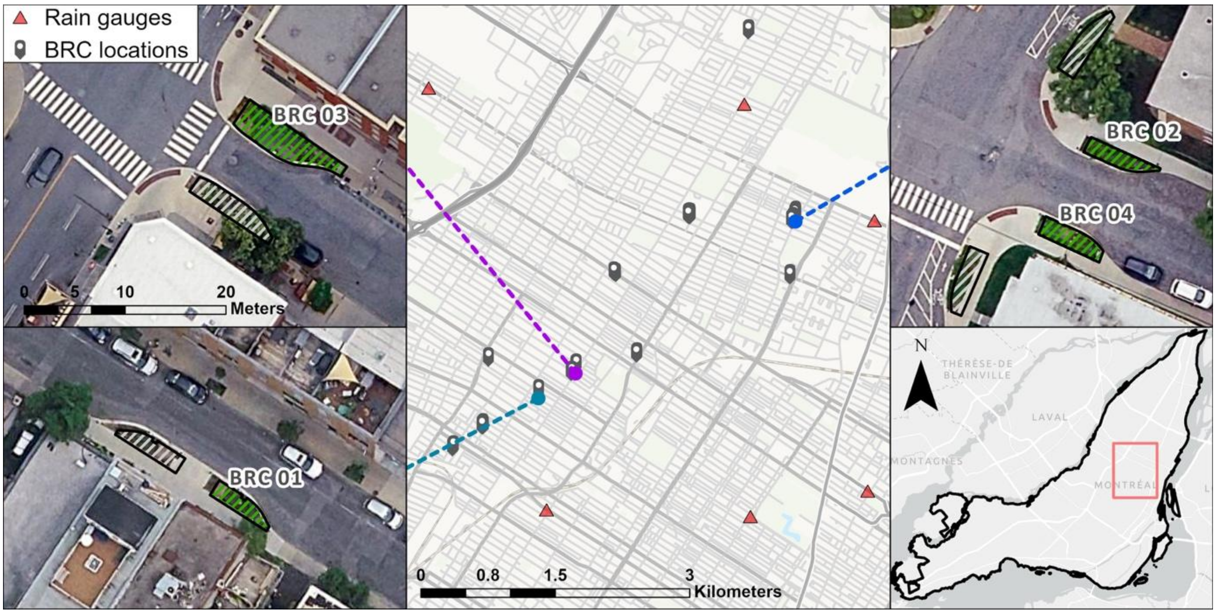


Figure 1. Location of the selected BRCs and rain gauges in the Rosemont–La Petite-Patrie borough, Montreal

The city provided detailed design characteristics of the selected BRCs, including BRCs area, contributing sub-catchment area, hydraulic conductivity, and expected infiltration time. According to the provided design parameters, the LID control parameters for the four selected BRCs are summarized in Table 1. Rainfall data, recorded at a 5-minute time step, were obtained from the city's rain gauge network, and then inverse distance-weighted (IDW) interpolation (Shepard, 1968) was performed using the three closest stations to each BRC.

Table 1. BRCs design parameters

Layer	Parameter	Units	BRC 01	BRC 02	BRC 03	BRC 04
Surface	Area	m^2	10	11	30	12
	Berm height	mm	230	400	400	400
	Vegetation volume	fraction	0.1	0.1	0.1	0.1
	Surface roughness (Manning's n)	-	0.3	0.3	0.3	0.3
	Surface slope	m/m	0.33	0.33	0.33	0.33
Soil	Thickness	mm	1000	450	450	450
	Porosity	Volume fraction	0.35	0.35	0.35	0.35
	Field capacity	Volume fraction	0.121	0.121	0.121	0.121
	Wilting point	Volume fraction	0.057	0.057	0.057	0.057
	Conductivity	mm/h	25	25	25	25
	Conductivity slope	Volume fraction	44	44	44	44
	Suction head	mm	50	50	50	50
Storage	Thickness	mm	0	0	0	0
	Seepage rate	mm/h	72	37.08	165.2	37.08

Instrumentation and field data collection

Each pressure probe was placed into a perforated pipe and inserted into the soil (see Figure 2). The perforated pipe was buried approximately 25 cm deep and extended 5 cm above the ground. These measurements were chosen according to the physical characteristics of the existing BRCs. Data were recorded during two separate periods, as only 16 pressure probes were available. The first monitoring period was from May 18 to August 16, 2023, and the second period was from August 16 to October 31, 2023.

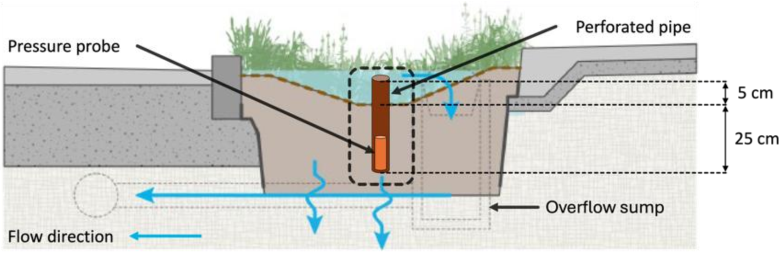


Figure 2. Schematic representation of pressure probe location in BRCs

Data integration and preliminary analysis

Rainfall data, hydraulic and physical parameters of the BRCs (berm height, soil thickness, BRC areas, seepage rate, and soil conductivity) from the city, as well as data collected from the pressure probes, were analyzed to provide a preliminary assessment of the behaviour of the selected BRCs. Subsequently, all the data were processed to verify temporal alignment across datasets (rainfall data, observed measurements, and simulated results); when necessary, observed measurements were interpolated. Finally, water levels gathered from field data were compared with results from PCSWMM (CHI, 2023) to identify the parameters in the LID control module from the SWMM model that significantly influence the model's accuracy in predicting water levels.

Model evaluation criteria

To evaluate the model's effectiveness in reproducing the measured water levels, four metrics were selected to assess the type of differences that may arise during the evaluation:

- The Nash-Sutcliffe Efficiency (NSE), a dimensionless measure, evaluates the goodness-of-fit between simulated and observed data, with values ranging from $-\infty$ to 1.0. Values closer to 1 indicate a better performance, while values below zero indicate very poor performance (Shamsi & Koran, 2017).

- The Kling-Gupta efficiency (KGE) is a dimensionless metric that considers multiple aspects of model performance in a single metric. It evaluates how well the simulated data matches the observed data in terms of shape (correlation), average magnitude (bias), and dispersion (variability). Values close to 1 indicate better agreement between model predictions and observations (Gupta et al., 2009).
- The Percent Bias (PBIAS) estimates the mean of errors in the same units (e.g. mm) as the variable being analyzed, which facilitates the interpretation of the results. A PBIAS of zero indicates a perfect match; a positive value indicates overestimation, whereas a negative value indicates underestimation (Moriasi et al., 2007).
- The Pearson correlation (r) coefficient assesses the overall trend or shape agreement between the observed and simulated data rather than the magnitude, making it valuable for comparing curve patterns. However, because the *r* coefficient is sensitive to extreme values and does not detect systematic shifts or proportional differences between series, it has limited ability to fully assess model accuracy. A value of 1 indicates a perfect positive linear correlation, -1 a perfect negative correlation, and 0 indicates no linear relationship (Moriasi et al., 2007).

Results and discussion

General observations for the 31 bioretention cells

Preliminary analysis of the field data showed that the retention and infiltration capacity of the BRCs varied depending on their design, the characteristics of the contributing watershed, and the presence of vegetation. Some overflows occurred from BRCs with smaller depression depths and larger contributing areas, highlighting the impact of the I/P ratio. Some BRCs maintained constant water levels below the surface, suggesting issues with the underlying soil conditions or a low infiltration capacity. Vegetation, such as trees, enhances the efficiency of BRCs, including increased infiltration rates and reduced standing water levels. This configuration is specific to the local design practice in Montreal, where trees are often integrated into BRCs to improve hydrological function.

Specific results for 4 of the 31 bioretention cells

Figure 3 shows the simulated and observed water levels at the surface along with the corresponding rainfall data for the four selected BRCs. The results for BRCs 02 and 04 cover the period from August to October and include two significant rainfall events: 87 mm over 35 hours on October 6, 2023, and 67 mm over 12 hours on August 30, 2023. For BRCs 01 and 03, the monitoring period covered from June to August and captured two major rainfall events: 78 mm over 2.5 hours on July 13, 2023, and 34 mm over 1.7 hours on July 4, 2023.

Table 2 presents the performance metrics comparing the simulation results from PCSWMM with field-measured surface water levels. Metrics were calculated using only the observed and simulated values corresponding to rainfall events equal to or greater than the first quartile (Q1) for each bioretention cell. The Q1 threshold was computed based exclusively on non-zero rainfall values to avoid biasing the analysis with dry periods. This filtering approach was necessary to obtain meaningful performance evaluations. When the full dataset was used, including rainfall values below the Q1 threshold, the error metrics were significantly inflated. Among the four BRCs, the model for BRC 01 achieved the best performance across all four metrics (NSE, KGE, PBIAS, and Pearson's r), indicating that the model effectively represents the observed behaviour.

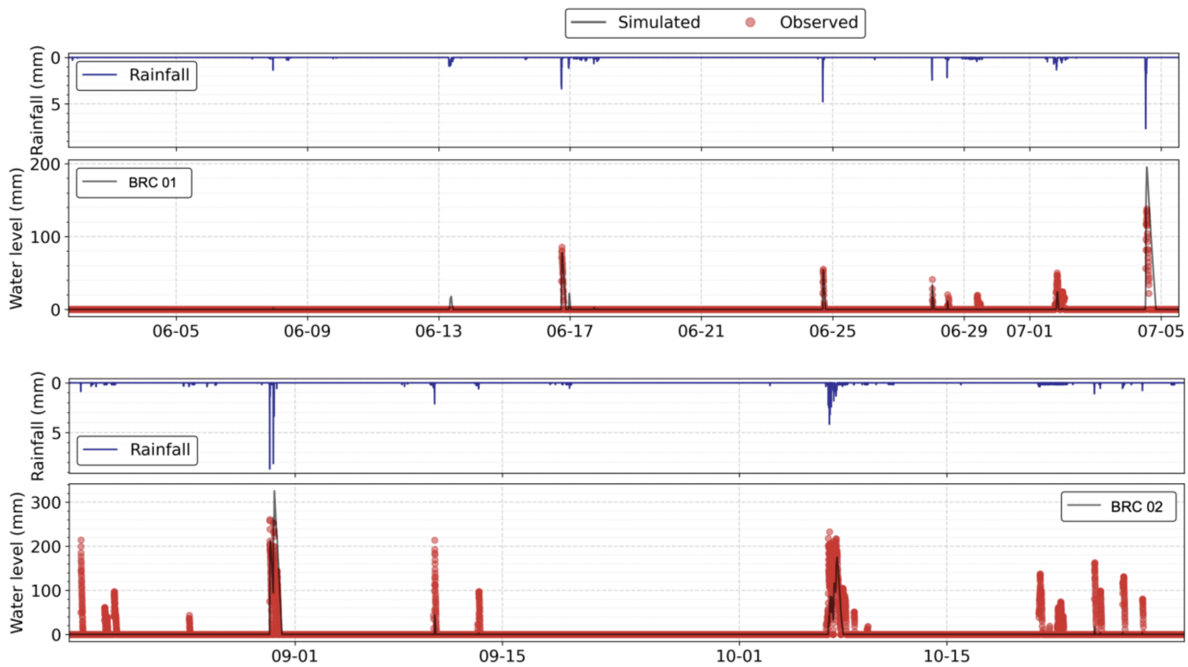
Simulation results for BRCs 02, 03, and 04 yielded low values for both the NSE and the KGE, indicating that the model was unable to accurately reproduce the observed water levels. This reflected its inability to capture peak levels during heavy rainfall events (underestimation) and its tendency to overestimate retention during smaller events, as shown in Figure 3. The model for BRC 03 exhibited a negative PBIAS, indicating an underestimation of water levels, while those for BRC 02 and 04 showed an overestimation. In general, the results of all models showed moderate to high Pearson correlations with the measurements for all BRCs, suggesting that the hydrologic response is partially well represented, although not the magnitudes.

Table 2. Error statistics for the selected BRCs, including the Nash-Sutcliffe efficiency (NSE), Kling-Gupta efficiency (KGE), Percent Bias (PBIAS), and Pearson correlation coefficient (r)

	NSE	KGE	PBIAS	Pearson r
BRC 01	0.74	0.72	-3.87	0.93
BRC 02	0.23	0.39	47.50	0.65
BRC 03	0.10	0.31	-57.41	0.67
BRC 04	0.14	0.56	18.05	0.62

Model performance results were verified against field conditions documented during concurrent measurement campaigns conducted by Gigan et al. (2024) and Leclerc (2024). Their field inspections showed differences between the modelled BCRs and actual site conditions. Issues such as improperly constructed slopes diverted runoff away from the BRCs, inlet levels above street level prevented water from entering, and drainage sub-catchments areas differed from design specifications. Site-specific factors such as steep or excessively flat slopes, sedimentation, vegetation, and drainage patterns (e.g., flow direction and contributing runoff) also influenced the retention and infiltration capacity of the BRCs.

For the four BRCs analyzed, field observations agreed with the model findings: BRC 01 was well-constructed, with slopes and levels in accordance with the design. In BRC 02, water entered mainly during heavy rains due to gentle slopes and elevated internal areas, where the soil surface was in some places higher than the berm, preventing inflow during smaller events. In BRC 03, steep street slopes led to rapid water inflows, resulting in overflows and bypasses. In BRC 04, water inflow was reduced because the curb inlet was higher than the street level, gentle slopes and sedimentation. These field inspections supported the findings of this study, as reflected in the performance metrics presented in Table 2.



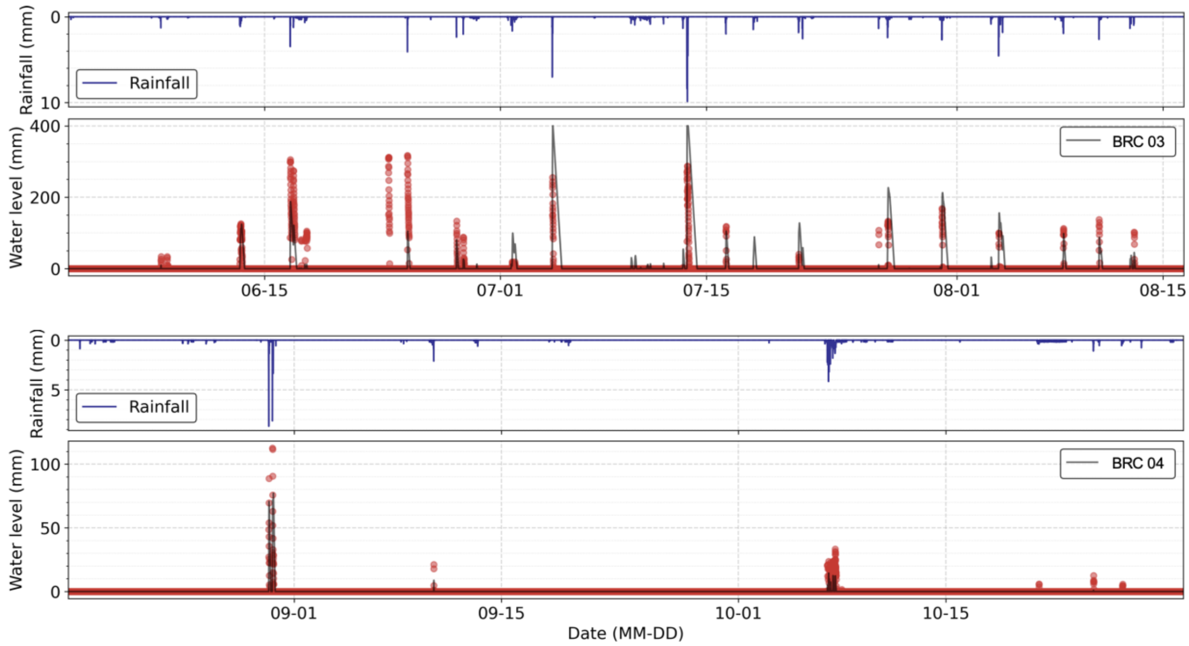


Figure 3. Comparison of water levels (mm) from field data and the SWMM model across four BRCs, along with their corresponding rainfall depths (mm)

These findings highlight the importance of verifying design conditions against on-site construction and field observations, as seemingly minor factors such as topographical differences, road infrastructure, and maintenance can influence the actual performance of BRCs and the accuracy of the models used to simulate their behaviour. Therefore, it is suggested that modelling should include parameters that allow for the integration of these types of real-life conditions. For example, a parameter that allows for the definition of the BRC curb inlet level, which would limit the amount of water entering the BRCs, so that only large-scale events would enter, more accurately representing what occurs at the site.

Conclusions and future work

This study shows how hydrologic modelling results can be used to verify whether the field-constructed characteristics of BRCs meet the original design specifications, pointing out the critical role of construction quality and field conditions on their hydrologic performance. Factors such as I/P ratio, presence of vegetation, inlet configuration, and physical characteristics of the BRCs significantly influence their retention and infiltration capacity. Performance metrics indicated that the SWMM model closely reproduced the hydrologic behaviour of well-constructed cells, such as BRC 01, while BRCs with physical discrepancies (e.g., slope irregularities, inflow barriers) showed less agreement with the model.

Field observations confirmed key factors influencing retention capacity, including slope gradient, inlet elevation, and drainage connectivity, which significantly affect runoff inflow and storage. These results underscore the need to incorporate site-specific physical characteristics into modelling frameworks to improve prediction accuracy. Finally, these results suggest that urban stormwater models should incorporate field-based adjustments and emphasize field verification to ensure realistic representation and effective performance evaluation of LID practices.

This approach of modelling and field verification of construction allows for the identification of construction issues and serves as a basis for BRC calibration strategies. Despite discrepancies between modelled and observed data, the model remains a valuable tool for investigating hydrological behaviour under real-world conditions and supporting informed decision-making. Future work will extend this methodology to a larger sample of BRCs and use GIS-based delineation to support systematic calibration, ultimately promoting more reliable performance assessment and optimized design of urban green stormwater infrastructure.

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