

Compact bioretention cell for urban stormwater management: Assessment of hydrologic, hydraulic, and water quality performance via laboratory and SWMM modelling

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ABSTRACT

Bioretention cells (BRCs) are widely implemented to restore undeveloped hydrologic cycle; however, conventional BRCs need considerable surface area, limiting their applicability in densely populated areas. Compact BRCs like Filterra® have been designed to provide comparable hydrologic and pollutant removal effectiveness with a smaller footprint. The hydraulic characteristics of Filterra's engineered media were assessed through laboratory testing using KSAT and HYPROP devices and these results were integrated with field monitoring to implement a field-validated storm water management model (SWMM). Laboratory results showed a hydraulic conductivity of 1750 mm/h. The validated SWMM model replicated the outflow dynamics with satisfactory accuracy ($KGE > 0.35$, $R^2 > 0.47$), and the total suspended solids (TSS) removal was suitably predicted ($R^2 = 0.83$). Results demonstrate that the field-validated SWMM model can be used to evaluate both hydrologic performance and pollutant TSS removal efficiency of compact BRCs, while noting its limitations in representing complex TSS dynamics.

1. Introduction

1.1. Motivation

Bioretention cells (BRCs) are among the most prominent low impact development (LID) practices worldwide, known for their effectiveness in restoring urban hydrologic processes to pre-development states, in alignment with the principle of hydraulic and hydrologic invariance (Chaves et al., 2024; Nazarpour et al., 2023). As nature-based solutions (NbS), BRCs perform a variety of co-benefits and ecosystem services, including recharging groundwater, fostering biodiversity, controlling microclimates, and improving urban runoff quality, in addition to hydrological benefits (Asleson et al., 2009; Kasprzyk et al., 2022; Baek et al., 2019).

In urbanized settings, conventional centralized stormwater systems, such as underground pipelines and detention chambers, face growing challenges in managing the increasing volumes and intensities of runoff resulting from rapid urbanization and climate change (Moazzem et al., 2024). Conversely, LID practices, specifically BRCs, offer decentralized solutions to deal with these issues. On average, these systems can

decrease stormwater volume by approximately 61 %, mitigate peak flows by more than 60 %, and improve water quality like total suspended solids (TSS) removal rates exceeding 78 %, while also supporting urban development (Hamel and Fletcher, 2014; W. Liu et al., 2016; Tameh et al., 2024; Vijayaraghavan et al., 2021; Winston et al., 2016). Regarding water quality, BRCs treat urban runoff through natural processes, including filtration, adsorption, and biological absorption, effectively reducing contaminants such as TSS, nutrients, and heavy metals (Nazarpour et al., 2023). These systems are particularly effective at source control for highly impervious urban surfaces, such as roadways and parking lots alleviating pressure on downstream infrastructure (Davis et al., 2012; Lammers et al., 2022; Zadeh et al., 2024).

However, the use of BRCs in highly urbanized settings has been restricted by the need for large installation areas, which has led to the development of compact and space-efficient variants of BRCs. These compact systems, designed to treat runoff from areas that are significantly larger than their own footprint, present a promising alternative to conventional BRCs. Indeed, as urbanization continues and space becomes increasingly limited, compact BRCs may become essential for enhancing sustainable stormwater management.

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1.2. Literature review

The effectiveness of conventional BRCs in urban stormwater management has been extensively studied (Huang et al., 2025). These systems commonly require large surface areas, often ranging from 5 % to 20 % of the contributing drainage area (CDA), to obtain meaningful hydrologic and water quality benefits. In this study, footprint is defined as the ratio of the BRC surface area ($Area_{BRC}$) to the CDA (Tameh et al., 2024). The hydrologic performance of conventional BRCs has been investigated extensively. For instance, Shrestha et al. (2018) and Spraakman et al. (2020) reported volume reductions of 75 % and 98 %, respectively, for systems with a $Area_{BRC}$ ranging between 8 % and 12 % of the CDA. Likewise, a study conducted by Hečková et al. (2022) demonstrated that a BRC with a surface area equal to 25 % of the CDA can reduce peak flows by 86 %. Willard et al. (2017) reported 84 % runoff volume reduction and 82 % peak flow attenuation for a BRC implemented in a parking lot, with a footprint of 2 %.

The pollutant removal capacity of conventional BRCs is also well established, particularly for total suspended solids (TSS). Jiang et al. (2017) monitored a non-exfiltrating BRC with sandy loam media and a footprint of 8 %, observing a 52 % decrease in TSS. Similarly, research conducted by Li et al. (2022) evaluated the effectiveness of the BRC with media amended and a footprint of 10 %, achieving a TSS reduction of 63 %. Shrestha et al. (2018) and Spraakman et al. (2020) reported a 94 % and 63 % TSS removal rate, respectively, for systems with footprint ranging from 8 % to 12 %. Likewise, Jeon et al. (2021) obtained an 85 % TSS reduction with sandy media for a BRC with a footprint of 10 %.

Despite their demonstrated effectiveness, conventional BRCs require a considerable surface area, which limits their applicability in highly urbanized environments where space is limited. To address these constraints, compact BRCs system have been developed, such as the proprietary Filterra® unit (Siviter et al., 2008), hereinafter named Filterra. These compact BRCs are designed to manage runoff from CDA that are up to 100 to 500 times larger than their surface footprint, corresponding to a footprint as low as 0.2 %–1 %. (e.g., Braswell et al., 2018).

Although research on compact systems remains limited as for conventional BRCs, early studies have demonstrated promising pollutant removal and hydrologic performance. For instance, Gilbreath et al. (2019) reported a 94 % TSS reduction using a semi-exfiltration compact BRC design with sandy loam media and a footprint of just 0.2 %, treating highly impervious roadway runoff. Braswell et al. (2018) evaluated a combined system that integrated permeable pavement with Filterra both as a standalone unit and in combination with permeable pavement. While the combined system did not show additional water quality benefits, the standalone Filterra obtained a 96 % of TSS reduction. However, the hydrologic effectiveness of standalone Filterra was limited with a 1 % of volume reduction and 14 % peak flow reduction. Smolek et al. (2018) monitored a Filterra system over two years, observing a 50 % peak flow reduction and 92 % TSS removal, despite 22 % of inflow bypassing the system due to the small footprint of the system and partial media clogging.

1.3. Research gaps

For the compact systems, additional research is necessary to validate their hydrologic and water quality capabilities as well as to improve modelling accuracy. First, the hydrologic performance of compact BRCs, such as Filterra, is not well understood across a wide range of climatic conditions and urban environments. This highlights the need for broader studies to capture system behaviour under a wide range of rainfall characteristics and operational contexts.

Second, the hydraulic characteristics of the media employed in compact BRCs are poorly defined. The soil water retention curve and saturated hydraulic conductivity are essential for modelling water flow and pollutant transport. Nevertheless, these properties are frequently inferred or estimated rather than measured, which introduces

uncertainties into model predictions.

Third, modelling frameworks for compact BRCs remain underdeveloped, particularly with respect to calibration and validation. Numerous studies employ uncalibrated models, reducing confidence in simulation outputs. There is a need for physically based field-validated modelling approaches that are specifically designed for compact bioretention systems. This gap limits the capacity to reliably model system performance, limiting both their integration into larger-scale stormwater planning and decision-making processes.

1.4. Contribution and objectives

This study seeks to enhance the comprehension and modelling of compact BRCs, specifically focusing on the Filterra system to address the research gaps identified in the previous section. A comprehensive approach was used, including laboratory characterization, field observed data, and numerical modelling to evaluate the hydrologic, hydraulic, and pollutant removal performance of this compact system.

The proposed modelling framework involves the integration, within the BRC LID module of SWMM, of measured media properties as input parameters that are not subjected to calibration. Unlike previous studies that rely on literature-based soil parameters or calibrated media properties based on outflow measurements, our research incorporates directly measured media properties as input parameters to enhance model reliability and increase confidence in simulation outcomes.

In this framework, the main objective is to demonstrate the effectiveness of the Storm Water Management Model (SWMM) in simulating the hydraulic behaviour and TSS reduction performance of the Filterra in urban settlements. This is accomplished through three specific objectives:

1. To assess the soil water retention characteristics and saturated hydraulic conductivity of the Filterra growth media, providing essential input for reliable modelling and enhancing the hydraulic characterization of engineered media employed in compact bioretention systems.
2. To provide a calibrated and validated SWMM-based modelling framework specifically designed for compact BRCs, using field data to reliably simulate both quantity and water quality performance.
3. To provide a set of model parameters that can be transferred to evaluate the Filterra's effectiveness in controlling runoff quality and quantity issues in the urban context.

The present study contributes to the advancement of compact BRC modelling and design by achieving these objectives, thereby facilitating the deployment of high-performance, space-efficient solutions for stormwater management in densely urbanized environments. The research is replicable and regarding the transferable outputs, the measured media characteristics as well as the calibrated water quality parameters—although obtained for a specific commercial product and a specific site—can be suitably applied in other modelling studies of compact BRCs in urban contexts.

2. Materials and methods

2.1. Field site description

The Filterra bioretention cell is located at the Earth Rangers building at Kortright in Vaughan, ON, Canada (43° 49' 38.25" N, 79° 35' 15.94" W). It was implemented by the Toronto and Region Conservation Authority's Sustainable Technologies Evaluation Program (TRCA STEP) in January 2017. This system effectively manages stormwater runoff from a roadway with about 300 m² of contributing impervious area, directing flow into the unit via a 70 m asphalt curb. The unit is a square concrete structure with dimensions of approximately 1.7 m on each side, and the Filterra surface area is equal to 1.44 m², which corresponds to a footprint

of 0.5 %. The Filterra cell comprises a 7-cm mulch layer, 53-cm engineered soil media (EM), and a 150-cm storage layer (TRCA STEP, 2020).

The system is configured as a non-exfiltrating BRC (i.e., stormwater does not infiltrate into the surrounding soil). Stormwater runoff is conveyed through a perforated underdrain with a 10-cm diameter to the downstream drainage pipeline (TRCA STEP, 2020).

The monitoring gauge station was designed to provide quantity and quality data of the Filterra inflow and outflow. Flow measurements were conducted in the drainage channel conveying runoff towards Filterra system using an area-velocity probe and at the outlet section using a small tank equipped with a V-notch weir and a piezometric level sensor. Water quality samples were collected with automated samplers both at the inlet and outlet sections of Filterra. Fig. 1 provides an overview of the field site and the monitoring gauge station.

2.1.1. Monitoring data

The TRCA STEP evaluated the hydrologic and water quality performance of the Filterra over two periods, from mid-June to November 2017 and from May to November 2018. Data from this project were shared with Carleton University in 2023 for modelling purposes. Rainfall data were collected with a tipping bucket rain gauge (TB3 0.2 mm, Hydrological Services, Lake Worth, FL), situated 500 m from the site at the TRCA weather station HY039 in Vaughan, ON, Canada (TRCA STEP, 2020). Monitoring program provided continuous flow data, while water quality samples were collected based on flow-proportional criterion into a single composite sample at the event scale and then analysed in a laboratory. Therefore, monitoring data examined in the present research study, included 5-min resolution rainfall data, 1-min resolution inflow and outflow measurements, and inlet and outlet event mean concentrations for TSS. In this study, TSS was prioritized as it is the primary regulated water quality parameter for urban stormwater in Ontario (Ontario Ministry of the Environment, 2003). Moreover, TSS is a widely accepted indicator of particulate-bound pollutants, including heavy metals and phosphorus, and is extensively used in urban stormwater modelling to evaluate treatment performance (Rügger et al., 2013).

Rainfall-runoff events for calibration and validation of the model were extracted from the continuous precipitation and inflow-outflow

2018 dataset. The 2017 data were excluded due to the adjustments of the flow monitoring device to guarantee a proper functioning even in high flow rate aimed at preventing the non-representative overflows noted during the 2017 monitoring period. To separate events, a defined rainless interval, referred to as the minimum antecedent dry weather period (ADWP) was applied (Dunkerley, 2008; Medina-Cobo et al., 2016). This study selected a minimum ADWP of 6 h, leading to the identification of 58 distinct rainfall-runoff events during the study period. The flow data set available for the monitored events were then validated based on the following criteria: data continuity, which is defined as uninterrupted and temporally consistent recordings across all variables, and data consistency, which is evaluated through flow metrics such as discharge coefficients. Therefore, all the operational anomalies (such as partial blockage, irregular inflow routing, and data gaps caused by sensor malfunction) that could alter the measurements were eliminated. It should be noted that only in limited cases were both the inflow and the outflow datasets validated for the same rainfall event.

In total, 15 rainfall-runoff events that satisfied the reliability criteria were employed for hydrologic and TSS calibration-validation purposes. Table 1 summarizes the characteristics of the selected rainfall events, including start and end date and time, rainfall depth and duration, ADWP, and maximum rainfall intensity over 5-min, as well as the role of each event in the SWMM calibration and validation procedures.

The calibration of the SWMM model for the hydrologic processes was conducted separately for inflow and outflow events, thus allowing to point out the processes occurring within the Filterra system. The calibration framework adopted in this study is developed according to a sequential (two-step) calibration strategy, in which hydrologic and hydraulic processes were calibrated first and subsequently used as a fixed framework for water-quality simulations. The inflow calibration events focused on simulating the runoff dynamics, while the outflow calibration ensured the accuracy of the system's discharge. Three inflow calibration events (July 16, July 30, and October 2) and three outflow calibration events (July 16, August 21, and September 30) were used to calibrate the catchment and the Filterra parameters independently. Similarly, for hydrological validation, three inflow events (August 7, August 21, and October 7) and three outflow events (August 8, August

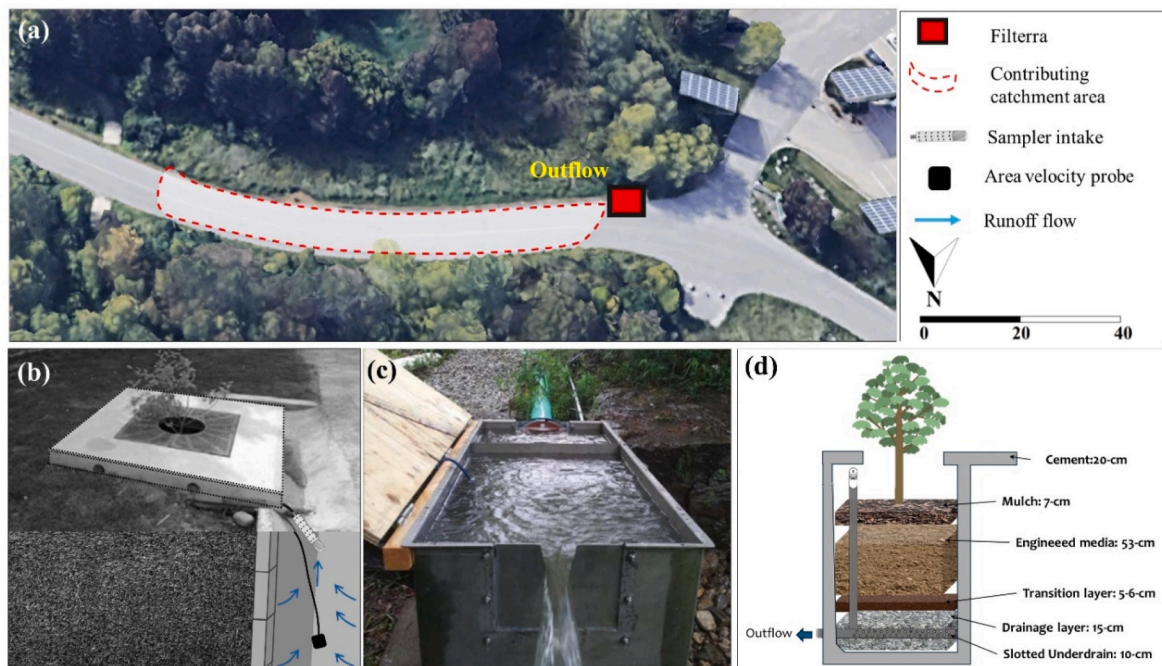


Fig. 1. Overview of the study site located at Kortright (Vaughan, ON): (a) View of the site with contributing drainage area and Filterra location; (b) Filterra monitoring system with inlet area velocity probe and sampler intake; (c) outlet V-notch weir box; (d) Schematic cross-section of the Filterra system, including the stratigraphy layer depths. The areal image is from Google Earth (2018). Photos are reprinted with permission from TRCA STEP (2020).

Table 1

Summary of the rainfall event characteristics (depth, duration, Antecedent Dry Weather Period – ADWP, maximum intensity) for 2018 events selected for calibration and validation (inflow, outflow and TSS) of the SWMM model. Note that Cal-In indicates Calibration Inflow, Cal-Out indicates Calibration Outflow and Cal-TSS indicates Calibration TSS. Val-In, Val-Out and Val-TSS are similarly reported for validation.

Rainfall event	Depth [mm]	Duration [h]	ADWP [days]	Max Intensity [mm/hr]	Event role
16 Jul	32.4	6.25	2.07	43.2	Cal-In, Cal-Out
30 Jul	6.8	3.00	0.80	33.6	Cal-In
06 Aug	4.2	1.75	6.98	19.2	Cal-TSS
07 Aug	3.6	4.67	0.30	16.8	Val-In
08 Aug	6.8	6.75	1.10	9.6	Val-Out, Cal-TSS
17 Aug	10.4	6.25	0.40	19.2	Val-Out
21 Aug	41.6	15.67	3.38	69.6	Cal-Out, Val-In, Cal-TSS
25 Aug	3.2	2.33	3.18	4.8	Val-TSS
02 Sep	3.0	4.33	6.13	21.6	Val-TSS
21 Sep	4.4	0.17	10.59	40.8	Cal-TSS
30 Sep	21.2	11.25	1.60	12.0	Cal-Out
02 Oct	9.0	13.58	0.77	12.0	Cal-In, Val-TSS
04 Oct	6.4	1.17	1.49	36.0	Val-TSS
07 Oct	2.8	1.67	2.80	7.2	Val-In
01 Nov	36.4	28.08	0.80	9.6	Val-Out

17, and November 1) were used to validate the model. It should be noted that, to guarantee a proper representation of different hydrologic conditions in the calibration and validation phases, the selection of the events attributed to each phase was carried out to include different rainfall-runoff event characteristics (such as total depth, duration, and maximum peak flow rate).

Regarding water quality, TSS calibration and validation events were chosen according to the availability of reliable water quality data, which did not consistently align with events used for hydrologic calibration/validation. This method ensured model robustness, while enabling the use of available TSS data under various storm conditions. The TSS calibration consisted of four events: August 6, August 8, August 21, and September 21. For TSS validation, four additional events—August 25, September 2, October 2, and October 4—were chosen to evaluate the model's accuracy in simulating TSS removal across varying conditions.

2.2. Media characterization

Two undisturbed soil samples from a second Filterra system were collected in November 2023 in order to better understand the soil water characteristic curve (SWCC) or soil water retention curve and the saturated hydraulic conductivity (K_{sat}) of the media. Soil samples were collected with 250 cm³ metal sampling rings (5 cm height, 8 cm diameter) at a depth of 30–35 cm below the surface following sampling procedures outlined in technical documentation (METER Group AG, 2018; Shokrana and Ghane, 2020). These parameters are critical for understanding the water retention dynamics and unsaturated flow through the EM in Filterra. The samples of Filterra units were located at the Carleton University Campus in Ottawa, Ontario. Although not from the Vaughan site, both locations have similar climatic and hydrological conditions, making the Ottawa units representative of the study area. The growing media of these units was assumed to represent the newly installed Filterra systems in Ontario. Because the growing media characteristics evolve over time, this system was selected for sampling since its age was more comparable to the Filterra system age of Vaughan site when the monitoring program was carried out.

HYPROP (hydraulic property analyser, METER Group, 2018) which measures unsaturated hydraulic conductivity and SWCC using an evaporation approach, was used for the Filterra media characterization.

Two tensiometers are positioned in the soil column (Figure S1) to measure the tension exerted by water during monitored evaporation. The HYPROP manual (METER Group AG, 2018) includes specific measurement details; however, a brief description of the procedure is provided below.

The experiment started with the degassing of deionized water using a vacuum bottle linked to the HYPROP system and a vacuum pump. The HYPROP sensor unit and tensio shafts were degassed with the HYPROP refill unit at a vacuum pressure of 85–90 kPa to remove air bubbles and ensure measurement accuracy. After degassing, soil samples were saturated with degassed water by being placed in a tray for 4 h. The tension shafts were inserted into the sensor unit while preserving moisture in the ceramic tips, and their functionality was confirmed through pressure stabilization tests. The sensor unit was connected to a USB adapter, calibrated, and mounted to the soil sample ring while maintaining saturation. The HYPROP-View application enabled data collection by recording weight and pressure variations over approximately 10 days.

In the present study, the measurement procedure was manually stopped following the observation of the four phases of the tension curve: the regular measurement range, the boiling delay phase, the cavitation phase, and the air-entry phase. The stop point was established by observing the tension values in both the long and short shafts. Following, the dry weight of the soil sample was measured to calculate the volumetric water content, and the data were analysed using the bimodal Van Genuchten – Mualem model (Durner, 1994).

This model differentiates between larger interparticle pores and smaller intraparticle pores. This approach provides an accurate assessment of the soil's hydraulic behaviour by estimating essential parameters, including saturated and residual water contents, as well as the shape characteristics related to air entry and curve bending. It effectively describes the variation of water content with matric potential in heterogeneous soils.

The K_{sat} was analysed with a KSAT® apparatus (METER Group, 2018). The KSAT uses the falling-head approach, which involves the vertical percolation of degassed water through a fully saturated soil sample at room temperature, with the soil sample carefully prepared to simulate field situations. A mesh is employed to guarantee correct installation and prevent water bypass.

The falling-head approach relies on Darcy's law, which relates the flow rate of water through the soil to the hydraulic head gradient, the length of the sample, and K_{sat} . The KSAT apparatus presents accurate measurements, making it appropriate for soils with diverse permeabilities without necessitating elevated water pressures. The KSAT VIEW software continuously recorded the pressure head with an accuracy of 0.01 cm, capturing dynamic changes in flow. Full experimental details are available in the KSAT manual (METER Group, 2018).

2.3. Modelling

2.3.1. Model setup

SWMM is a semi-distributed deterministic tool widely used for both event-based and long-term simulations of drainage systems, providing the modelling of hydrological and hydraulic processes, including surface runoff, channel routing, and pollutant transport, through empirical and physically based equation systems (Lisenbee et al., 2021; Palla and Gnecco, 2022; Rauch et al., 2002; Rossman, 2010). Because of its open-source design and adaptability, SWMM is the preferred option for stormwater management planning, pluvial flood risk analysis, and water quality assessments (Rai et al., 2017).

This study used the version SWMM 5.2, coupled with the R swmmr package (Leutnant et al., 2019), to simulate rainfall-runoff processes and pollutant dynamics in the catchment area. The dynamic flow routing method with 1-min time intervals was used. As the event-scale simulations were performed, hydrologic processes such as evapotranspiration and snowmelt and therefore climate data such as temperature and wind

speed snowmelt were not accounted for. These latter processes have minimal impact on short-duration events, which is the reason this simplification is acceptable.

The nonpoint source runoff quality can be modelled by SWMM using the build-up and wash-off functions, considering the specified land uses. To model pollutant build-up and wash-off, SWMM provides a range of equations including power, exponential, and saturation equations for build-up, and exponential, rating curve, and event mean concentration equations for wash-off (Rossmann, 2010). Considering that this study focused solely on TSS delivery behaviour, exponential equations were employed for the build-up and wash-off processes. The equations effectively represent the nonlinear dynamics of TSS accumulation and transport, facilitating direct comparison of the resulting parameters with previously reported findings (Gaut et al., 2019).

Even if the build-up process is influenced by the ADWP as well as the remaining pollutant load from prior events, the exponential build-up model simplifies the process by capturing the accumulation of pollutants until it reaches an equilibrium state, reflecting the balance between deposition and removal processes. The build-up model is described as follows

$$B = C_1 \cdot (1 - e^{-C_2 \cdot t}) \tag{1}$$

where B is the pollutant build-up (mass per unit area or curb length), C_1 is the maximum potential build-up (mass per unit area or curb length), and C_2 is the rate constant [1/days], while t represents the ADWP [days].

The exponential wash-off model links pollutant removal to runoff intensity, ensuring a representative pollutant transport prediction.

$$W = C_3 \cdot Runoff^{C_4} \cdot B' \tag{2}$$

where W is the wash-off load in units of mass per hour, where C_3 is the wash-off coefficient [h^{C_4-1}/mm^{C_4}], C_4 is the wash-off exponent (-), which defines the nonlinearity between $Runoff$ (corresponding to runoff rate per unit of area [mm/h]) and pollutant transport, and B' (units of mass) is the available pollutant mass for wash-off.

Concerning the bioretention pollutant removal rate, in SWMM it is represented as a lumped first-order coefficient that directly scales simulated effluent concentrations.

2.3.2. Hydrologic calibration and validation

The calibration process of the SWMM model for the hydrologic processes involved the selection of a set of parameters for inflow and outflow dynamics of the Filterra system (Table 2). Four calibration parameters were used to characterize the dynamics of inflow to the Filterra system. These are the depression storage in impervious zones (DS_{imp}), the percentage of impervious zones without depression storage ($Zero_{imp}$), the surface roughness of impervious zones (N_{imp}), and the average surface slope (Slope). These parameters were chosen to accurately capture the hydrological dynamics of the fully impervious contributing drainage area influencing the runoff generation. Seven calibration parameters were used to characterize the outflow dynamics including: the vertical distance from the storage bottom to the underdrain outlet (Offset-underdrain), the thickness of the storage layer ($Depth_{storage}$), and the surface roughness affecting overland flow on the bioretention surface (Surf-roughness).

Additionally, the slope of the cross-sectional surface (Surf-slope), the parameters defining flow rate under variable hydraulic head (Flow-coefficient, Flow-exponent), and the initial water level in the storage media (Ini-saturation) were also considered. The selected parameters focus on the internal functionality of the Filterra, which directly influences the runoff flow and treatment through the Filterra system.

As illustrated in Table 2, each parameter is assigned upper and lower bounds. The ranges of N_{imp} and Slope were chosen according to the literature (Huber and Barnwell, 1988; Temprano et al., 2007), while

Table 2

SWMM parameters for the hydrologic calibration of the inflow and outflow processes and the related ranges of variation (Lower and Upper bound).

Hydrologic process	Parameter	Abbreviated name	Unit	Lower bound	Upper bound	
Inflow	Depression storage in impervious zones	DS_{imp}	mm	10	40	
	Percent of Impervious zones without depression storage	$Zero_{imp}$	%	40	65	
	Surface roughness affecting flow rate on impervious zones	N_{imp}	$s/m^{1/3}$	0.011	0.033	
	Average surface slope	Slope	%	0.5	3.5	
	Outflow	Vertical distance from storage bottom to underdrain outlet	Offset-underdrain	mm	1	15
		Thickness of the bioretention cell's storage layer	$Depth_{storage}$	mm	150	160
		Surface roughness affecting the overland flow on surface soil cover	Surf-roughness	$s/m^{1/3}$	0.3	0.5
Slope of bioretention cell cross section walls		Surf-slope	%	0.5	2	
Parameter defining flow rate under varying hydraulic head	Flow-coefficient	-	2	6		
Exponent representing the relationship between flow rate and hydraulic head	Flow-exponent	-	0.2	0.4		
The initial water level in the storage media (saturation percentage)	Ini-saturation	%	1	30		

those for DS_{imp} and $Zero_{imp}$ were derived from site-specific conditions. The other catchment parameters were fixed based on the TRCA STEP (2020) and QGIS analysis. The ranges of Surf-roughness, Surf-slope, Flow-coefficient, Flow-exponent, and Ini-saturation were selected according to SWMM manuals (Rossmann, 2010). The calibration ranges for $Depth_{storage}$ and Offset-underdrain were informed by TRCA STEP (2020) design values and they were given a narrow calibration range (± 10 mm) to account for minor deviations caused by field conditions or media settlement over time, while remaining consistent with the original design.

Additionally, the Filterra parameters which influence outflow, such as porosity, wilting point, field capacity, K_{sat} , suction head and conductivity slope, were determined through laboratory experiments.

The calibration of inflow and outflow aimed to replicate the complete shape of the observed hydrographs, emphasizing peak flow magnitude and timing over merely matching cumulative volumes. This strategy has been adopted to prevent distortions in hydrograph shape that may result from volume-based calibration methods (Lisenbee et al., 2020). The Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) was used as the objective function for the calibration procedure, assessing the

goodness-of-fit between modelled and observed flow data. KGE allows assessing the performance of models in multiple dimensions—correlation, flow variability, and bias—which offers a more comprehensive evaluation than conventional metrics (e.g., NSE). In addition to KGE, other metrics, including the coefficient of determination (R^2) and root mean square error (RMSE) were used to evaluate the model accuracy. A minimum performance threshold of $KGE > 0.35$ was established, following the benchmark framework set by [Knoben et al. \(2019\)](#). Their investigation revealed that a model that merely predicts the mean of the observed time series—often used as a baseline or reference predictor—produces a KGE of approximately -0.41 . The value is derived from the mathematical formulation of the KGE metric: when a model predicts solely the mean of the observed data, it does not capture variability or correlation, resulting in a result of approximately $KGE \approx -0.41$. A KGE exceeding this value signifies that the model shows skill in comparison to the baseline. The chosen threshold of 0.35 establishes a conservative margin above the reference point, thereby ensuring that model simulations demonstrate sufficient accuracy regarding correlation, variability, and bias. In addition to the benchmark-based assessment, further criteria were utilized: $R^2 > 0.45$, indicating a moderate to strong linear relationship, and $RMSE < 0.25$ L/s, confirming minimal residual error in flow magnitude. The thresholds were used to assess the model's ability to replicate hydrologic responses at the event scale under varying rainfall conditions.

The calibration was performed at the event scale using the Differential Evolution (DE) method ([Storn and Price, 1997](#)), implemented with the DEoptim library in R ([Mullen et al., 2011](#)). DE is a population-based optimization technique to rapidly navigate complex, multi-dimensional solution spaces by applying evolutionary principles using mutation, crossover, and selection ([Le Floch et al., 2022](#)) as illustrated in [Figure S2](#) in the supplementary materials. The method starts with a population of random solutions, each of which indicates a specific set of model parameters. New populations are iteratively generated by enhancing or retaining solutions, and solutions are evaluated using the objective function. For the present study, 100 iterations were implemented, and the optimal parameter set was determined by selecting the most effective final solution according to the above-mentioned goodness-of-fitness.

Hydrologic model calibration was performed in three phases:

- 1) Initial calibration: Each calibration parameter was evaluated using KGE as an objective function, thus providing specific values for each event's calibrated parameter. Based on the calibrated values, the R^2 and RMSE are then assessed to verify that they are in acceptable ranges ($R^2 > 0.45$ and $RMSE < 0.1$).
- 2) Weighted average calibration: For each parameter, a weighted average of the event calibrated parameters from the first step was computed ([Assaf et al., 2024](#); [Snieder and Khan, 2023](#)). The weights were calculated based on the rainfall event characteristics including rainfall depth (H), event duration (D), ADWP, and maximum rainfall intensity (I). Each characteristic was normalized across the N calibration events, and the final weight for each event was calculated as a composite score:

$$w_i = \frac{H_i}{\sum_{i=1}^N H_i} + \frac{D_i}{\sum_{i=1}^N D_i} + \frac{ADWP_i}{\sum_{i=1}^N ADWP_i} + \frac{I_i}{\sum_{i=1}^N I_i} \quad (3)$$

- 3) Where w_i is the weight for event i , and the summations are taken over the N rainfall events used in the calibration phase. These weights were then applied to each calibrated parameter to compute a weighted average value used in the pre-validation phase. Specifically, the weighted average parameter was calculated as the sum of all event-specific parameter values multiplied by their corresponding weights. Model pre-validation: the SWMM model was run using the

weighted average parameters for each event, and the corresponding accuracy was verified against all the above-mentioned goodness-of-fit criteria (KGE, R^2 , RMSE).

The calibration was performed for three events for both inflow and outflow processes as illustrated in [Table 1](#). The validation was then performed for the other three events (see [Table 1](#)), assessing the above-mentioned goodness-of-fit metrics based on the calibrated weighted average parameters.

2.3.3. TSS calibration and validation

[Table 3](#) reports the SWMM parameters of the exponential build-up and wash-off equations documented in the literature. Note that while the unit of measurement of C_2 , C_3 and C_4 are univocally defined, C_1 can be expressed in terms of unit of mass per area or alternatively for curb length. These parameters show a considerable range of variation even within the same location, illustrating the complexity of the hydrological, physical, and mechanical processes affecting the pollutant delivery behaviour in urban runoff. Specific local characteristics, including traffic volume, land use category, maintenance standards, drainage system design, and vegetation cover, contribute to affect the pollutant the build-up and delivery behaviour. For example, urban residential areas typically show lower C_1 values than commercial and industrial zones, indicating less intensive building-up of pollutants. Besides, precipitation features play a significant role in pollutant dynamics, including rainfall patterns, volume, intensity, duration, and ADWP ([Tu and Smith, 2018](#)).

The build-up parameters, C_1 and C_2 , were set to 60 [kg/ha] and 0.177 [1/day], respectively, based on literature values adopted in similar research studies ([Table 3](#)). These values were selected to be constant to maintain model parsimony and reduce calibration uncertainty, as recommended in [Wagener et al. \(2002\)](#) and [Koutsouyiannis \(2016\)](#). Calibrating C_1 and C_2 would have increased the risk of equifinality, particularly given the absence of site-specific data on dry-weather pollutant accumulation.

Once the hydrologic and hydraulic parameters were validated, the calibration procedure for the wash-off parameters (C_3 and C_4) was implemented: a range of 0.1–1.5 for C_3 and from 0.5 to 3 for C_4 were assumed in the calibration phase based on the value reported in the literature.

Similarly to the hydrologic model optimization procedure, the TSS calibration was organised into three phases: initial calibration, weighted average calibration, and model pre-validation. For each event, the wash-off parameters were evaluated using as the objective function the relative error (RE) of the simulated TSS inflow concentration value with respect to the observed one. Following the calibration of individual events, a weighted criterion based on the rainfall event characteristics was used to calculate the average value of each wash-off parameter. Finally, the SWMM model was run using the weighted average parameters for each event, and the corresponding accuracy was evaluated based on the RE of TSS concentrations, thereby enabling a comprehensive assessment of performance across all events.

[Table 1](#) reports the eight rainfall events selected for TSS calibration and validation: four calibration events (Cal-TSS) and four validation events (Val-TSS).

For each event, the observed removal efficiency was calculated by evaluating the proportionate reduction in TSS concentrations monitored at the inlet and outlet. Based on the inlet and outlet concentration observed for the four calibration events, an average TSS treatment efficiency of 81 % was calculated and then used in the SWMM LID module as the pollutant removal rate for underdrain outflow, in accordance with the module's structure, which applies a fixed removal efficiency to underdrain discharge. The Observed inlet and outlet TSS concentration of Filterra is shown in [Table S1](#).

Table 3
SWMM Parameters of the exponential build-up and wash-off equations reported in the literature.

Location	Land use	C ₁ [kg/ha or kg/m]	C ₂ [1/days]	C ₃ [h ^{0.4} /mm ^{0.4}]	C ₄ [-]	Reference
Pavia, Italy	Residential urban area	24.24 [kg/ha]	0.62	0.21	1.48	Assaf et al. (2024)
Tehran, Iran ¹	Residential urban area	29.8–74.5 [kg/ha]	0.98–3.07	0.4–0.7	2–2.2	Zakizadeh et al. (2022)
Jasper, Canada ²	Residential urban area	10–20 [kg/ha]	0.5–1	2.5	3	Sofijanic et al. (2022)
	Commercial area	40 [kg/ha]	2	2.5	3	
Kuala Lumpur, Malaysia	Residential urban area	1.5 [kg/m curb]	0.3	0.4	0.9	Rezaei et al. (2019)
	Commercial area	12 [kg/m curb]	0.3	1.5	0.6	
Austin, US ³	Mixed urban area	0.03–16.49 [kg/ha]	0.21–5.54	3.27–12.53	4.06–8.98	Tu and Smith (2018)
	Industrial area	380.72–470.46 [kg/ha]	0.32–1.05	11.24–16.25	4.54–7.48	
	Commercial area	20.92–92.50 [kg/ha]	0.45–3.65	3.42–13.39	1.87–7.42	
Paris, France ⁴	Residential urban area	2–300 [kg/ha]	0.03–20	0.01–10	0.2–3	Bonhomme and Petrucci (2017)
Calgary, Canada	Residential urban area	56 [kg/ha]	1	0.087	1.53	Shrestha and He (2017)
	Industrial area	56 [kg/ha]	1	0.098	1.79	
Skudai, Malaysia	Residential urban area	0.003 [kg/m curb]	0.8	0.2	1.4	Chow et al. (2012)
	Industrial area	0.013 [kg/m curb]	0.7	4	0.6	
	Commercial area	0.015 [kg/m curb]	0.8	1.4	0.9	
Cosenza, Italy	Mixed urban area	150 [kg/ha]	0.01	0.025	8	Piro et al. (2010)
Odivelas, Portugal	Mixed urban area	65–450 [kg/ha]	0.08	0.13	1.26	João Cambez and Mesquita David (2008)

The range of the variables is related to:

¹ The land use from residential from low population density to high population density.

² The land use from residential area with single-unit to multi-unit.

³ The variety of selected rainfall events.

⁴ The land use from homogeneous catchment to 4 separated subcatchments (spatial variability).

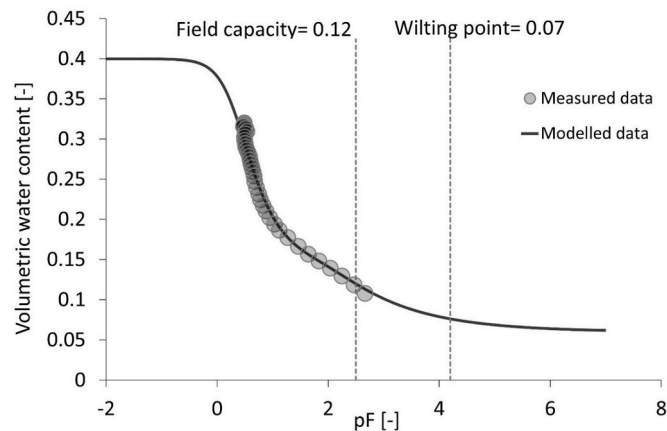


Fig. 2. Volumetric water content vs. pF (log scale of tension in hPa) and fitted soil water characteristic curve according to the bimodal Van Genuchten – Mualem model of the Filterra's EM.

3. Result and discussion

3.1. Filterra media characteristics

The laboratory results obtained from the HYPROP and KSAT apparatus are used for the modelling of the hydrological performance of the EM within Filterra, particularly in terms of water retention behaviour and saturated hydraulic conductivity.

Fig. 2 shows the measured SWCC of the Filterra's EM alongside a fitted bimodal Van Genuchten-Mualem, which describes the relation

Table 4
Hydraulic characteristics of Filterra EM and comparison with other sandy soil.

Feature	Unit	Filterra EM	Sandy soil (Saxton and Rawls, 2006)	Sandy soil ¹ (Rawls et al., 1983)	Sandy soil (Sprakman and Drake, 2021)
Porosity	cm ³ /cm ³	0.42	0.46	0.44	0.45
Field capacity	cm ³ /cm ³	0.12	0.09	0.06	0.18
Wilting point	cm ³ /cm ³	0.07	0.05	0.02	0.10
K _{sat}	mm/hr	1750	108.1	120.4	152 ²
Conductivity slope	–	47.4	46.5	42.2	–
Suction head	mm	20.5	51.3	49.5	–

¹ Estimated values are in average.

² Median of 8 years bioretention cell's age.

between water content and the matric potential on a logarithmic pF scale (logarithmic scale of the tension in hPa). The near-saturated part of the curve shows a sharp fall in water content at relatively low suction, indicating that the majority of water drains quickly due to a predominance of larger pores—approximately 73 % of total pore capacity (obtained from the fitted model). The flatter portion under greater suction emphasizes the role of smaller pores in retaining water more efficiently under tension. The fact that the observed data and the fitted curve closely match, together with this two-stage drainage pattern, indicates that the majority of the pore-size distribution in the EM is large and fast draining. With a design that allows for rapid infiltration rates while maintaining sufficient moisture available for vegetation, the EM can be considered a well-suited for stormwater management applications. The fitted curve provided the essential hydraulic parameters: a saturated water content of 0.4 cm³/cm³ and a residual water content of 0.06 cm³/cm³. As illustrated in Fig. 2, the field capacity of the EM obtained from the model at pF 2.5 is 0.12 cm³/cm³, while the wilting point at pF 4.2 is 0.07 cm³/cm³, giving essential inputs for SWMM modelling.

Additionally, the porosity obtained from HYPROP is 0.4 cm³/cm³, which is the saturated water content of the fitting model. However, the porosity for the SWMM (LID module, BRC) was chosen 0.42 cm³/cm³. The slight increase indicates that not all pore space is fully saturated, influenced by factors like entrapped air, incomplete saturation, and isolated pores, as stated by Buckles (1965) in the inverse correlation between porosity and irreducible water saturation. The saturated water content of 0.4 cm³/cm³ represents approximately 90–95 % of the total porosity selected. Considering this, a more precise input for the SWMM model is necessary to ensure that the simulation accurately reflects the actual hydraulic behaviour of the engineered media.

Table 4 outlines the key hydraulic properties of the Filterra's EM

required for SWMM modelling encompassing porosity, field capacity, wilting point, K_{sat} , conductivity slope, and suction head, and compares them with values reported for similar sandy soil (Saxton and Rawls, 2006; Rawls et al., 1983; Sylvie and Drake, 2021).

The Filterra's EM's porosity of $0.42 \text{ cm}^3/\text{cm}^3$, which is comparable with the reported values for sandy soils between 0.44 and $0.46 \text{ cm}^3/\text{cm}^3$. Its field capacity of $0.12 \text{ cm}^3/\text{cm}^3$ and the wilting point of $0.07 \text{ cm}^3/\text{cm}^3$, indicative of limited moisture retention, reflect the typical behaviour of coarse-textured media, where larger pore spaces promote rapid drainage. These hydraulic parameters of Filterra's EM are in accordance with the ones reported by Sprakman and Drake (2021), which revealed quick drainage and low drawdown times.

Notably, the K_{sat} of the Filterra's EM, measured with the KSAT instrument in the laboratory, is equal at 1750 mm/h , but aligns well with Filterra system design, which targets hydraulic conductivities in the range of 2540 – 3556 mm/h (Lenth et al., 2010). This value markedly exceeds the K_{sat} found in sandy soils reported in Table 2, which ranges from 100 to 150 mm/h . The elevated permeability points out the ability of Filterra's EM to guarantee fast infiltration, making it highly efficient despite the limited area ratio.

The conductivity slope was estimated using the formula proposed by Rossman (2010). According to the texture of Filterra's EM, with were an estimated sand composition of roughly 90% and a clay part of 5% , the conductivity slope equals 47.4 . Although some studies have revealed substantially less conductivity slope values than recommended by SWMM documentation in BRC simulations (e.g. Liu and Fassman-Beck, 2017; Lynn et al., 2018) ranging from 7 to 60 , the outcome of this study is within the typical range of 30 – 60 for sandy soils. It suggests that although the Filterra's EM retains high permeability in saturated conditions, its hydraulic conductivity decreases at a moderate and predictable rate as it dries out.

The suction head of the Filterra's EM was estimated to be 20.5 mm according to the formula recommended in SWMM manuals (Rossman, 2010). This value is significantly lower than the average range for sandy soils (49.5 – 51.3 mm), indicating that the Filterra's EM requires less capillary pressure to trigger the movement of water, resulting in faster infiltration and wetting front progression (Ball and Hunter, 1988). This attribute greatly benefits stormwater management by minimizing surface ponding and improving drainage efficiency during heavy rainfall. Nevertheless, the reduced suction head additionally indicates that the surface water retention is limited, emphasizing the necessity of selecting drought-tolerant vegetation that can thrive in the rapid drainage conditions while preserving the system's functionality (Bordoloi et al., 2024).

3.2. Hydrologic calibration-validation

The detailed list of the assigned parameters and corresponding sources for the Filterra system can be found in Table 5. Parameter sources are classified as: Measured (M), based on field inspection or laboratory tests; Calculated (C), derived from empirical formulas; Estimated (E), based on literature; and Calibrated (Cal), obtained through model calibration.

The calibrated value of DS_{imp} (30.6 mm) is greater than the typical range of 0 – 4 mm reported in the literature (Dayaratne and Perera, 2008; Dong et al., 2008; Skotnicki and Sowiński, 2015) and exceeds the recommended values in SWMM manual which reports typical DS_{imp} ranges between 0.6 mm and 2.5 mm (Rossman, 2010). However, depression storage is a very site-specific parameter that can be calculated by calibrating the model to actual rainfall-runoff data (Dayaratne and Perera, 2008). In this study, the higher DS_{imp} value is most likely due to localized catchment characteristics such as pavement cracks, construction joints, and degraded curb zones that enhance surface retention and delay runoff initiation. It is important to note that, the calibrated $Zero_{imp}$ was 58.5% , which is higher than the typical range of 1% – 45% reported in the literature (Temprano et al., 2006). In SWMM, this latter parameter

Table 5

Filterra and site study parameters implemented in SWMM LID module.

Layer	Sub-layers	Abbreviated name	Unit	Value	Source
Geometry	Area		m^2	1.44	M ¹
	Width		m	1.2	M ¹
	Initially saturated	Ini-saturation	%	30	Cal
Surface	Berm height		mm	100	M ¹
	Vegetation volume		–	0.25	E
	Surface roughness	Surf-roughness	$\text{s/m}^{1/3}$	0.36	Cal
	Surface slope	Surf-slope	%	0.86	Cal
Soil	Thickness		mm	533	M ¹
	Porosity		cm^3/cm^3	0.42	M ²
	Field capacity		cm^3/cm^3	0.12	M ²
	Wilting point		cm^3/cm^3	0.07	M ²
	Hydraulic Conductivity	K_{sat}	mm/hr	1750	M ³
	Conductivity slope		–	47.45	C ⁴
	Suction head		mm	20.5	C
Storage	Thickness	$Depth_{storage}$	mm	152.8	Cal
	Void ratio		cm^3/cm^3	0.75	E
	Seepage rate		mm/hr	0	
	Clogging factor		–	0	
Drain	Flow coefficient	Flow-coefficient	–	4.87	Cal
	Flow exponent	Flow-exponent	–	0.38	Cal
	Offset Height	Offset-underdrain	mm	3.3	Cal
Pollutant Removals	Total suspended solids		%	81	M ⁵

¹ Field inspection by TRCA STEP (2020).

² Measured using HYPROP tool.

³ Measured using KSAT tool.

⁴ Calculated using formula $0.48 \cdot (\%sand) + 0.85 \times (\%clay)$ as recommended by (Rossman, 2010).

⁵ The average field monitoring of TSS reduction of Filterra in 2018.

Source: M = measured; C = calculated; E = estimated; Cal = calibrated.

interacts directly with the DS_{imp} parameter, and larger DS_{imp} values correspond to lower runoff volume and delayed runoff generation. Therefore, based on the calibrated parameters, only on 41.5% of the impervious surface, runoff generation occurs only after the depression storage has been filled.

All other inflow parameters fall within ranges commonly reported in similar studies. The calibrated catchment slope (1.9%) varies from 0.5% to 3.5% in urban catchments (Rossman, 2010; Zakizadeh et al., 2022). The calibrated N_{imp} value ($0.013 \text{ s/m}^{1/3}$) is consistent with standard Manning's roughness values for impervious surfaces, which generally range from 0.011 to 0.033 (Rossman, 2010).

Outflow calibration parameters, offset-underdrain (3.3 mm) and $Depth_{storage}$ (152.8 mm) are design-dependent parameters that reflect the specific geometric configuration of the Filterra system. Notably, the Ini-saturation value can vary considerably depending on factors such as the presence of a saturation zone, the composition of the media, and amendments. The relatively high Ini-saturation of Filterra's EM can be attributed to its distinctive properties, which enable the porous media to retain moisture efficiently between storm events, thereby ensuring the sustained infiltration performance without excessive surface ponding.

The goodness-of-fit metrics (KGE, R^2 and RMSE) of the SWMM model in the prediction of both the Filterra inflow and outflow are listed in Table 6 for the calibration and validation events. Results illustrated in Table 6 confirm the suitability of the SWMM model in reproducing both

Table 6

Goodness-of-fit metrics, KGE, R^2 and RMSE of the SWMM model in the prediction of the Filterra inflow and outflow for the observed rainfall events used for calibration and validation.

Hydrologic process	Event role	Rainfall event	KGE [-]	R^2 [-]	RMSE [l/s]
Inflow	Calibration	16 Jul	0.83	0.77	0.20
		30 Jul	0.40	0.69	0.28
		02 Oct	0.64	0.49	0.06
	Validation	07 Aug	0.5	0.80	0.07
		21 Aug	0.38	0.15	0.40
Outflow	Calibration	07 Oct	0.47	0.28	0.10
		16 Jul	0.57	0.76	0.23
		21 Aug	0.71	0.47	0.26
	Validation	30 Sep	0.49	0.71	0.08
		08 Aug	0.37	0.50	0.06
		17 Aug	0.39	0.58	0.12
		01 Nov	0.37	0.56	0.09

the inflow and outflow as demonstrated by KGE values above of 0.38 and 0.37 for inflow and outflow, respectively. Results revealed good performance even for the validation events even if the model performance was lower compared to the ones obtained in the calibration phase, as expected.

For calibration events, the R^2 values above 0.49 and 0.47 and the RMSE below 0.28 l/s and 0.26 l/s are generally assessed in the

prediction of inflow and outflow, respectively. For validation, inflow performance showed R^2 values between 0.15 and 0.80 with RMSE ranging from 0.07 to 0.40 l/s, while outflow performance showed R^2 values between 0.50 and 0.58 with RMSE ranging from 0.06 to 0.12 l/s. The exceptions occur only in the inflow prediction for two validation events (the 21 Aug and the 7 Oct events) for which the model performance appears reduced that represent the rainfall events with the highest and lowest rainfall depth among the selected inflow events.

In Zakizadeh et al. (2022), SWMM model used to reproduce catchment-scale runoff generation was calibrated on two events and validated solely on a single event. Although the calibrated NSE of 0.71 and the validated NSE of 0.72 with an R^2 of 0.73 suggest that the model is performing well, the dataset was restricted to very low rainfall depths of 1.8–2 mm and short durations of 25–60 min, making it less applicable to a wide range of hydrological conditions.

The results of the hydrologic calibration of the SWMM model in reproducing the Filterra outflow are reported in Fig. 3 for the six selected events of calibration and validation. Furthermore, the calibration and validation of Filterra inflow are presented in Figure S3.

Results plotted in Fig. 3 confirm the suitability of the model in reproducing the outflow volume, the peak flow, the time to peak, and, generally, the timing of the BRC outflows. The overall outflow volume is generally well predicted by the model, even if a slight tendency toward volume underprediction can be detected due to the incorrect simulation

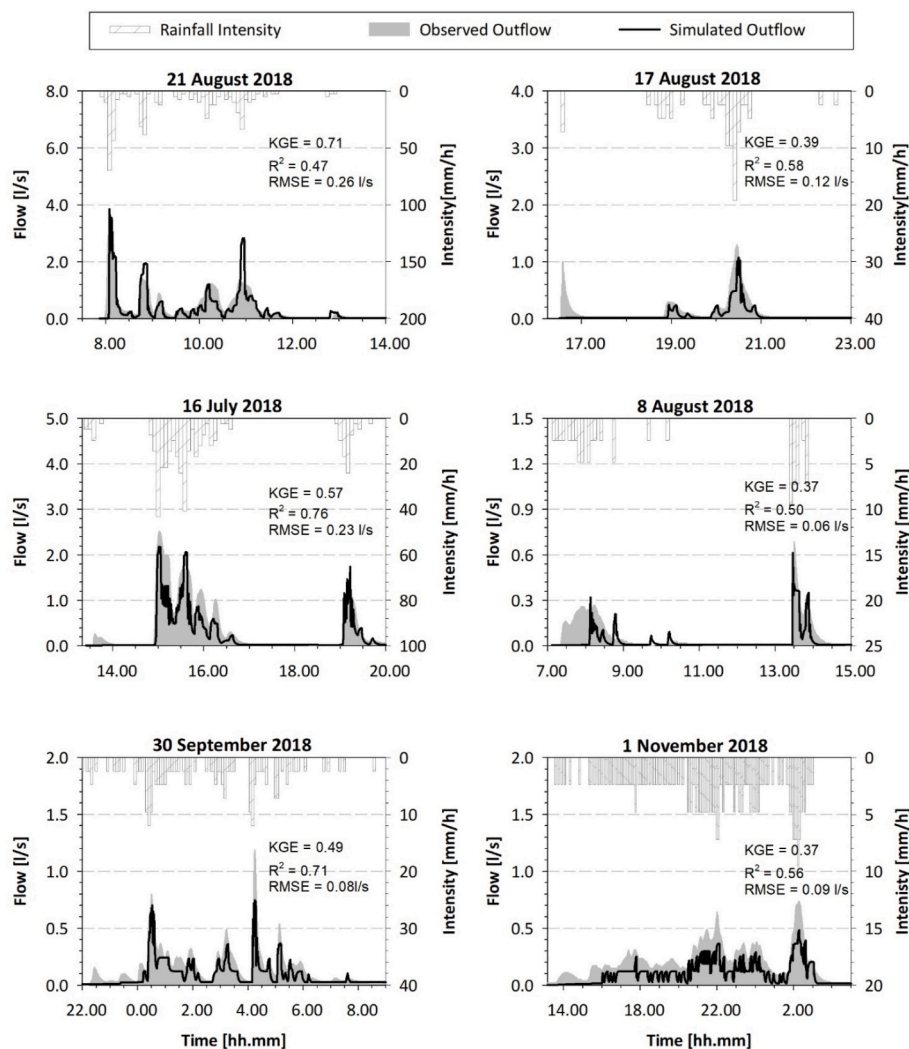


Fig. 3. The hyetographs and the corresponding observed and simulated hydrographs of the Filterra outflow at the study site. The left column refers to the calibration events while the right column refers to the validation events.

of the beginning of the outflow process (see the 17 Aug and the 8 Aug events in Fig. 3) that could be postponed due to the assigned initial saturation value (constant weighted calibrated value) and the simplified scheme of the infiltration process (Tameh et al., 2024).

As shown in Fig. 3, there is no clear tendency in peak underprediction or overprediction in outflow. As an example, the observed peak flows for the 16 Jul event are slightly underpredicted, while for the 21 Aug event the overprediction of peak flow is significant: equal to 29 % with respect to the observed one. The slight underestimation observed for the 16 Jul event may be attributed to an incorrect assumption of the initial saturation level of the Filterra system, as well as a moderate underestimation of the inflow (see also Fig. S3). The overprediction for the 21 Aug event may be attributed to SWMM's limitations in modelling the dynamic behaviour of the Filterra's media during intense rainfall events. According to several studies (e.g., Gülbaz and Kazezyilmaz-Alhan, 2017), SWMM may fail to accurately represent percolation and infiltration processes in systems with complex media compositions, which could result in disparities during extreme events. Liu and Fassman-Beck (2017) also observed high peak flows, slow rising limbs and shorter hydrograph recessions limbs while modelling BRC column using SWMM. According to their research, these errors occurred because SWMM oversimplified the processes of soil infiltration, particularly under conditions of high inflow rates. In contrast to their findings, which indicated that SWMM resulted in slow-rising limbs, the current study observed well-matched rising limbs. This is likely due to the Filterra's media that facilitated fast saturation and drainage. Notwithstanding these fluctuations in peak flow size, the predictions for time-to-peak are accurate with average variances of less than 2 min in most instances. It signifies that the model is successful in accurately capturing the timing of peak flow runoff. Regarding the model's ability to predict the first peak, the results accurately reproduce the initial peak observed in both inflow and outflow during the 21 Aug event (see Fig. 3 and Fig. S3). This demonstrates that the hydrologic and hydraulic behaviour of the study site, including the Filterra system, is well represented even under high-intensity rainfall conditions (>60 mm/h). In this event—unlike others such as the one on 16 Jul—the intense rainfall generated substantial runoff (inflow), leading to saturation in the upper soil layers of the Filterra system. This saturation triggered infiltration, percolation, and drainage processes, ultimately resulting in measurable outflow. Notably, the SWMM-BRC LID module simulates infiltration beginning from a saturation condition at the top of the soil layer, as described by Tameh et al. (2024).

Another notable observation was that SWMM occasionally produced rectangular-shaped outflow hydrographs, characterized by truncated and extended peak durations, especially when the BRC was fully saturated. This behaviour, that could be detected in the 16 Jul event between the 15:10 and the 15:20 but also moderately observed in the 30 Sep and 1 Nov events (see Fig. 3), results from SWMM's simplified representation of soil moisture dynamics, particularly the percolation equation. SWMM assumes a uniform saturation threshold and employs a simplified drainage process that fails to account for the complex infiltration dynamics observed in real-world systems (Tameh et al., 2024). The tendency to simulate rectangular hydrographs has been verified in other research, including Gülbaz & Kazezyilmaz-Alhan (2017), that reported similar hydrograph shapes in column BRCs with differing rainfall intensities and durations. Similarly, Lisenbee et al. (2022) observed that

during high-intensity rainfall events, when the k_{sat} of the BRC media was reached, most outflow hydrographs had a rectangular shape and overestimated peak outflow. The results support the idea that the simplified and rectangular shape of the outflow hydrograph is a result of SWMM's simulation of drainage under saturated situations.

3.3. TSS calibration and validation result

After calibrating and validating the hydrologic model of the system, the calibrated wash-off parameters (C_3 and C_4) and RE of the inlet concentration at the event scale over four rainfall events selected for TSS calibration, Cal-TSS, are outlined in Table 7. By considering C_1 equal to 60 [kg/ha] and C_2 0.177 [1/day] and a removal rate equal to 81 %, the parameter C_3 , fluctuated between 0.017 and 0.098 [h_4^Q/mm_4^Q], whilst C_4 spanned from 0.71 to 0.9 [-], which indicates a more consistent behaviour across the storm events. At this phase of calibration (phase 1), the RE at the inlet constantly remained below 2.5 %, underscoring the acceptable accuracy of inlet TSS simulation.

The C_3 and C_4 values obtained in this study are lower than those reported in previous studies, aligning more closely with the lower boundary of the literature data (refer to Table 3). For instance, Shrestha and He (2017) reported an average C_3 value equal to 0.087 for residential area and Piro et al. (2010) an average of 0.025 which are in good agreement with the results obtained in the present research. Likewise, the C_4 values reported by Rezaei et al. (2019) for residential land use are align more closely with those recorded in this study.

Pollutant wash-off rates are markedly site-specific being affected by rainfall characteristics coupled with other factors such as the sub-catchment and the pollutant constituent characteristics. While previous studies, such as Shrestha & He (2017) suggest that longer and more intense storm events result in increased pollutant wash-off delivery; this correlation is not consistently found in the investigated monitoring study. It has to be noticed that if the rainfall intensity may account the capability of potential pollutant detachment and transport during rainfall event, the pollutant availability resulting from the build-up process may play a crucial role on pollutant mass delivery. For example, the 21 Sep rainfall event, with a maximum intensity of 40.8 mm/h, revealed the highest C_3 value of 0.098 [h_4^Q/mm_4^Q], nevertheless, the 21 Aug event showed a lower C_3 value (0.05) even though it had the highest rainfall intensity (69.6 mm/h), indicating that other factors beyond rainfall intensity alone may play a dominant role in wash-off behaviour. Note that the monitored TSS concentration from the Filterra inlet and outlet is a composite value for each storm event, lacking the characterization of the pollutant behaviour during the runoff event. As a result, the correlation between storm characteristics and wash-off rates may be even less predictable. In addition, the build-up process is modelled using an ADWP exponential law, potentially oversimplifying the dynamics of pollutant accumulation. Additional sources of pollutants, including maintenance activities and surface washing can significantly modify the initial pollutant mass present at the beginning of each rainfall-runoff event, resulting in variations in wash-off loads despite comparable rainfall conditions. The findings underscore the complexity of stormwater pollutant transport, indicating that wash-off is influenced by multiple interacting factors rather than an individual dominant variable. This is consistent with the findings of Tu & Smith (2018), who demonstrated that pollutant build-up is more predictable than wash-off.

Following the calibration process, the weighted average calibrated values for the wash-off parameters were established as follows: $C_3 = 0.056$ [h_4^Q/mm_4^Q] and $C_4 = 0.77$ [-]. Fig. 4 shows a comparison of the simulated and observed TSS concentrations at the inlet and outlet of the Filterra system for all the modelled events including both the calibration and the validation events. The predicted TSS concentrations, based to the weighted average calibrated values, are reported in Fig. 4a for the inlet and in Fig. 4b for the outlet. RE of TSS modelling at inlet and outlet are reported in Table S2 for each event using the above mentioned weighted calibrated wash-off parameters.

Table 7
Initial calibrated wash-off parameters (C_3 and C_4) and relative error (RE) of TSS modelling for each event.

Rainfall event	C_3 [h_4^Q/mm_4^Q]	C_4 [-]	RE Inlet [%]
06 Aug	0.017	0.77	0.7
08 Aug	0.019	0.77	2.3
21 Aug	0.059	0.8	0.7
21 Sep	0.098	0.71	0.2

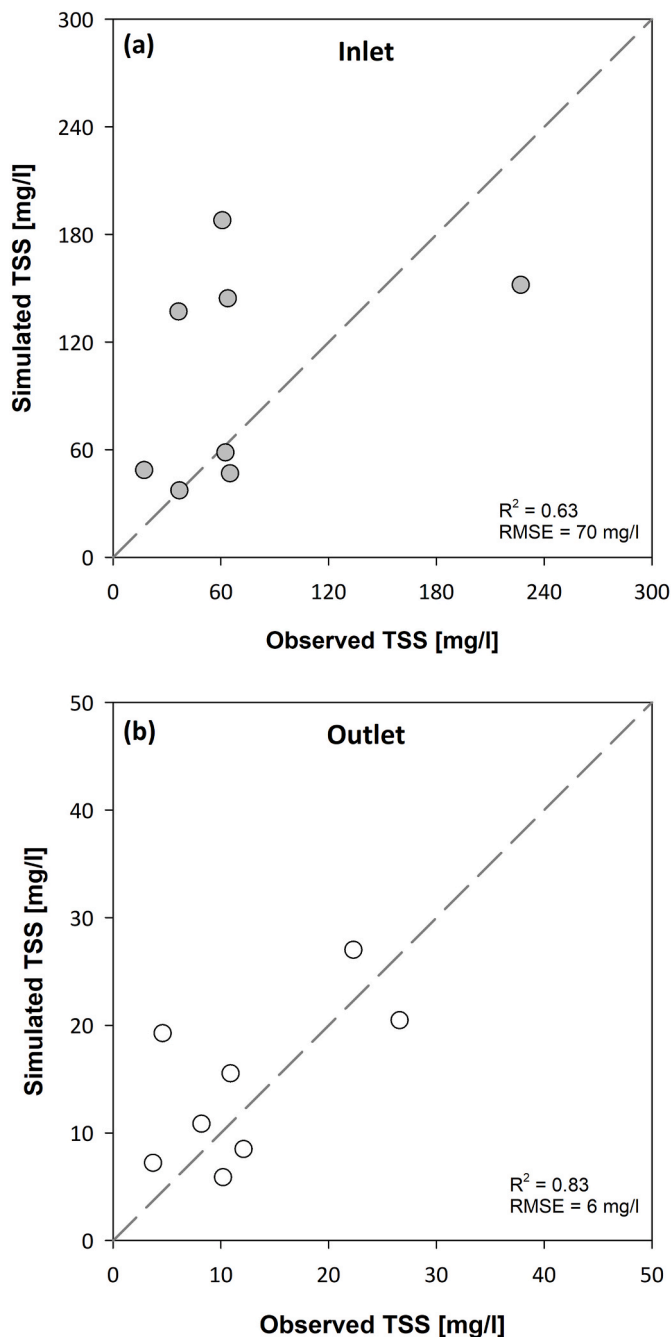


Fig. 4. Observed vs simulated TSS concentration at the (a) inlet and (b) outlet of Filterra for calibration and validation events. The simulated is based on the weighted average of C_3 and C_4 .

The calibration and validation data at the inlet (Fig. 4a) reveal an increasing divergence between simulated and observed TSS concentrations at high concentration values. Such increasing divergence occurs because the set values of C_3 and C_4 fail to account for event-specific fluctuations in TSS concentrations, although the fixed parameters offer a stable framework for evaluating average system performance. This is particularly beneficial for setting baseline expectations and ensuring regulatory compliance, since it streamlines analysis and aids stakeholders in comprehending standard removal efficiencies. Although fixed C_3 and C_4 values may not encompass all variations, they enhance the comprehension of system dynamics over time.

At the outlet (Fig. 4b), the simulated TSS concentrations well reproduce the measured ones. The enhanced alignment indicates that

the SWMM model, although using a constant treatment rate of 81 % applied to the underdrain flow as per SWMM's LID module structure, provides an effective estimation of average treatment efficacy. Although this fixed efficiency is advantageous for establishing baseline performance expectations, it does not accurately represent the dynamic behaviour of TSS removal through Filterra system under changing hydrologic and hydraulic conditions, including the physical filtration of colloids and particles as they percolate through the media profile, in addition to adsorption and microbial interactions (Nazarpour et al., 2023). As a result, Fig. 4 illustrates that the model's performance is satisfactory in TSS removal prediction, as indicated by $R^2 > 0.8$ and $RMSE < 10$ mg/l for the Filterra outlet; however, the deviations observed in specific events suggest that a more adaptable modelling approach is required to account for the variability in removal efficiencies that is affected by the LID system characteristics as well as by the pollutant constituent of concern.

4. Conclusion

The lack of a clear understanding of the hydraulic behaviour of compact BRCs, such as Filterra, and the need for suitable and field-validated models that can effectively predict the hydrologic and pollutant removal performance of Filterra continue to be a barrier to their optimization and wider deployment at the city scale. The purpose of this study is to overcome this gap by defining the hydraulic characteristics of Filterra's EM through laboratory testing as well as implementing a comprehensive SWMM model calibrated and validated based on a quality and quantity dataset observed in the study site located at Kortright in Vaughan (ON, Canada).

The Key findings can be summarized below:

- The laboratory tests highlight the specific hydraulic properties of the Filterra's EM, showing high K_{sat} of 1750 mm/h coupled with a total porosity of $0.42 \text{ cm}^3/\text{cm}^3$ and a field capacity of 0.12 at pF 2.5.
- The field-validated SWMM model is capable of reproducing inflow and outflow dynamics with acceptable accuracy ($KGE > 0.37$, $R^2 > 0.47$), capturing key hydrologic processes at the event-scale such as peak flow, time to peak, and total volume. However, the tendency to the volume underprediction in outflow can be detected due to the initial saturation value and to the simplified infiltration process in SWMM.
- TSS modelling demonstrated a suitable prediction of TSS outflow concentration values, although the constant removal rate in SWMM LID modules does not adequately account for the variability in TSS removal processes.

These results demonstrate that a calibrated and validated SWMM model of the Filterra system can potentially be used to assess the hydrologic and pollutant removal capabilities of compact BRCs. However, it remains a simplified description of the complex interactions that govern infiltration, drainage, and pollutant dynamics in compact BRCs. It should be noted that the event-scale water-quality modelling approach, which relies on literature-based build-up parameters and calibrated wash-off parameters, does not explicitly represent pollutant accumulation during extended dry periods; nevertheless, it is suitable for predicting the BRC pollutant removal efficiency and is easily replicable. Future investigation into water quality performance should include a high temporal resolution monitoring program to accurately capture the pollutants delivery dynamics and treatment behaviour that may yield a clearer comprehension of pollutant dynamics across different hydrologic conditions, supporting improvements to the water quality algorithms in the SWMM LID module. Furthermore, assessing and/or predicting Filterra's performance under varying rainfall patterns, land uses, and pollutant loading scenarios is essential for evaluating its adaptability and effectiveness in urban stormwater management. In addition, future studies should explore continuous simulation

frameworks when sufficient data are available to better represent temporal variability and internal treatment processes.

This study contributes to the development of compact BRC modelling by incorporating detailed laboratory measurements, targeted field observations within the comprehensive SWMM-based framework, including the two-step calibration strategy that enhances the available quali-quantity experimental data. By achieving the outlined objectives, the research supports the development of transferable, physically grounded modelling tools and design guidelines, thereby facilitating the wider implementation of high-performance, space-efficient stormwater solutions, like Filterra, in densely urbanized environments.

CRedit authorship contribution statement

Shaahin Nazarpour Tameh: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation, Conceptualization. **Jennifer Drake:** Writing – review & editing, Resources, Methodology, Conceptualization. **Anna Palla:** Writing – review & editing, Validation, Software, Resources, Methodology, Conceptualization. **Ilaria Gnecco:** Writing – review & editing, Validation, Software, Resources, Methodology, Data curation, Conceptualization.

Software and code availability

The primary hydrologic simulations were conducted using EPA SWMM version 5.3, developed by the U.S. Environmental Protection Agency (EPA). The core engine is implemented in C, and the official source code and documentation are available at:

<https://www.epa.gov/water-research/storm-water-management-model-swmm>.

Custom routines for model calibration and validation were developed in R version 4.2.3, using the hydroGOF and DEoptim libraries. The environment of the author was as follows:

- OS: Windows 11
- System type: 64-bit operating system, x64-based processor
- CPU: Intel(R) Core(TM) i7-1165G7 @ 2.80 GHz
- RAM: 8.00 GB
- Software: EPA SWMM 5.3, R 4.2.3

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envsoft.2026.106877>.

Data availability

The dataset used in this study is available upon request at the

following Zenodo repository:

<https://doi.org/10.5281/zenodo.15582895>.

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