Bioretention Cells in Urban Stormwater Management: An Integrative Framework for Hydrologic, Hydraulic, and Water Quality Performance Assessment

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Abstract

Bioretention cells (BRCs) are widely adopted as sustainable, low-impact development solutions for managing urban stormwater and improving load reduction. Notwithstanding extensive research and widespread implementation, an understanding of the optimal design, effectiveness, and placement strategies for BRCs remains limited. This Ph.D. dissertation addresses these gaps with a thorough investigation comprising three research chapters: a systematic review of existing BRC studies, an evaluation of improved BRC design using a multi-criteria decision-making framework, and a full-scale assessment of a compact BRC system. The systematic analysis examined 114 studies, including field measurements, laboratory experiments, and numerical modelling studies, to synthesise and evaluate the performance of BRCs across a range of designs and site conditions, highlighting significant variability in key indicators, such as runoff volume reduction, peak flow mitigation, and constituent load reduction. This chapter highlights that the variability in performance can stem, sometimes to a significant extent, from a BRC design configuration and site-specific conditions. The analysis illustrates that BRC design improves the functionality of the anthropogenic hydrologic cycle and facilitates load reduction. However, the systematic analysis also highlights critical research gaps, including limited evaluation of BRC effectiveness beyond the site scale and lack of reliable, standardized models to predict long-term performance under highly variable urban conditions. The second research chapter focused on improving BRC design and placement within urban residential settings, building on the insights from systematic analysis presented in chapter 2. Chapter 3 investigated how effectively BRCs perform when implemented across urban residential settings and examined their response under varying rainfall intensities, imperviousness degree, and different BRC configuration settings. For this purpose, an analytic hierarchy process (AHP) was employed within a multi-criteria decision-making (MCDM) framework to identify the suitable spatial footprint for BRCs. The analysis considered five key criteria—hydrologic metrics (volume reduction and peak flow reduction), hydraulic metrics (node flooding reduction and network stress reduction), and total cost—to determine BRCs' footprint and spatial distribution that balance technical performance with economic considerations. This integrated approach contributes to practical design guidelines for urban planners aiming to increase stormwater management benefits while reducing land use and cost. The third research chapter involved a full-scale evaluation of the proprietary compact bioretention system. Conventional BRCs often require substantial land area, making them

impractical in densely populated urban environments. In contrast, the compact BRCs offers the potential for effective urban stormwater management in space-constrained settings. However, further validation is needed to better characterize performance under site-specific conditions, particularly by linking laboratory-determined hydraulic properties of engineered media with field-based quality and quantity data. This study assessed the hydraulic characteristics of a compact BRC's engineered media through laboratory testing and integrated these results with field monitoring to implement a calibrated and validated stormwater management model (SWMM) model. The results of laboratory experiments show saturated hydraulic conductivity of 1750 mm/h. The validated SWMM model effectively replicates the outflow dynamics with a Kling–Gupta Efficiency (KGE) average of 0.50, indicating acceptable agreement with observed data. Additionally, the model captures the trends of total suspended solids (TSS) concentrations at the outlet with reasonable consistency across multiple storm events, demonstrating its ability to simulate pollutant transport dynamics under the tested conditions. The results indicates that a calibrated and validated SWMM model of the Filterra can potentially be utilized to evaluate the hydrologic and pollutant removal efficiencies of compact BRCs in urban catchments under rainfall events with intensities up to 60 mm/h and inflow TSS concentrations between 17 and 227 mg/L in urban catchments. While the model shows good agreement with observed data in this context, its applicability beyond this range—particularly across varying catchment scales, BRC configurations, or pollutant loadings—requires further validation. In conclusion, this dissertation contributes to urban stormwater management by developing an integrative methodological framework that addresses some of the issues regarding the design and implementation of BRCs. The approach not only provides robust evidence of the effectiveness of BRCs in facilitating natural hydrologic processes and enhancing water quality but also delivers a valuable decision-support tool for improving BRC design and placement. Additionally, the dissertation provides a calibrated and validated model of a compact BRC that can be potentially used to evaluate the hydrologic and pollutant removal efficiencies of compact BRCs in urban catchments before installations. These contributions are expected to advance the planning, evaluation, and implementation of bioretention-based solutions for urban stormwater management.

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List of Abbreviations

Abbreviation	Definition
ADWP	Antecedent dry weather period
AHP	Analytic hierarchical process
BMPs	Best management practices
BOD	Biochemical oxygen demand
BRC(s)	Bioretention cell(s)
CDA	Contributing drainage area
CN	Curve number
COD	Chemical oxygen demand
DO	Dissolved oxygen
EM	Engineered media
ET	Evapotranspiration
HoT	Hot Temperate
HPR	High precipitation regime
HuT	Humid Temperate
IWS	Internal water storage
K_{sat}	Saturated hydraulic conductivity
LID	Low impact development
LPR	Low precipitation regime
MCDM	Multi-criteria decision making
MeC	Mediterranean Continental
NFR	Node flooding reduction
NSR	Network stress reduction
PR	Peak flow reduction
Sub	Sublitoral
SWCC	Soil water characteristics curve
SWMM	Storm water management model
TSS	Total suspended solids
VR	Volume reduction

Chapter 1

Introduction and dissertation overview

This chapter presents an overview of urban stormwater management and its challenges, as well as bioretention cells (BRCs) as a sustainable solution. It explores concisely the evolution of urban stormwater management, the role of BRCs in mitigating hydrologic and water quality challenges, and the current research gaps in this field. The chapter outlines the framework of the dissertation and explains how each chapter contributes to the overall research objectives.

1.1 Background

1.1.1 Urbanization and its impact on stormwater

Over the last two centuries, urban populations have grown at an unprecedented rate, and this trend is expected to continue in the next decades. The world's population is projected to reach 9.8 billion by 2050 according to the United Nations Population Division (UNPD, 2017), with approximately 68% of the world's population expected to reside in urban areas by that time (Walsh et al., 2005). Notably, developed areas such as North America, Western Europe, and Australasia had already reached or exceeded these urbanization levels by 2018 (Axelsson et al., 2021; Fereshtehpour & Najafi, 2025; Madsen et al., 2014).

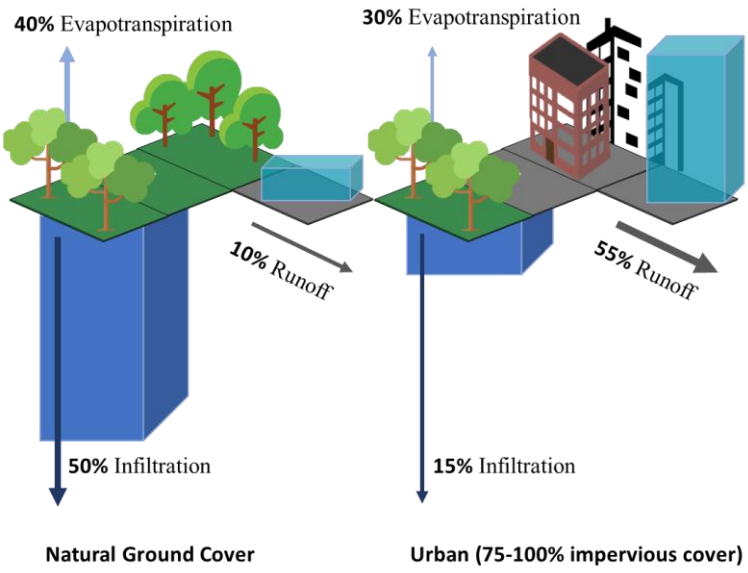

Figure 1. 1 Effects of urbanization on surface runoff (adapted from Environmental Protection Agency, 2009)

This rapid urban expansion has hydrological consequences, altering the natural rainfall-runoff processes. In natural landscapes, precipitation is intercepted by vegetation, infiltrates into the soil, replenishes groundwater, and contributes to the baseflow of streams and rivers. In undeveloped landscapes, approximately 50% of the annual precipitation

infiltrates into deep groundwater, 40% evapotranspires, and only 10% becomes runoff, as illustrated in Figure 1.1. Nevertheless, urbanization has impacted this hydrological balance due to the expansion of impervious surfaces—such as roads, rooftops, parking lots, and paved areas—which reduce infiltration capacity and elevate surface runoff, thereby increasing flood risks (Fletcher et al., 2015; C. Li et al., 2017; Walsh et al., 2015, 2022). The decrease in infiltration capacity reduces the hydrologic response time, resulting in shorter lag times, higher runoff volumes, and elevated peak flows. Furthermore, Urbanization decreases evapotranspiration, interception, and soil moisture retention, hence lowering groundwater recharge, reducing river baseflows, and exacerbating water shortages during droughts (Hamel & Fletcher, 2014; Nazarpour et al., 2023; Vijayaraghavan et al., 2021).

In addition to increased flood risk, urbanization further increases nonpoint source pollution, because impermeable surfaces allow accumulation of pollutants, including potentially toxic metals (e.g., zinc, copper, lead, and cadmium), polycyclic aromatic hydrocarbons (PAHs), microplastics, and excess nutrients from sources like vehicle emissions and atmospheric deposition. For example, studies have shown that metal loadings from vehicle-related emissions, notably zinc (Zn), copper (Cu), lead (Pb), and cadmium (Cd), in urban stormwater can exceed levels observed in untreated municipal wastewater, emphasizing the contamination potential in urban stormwater (Li et al., 2012; Sansalone et al., 2005). During rainfall events, these contaminants are mobilized and transported by stormwater, degrading the water quality of the receiving water bodies or putting significant pressure on the drainage treatment system. Moreover, the expansion of impervious surfaces disrupts the urban surface energy balance, resulting in a decrease in evaporative cooling and an increase in heat retention, in addition to the impacts on water quality and hydrology. This phenomenon exacerbates the urban heat island (UHI) effect, resulting in amplifying the UHI and elevated surface temperatures (Kertesz & Sansalone, 2014; Livesley et al., 2016; Nazarpour et al., 2023).

The adverse effects of urbanization are expected to be exacerbated by climate change, which causes more frequent and extreme storm events (Zhou et al., 2022). These changes increase peakflow rates, overwhelm existing drainage system, and extend the duration of inundation in urban areas. The conventional stormwater drainage systems, purely structural approach, which were originally designed for historical hydrological conditions, are becoming ineffective at managing urban stormwater adequately under these evolving climatic

conditions (Madsen et al., 2014; Walsh et al., 2015). These combined challenges highlight the critical need for robust and sustainable stormwater management solutions that integrate hydrological, ecological, and technical concepts to reduce flooding, improve water quality, and help restore urban hydrological balance.

1.1.2 Evolution of urban stormwater management

The increasing challenges caused by urbanization and climate change demand a fundamental transformation in the approach to urban stormwater management. The underground stormwater infrastructure in several developed cities has undergone a series of historical phases, including the influence of 19th-century European combined sewer systems (Bertrand-Krajewski, 2021). However, its origins can be traced back to ancient civilizations such as the Indus Valley, Mesopotamia, and Rome, which developed remarkably advanced systems for water transport, flood control, and sanitation (Mays et al., 2007).These centralized systems were built to quickly collect and convey stormwater away from urban areas, with a focus on technical factors such as flood protection, public health, and sanitation, but largely overlooked environmental sustainability (Nazarpour et al., 2023; Dhakal & Chevalier, 2016). Although these systems provided immediate advantages in terms of urban flooding, they disrupted natural hydrological processes by increasing runoff, reducing infiltration, and degrading water quality (Bertrand-Krajewski, 2021).

Building on the cumulative knowledge of earlier civilizations, modern urban planning increasingly recognized the limitations of purely conveyance-based approaches, prompting a shift toward more sustainable and multifunctional stormwater management strategies (Chocat et al., 2001). These novel methodologies consider not just technical aspects but also environmental, ecological, social, and governance dimensions. By the 1970s, stormwater management had undergone an important change, with a focus on source control and decentralized approaches that aimed to mimic components of the pre-development hydrological cycle. The change originated by increasing concerns about water quality deterioration, urbanization, and the limitations of traditional drainage systems. The new strategy aimed to move away from the concept of "conveyance and disposal without treatment of stormwater" and toward "retain, detain, and infiltrate," which mimicked the natural hydrological cycle (Hamel & Fletcher, 2014). By the 1990s, urban stormwater management had broadened to include biological, ecological, and social-environmental

objectives. The implementation of green and blue infrastructure led to a transition from underground conveyance systems to landscape-oriented solutions, thus contributing to a more effective stormwater management (Novotny, 2014).

In the 21st century, urban stormwater management has continued to evolve in a more comprehensive and sustainable direction. Modern solutions are designed to manage the volume and quality of stormwater while also including ecological, esthetic, and socio-economic advantages. This change has been enhanced by global regulatory frameworks such as the European Union Water Framework Directive (WFD), which encourages the preservation of water quality and the sustainable management of urban water systems (Bennion & Battarbee, 2007). The Australian leadership, which has pioneered integrated approaches to stormwater harvesting, reuse, and treatment, is equally influential. Their national and state-level guidelines, including the Australian guidelines for urban stormwater management (Anzecc, 2000) and Melbourne water's "Water Sensitive Urban Design" (WSUD) framework have positioned stormwater as a critical resource within the urban water cycle. The contemporary stormwater management approaches emphasize decentralized and adaptive strategies that integrates nature-based and engineered solutions. This paradigm shift indicates a significant evolution in urban water governance, wherein stormwater is recognized not as waste but as an essential resource within an integrated and sustainable water management framework.

1.1.3 Transition to integrated and sustainable stormwater solutions

The transition in urban stormwater management from conventional grey infrastructure to integrated solutions has been influenced by the growing challenges of urbanization, climate change, and the increasing frequency and intensity of urban flooding events, including pluvial and fluvial. Recent developments support the use of hybrid stormwater management solutions, which combine engineered drainage systems with green infrastructure that is appropriate to the site (Beceiro et al., 2020). These approaches aim to reduce volume and peak flow, enhance infiltration, and mitigate pollutant loads at the source, thereby minimizing dependency on conventional drainage systems (centralized conveyance systems). In this context, “sustainable” refers to systems that achieve quantifiable hydrologic and water quality performance targets—such as meeting volume retention and pollutant removal benchmarks—while maintaining long-term operational viability and minimizing

environmental externalities. Accordingly, regulations increasingly support the use of multifunctional stormwater controls, such as bioretention cells, permeable pavements, green roofs, and constructed wetlands, which provide both hydrological and water quality advantages (Alves et al., 2019; Xu et al., 2021). As a result of these advancements, several stormwater management frameworks have been established across the world, with a focus on sustainability, water sensitivity, and integrated urban hydrology, each shaped by governance structures, institutional arrangements, and regulatory approaches (Fletcher et al., 2015).

In North America, the term Best Management Practices (BMPs) originated in the United States following the Clean Water Act (CWA) in 1972, which initially targeted point-source pollution through structural controls for wastewater discharges. With the implementation of the National Pollutant Discharge Elimination System (NPDES) Phase I (1990) and Phase II (1999) programs, the scope of the CWA expanded to include urban stormwater as a significant source of non-point pollution. BMPs were subsequently adopted as a broad category encompassing both non-structural approaches (e.g., operational policies, public education, and source control) and structural measures (e.g., detention basins, infiltration trenches) to reduce pollutant loads (Ice, 2004). By the 1990s, BMPs were widely institutionalized across the United States and Canada. However, the inconsistent use of the term led to growing concerns regarding its effectiveness as a regulatory tool. In response, the 2008 National Research Council (NRC) report proposed a more structured and performance-based classification system. The concept of Stormwater Control Measures (SCMs) was introduced in academic and technical contexts to more clearly differentiate between structural and non-structural practices based on their quantifiable hydrologic and water quality performance, despite the fact that BMP remains the dominant regulatory term in the U.S. (National Research Council, 2008; Fletcher et al., 2015).

stormwater

Simultaneously, in North America and New Zealand, Low Impact Development (LID) gained popularity in the early 1990s because of the necessity for decentralized stormwater management solutions (Prince & County, 1999; Shaver, 2003). LID focuses on small-scale, site-specific solutions like bioretention systems and green roofs, located at or near the source (Fletcher et al., 2015). This approach aims to preserve pre-development hydrology and reduce

the effects of effective impervious surfaces. In the United Kingdom, the concept of Sustainable Urban Drainage Systems (SUDS) or sustainable drainage systems (SuDS) was established in the late 1990s as a viable alternative to traditional piping drainage systems (CIRIA, 2001). SUDS was developed as a component of national initiatives aimed at minimizing flood risks, enhancing stormwater quality, and improving urban environments (e.g., enhanced biodiversity, mitigation of the UHI effect, and the creation of recreational spaces) through the incorporation of elements like swales, detention ponds, and permeable pavements.

In Australia, Water Sensitive Urban Design (WSUD) was introduced in the late 1990s and early 2000s as a holistic approach to incorporate stormwater management, water conservation, and environmental sustainability into urban planning (Mouritz, 1992; Wong, 2006). Brown & Clarke (2007) later clarified the distinction between WSUD as a process and the concept of water-sensitive cities as an objective. Over time, WSUD has achieved global recognition, particularly in the UK and New Zealand, as an effective approach that promotes multi-functional landscapes, ecosystem restoration, and sustainable urban drainage (Ashley et al., 2013).

In France, Alternative Techniques (ATs) and Compensatory Techniques (CTs) emerged in the 1980s as a response to the fast urbanization and corresponding increase in surface runoff (Fletcher et al., 2015). These approaches sought to mitigate the hydrological effects of urbanization through infiltration-based stormwater management, which compensated for the loss of natural infiltration capacity (Azzout, 1995). Although ATs were considered unconventional at first, they eventually became part of urban planning standards and are now considered standard design concepts.

In the United States, Green Infrastructure (GI) originated int the early 2000s as a multifunctional planning strategy for incorporating engineered and nature-based systems into urban planning (Walmsley, 1995). The United States Environmental Protection Agency (US EPA, 2012) defines GI as a set of measures that retain, infiltrate, and treat stormwater at its source, minimizing runoff pollution and urban floods. Over time, GI has grown to include not only stormwater control, but also a wider range of environmental and social advantages, including enhancements in air quality, increased climate resilience, and reductions in urban heat (Fletcher et al., 2015; Keeley et al., 2013).

Notwithstanding variations in terminology, these frameworks have a common objective: restoring urban hydrological process to closely pre-development (natural) conditions, in line with the principle of hydraulic and hydrologic invariance, enhancement of stormwater quality, and promotion of sustainable urban water management. In this dissertation, the terminology of LIDs is adopted. The following section, one of the widely implemented LID practices, bioretention cells (BRCs), is explored which is the primary focus of this Ph.D. study.

1.1.4 Bioretention Cells (BRCs)

Bioretention systems, known as biofiltration, bioinfiltration, bioswales, or rain gardens—terms that may have slight differences (Dagenais et al., 2018)—are recognized for their effectiveness in managing urban stormwater including reducing volume and peak flow, mitigating runoff pollutants, enhance biodiversity, urban esthetics, and contribute to UHI mitigation (Lisenbee et al., 2022; Nazarpour et al., 2023). To maintain consistency, the abbreviation of BRCs is employed throughout this dissertation. Due to their multifunctionality, BRCs have been widely adopted in North America, Australia, Europe, and Asia, with various commercial designs tailored to different climatic conditions (Kratky et al., 2017). Their flexibility in design enables integration into diverse urban landscapes, including roadways, parking lot islands, and tree box filters.

BRCs can be implemented in a variety of configurations to meet the performance objectives, regulatory requirements, and site-specific conditions. These configurations usually have variations in their drainage design, internal storage components, and infiltration capacity. For instance, systems can be designed to promote full infiltration in locations with highly permeable native soils (fully exfiltrating), or to incorporate underdrains that enable partial (semi- exfiltrating) or no infiltration (non-exfiltrating) in regions with low-permeability native soils or concerns regarding groundwater pollution. To enhance specific treatment functions, including nutrient removal or flow regulation, additional characteristics, such as elevated underdrains or internal water storage zones, are frequently implemented. This design versatility enables BRCs to be incorporated into a broad range of urban environments, from open areas to densely populated environments with spatial constraints (Tirpak et al., 2019), while maintaining their efficacy in stormwater quantity and quality management (Nazarpour et al., 2023) — as demonstrated in chapter 2, with volume reductions ranging from

50% to 98%, peak flow reductions between 35% and 99%, and average TSS removal efficiencies exceeding 78%.

1.2 Dissertation structure

This Ph.D. dissertation is structured as a compilation dissertation, consisting of three research papers along with an introduction (Chapter 1) and a conclusion with recommendations for future study (Chapter 5). It should be noted that the major body of this dissertation, provided in Chapters 2-4, is structured in the format of research papers that have either been published or is submitted and hence are subject to limitation of length of the paper, and number of tables, and figures. To provide a more detailed explanations, each chapter has been expanded with supplementary methodological details, enlarged discussions, and contextual analyses. Furthermore, all supplemental information and appendices from the original articles have been integrated directly into the chapters, producing a fully self-contained work. This dissertation meets the applicable requirements in compliance with the copyright policies of MDPI and Elsevier, which explicitly permit the inclusion of the article in a dissertation or thesis. Table 1.1 provides an overview of the publishing details, including the article title, authors, journal name, and status of the paper.

Table 1. 1 Summary of articles

Paper Title	**Authors ***	**Journal**	**Publication Status**
Evaluating the Effectiveness of Bioretention Cells for Urban Stormwater Management	S.N., I.G., A.P.	Water (MDPI)	Published (2023)
Analytic hierarchy process in Selecting Bioretention Cells in Urban settings: Analysing Hydrologic and Hydraulic Metrics for Sustainable Stormwater Management	S.N., I.G., A.P.	Environmental management (Elsevier)	Published (2024)
Hydrologic, hydraulic, and water quality characterization from laboratory test and SWMM modelling: A full-scale evaluation of Filterra® bioretention cell for urban stormwater management of Filterra® bioretention cells for urban stormwater management	S.N., J.D., A.P., I.G.	Environmental Modelling and Software (Elsevier)	Submitted (2025)

** S.N.: Shaahin Nazarpour Tameh; I.G.: Ilaria Gnecco; A.P.: Anna Palla; J.D.: Jennifer Drake*

In this format, chapter 1 provides a concise overview of the impacts of urbanization on hydrologic processes and water quality. The evolution of stormwater management methods and review of various terminologies and conceptual frameworks related to

sustainable urban stormwater management, which, despite their differences, converge on a common goal of mimicking the urban hydrologic cycle to its pre-development state, are presented. Furthermore, it defines the study's focus on evaluating the effectiveness of BRCs in terms of hydrologic and load reduction in the urban stormwater management context. This chapter establishes the research gaps, objectives, and significance of the study.

Chapter 2 presents a systematic review evaluating the effectiveness of BRCs in terms of hydrologic and load reduction for urban stormwater management, focusing on field, laboratory experiments, and modelling. Moreover, this chapter provides recommendations for BRC implementation design that enhance performance outcomes. This chapter is in the journal of Water (MDPI; DOI: 10.3390/w15050913).

Chapter 3 assesses the hydrologic performance of BRCs in urban residential areas through a web-GIS based application that incorporates the stormwater management model (SWMM) (Rossman, 2010). This chapter examines the effectiveness of BRCs beyond site and laboratory scales through the integration of hydrologic-hydraulic performance metrics. The study employs a multi-criteria decision making (MCDM) approach to determine the optimal BRC footprint under different rainfall conditions and imperviousness. This chapter is published in the journal of Environmental Management (Elsevier; DOI: 10.1016/j.jenvman.2024.123142).

Chapter 4 presents a hybrid evaluation of a compact BRC called Filterra® system (Vaughan, Canada) through laboratory testing, monitoring data, and SWMM modelling. This chapter characterizes the hydraulic properties of Filterra media, specifically measuring water retention (measured with HYPROP) and saturated hydraulic conductivity (measured with KSAT). The process of calibrating and validating a SWMM model is elaborated, focusing on hydrologic performance and water quality, particularly TSS reduction, through the integration of field data and laboratory measurements. This integrated approach offers insights into the performance of Filterra and improves the implementation of the Filterra system in the similar urban catchments through a modelling approach. In addition, this chapter illustrates the planning and design of a monitoring Filterra system, which features a slightly different design compared to the Vaughan site. This system has been implemented in a different climatic and land-use context in Venice, Italy. This monitoring program was intended to evaluate hydrologic performance, TSS reduction, and other water quality parameters (e.g., nutrients,

microplastic); however, the data analysis phase is excluded from this dissertation due to challenges faced during installation and data collection. Nonetheless, this dissertation outlines the detailed description of the monitoring design and planning, offering more information into the methodology for assessing compact systems. This chapter is submitted in the journal of Environmental Modelling and Software and includes only the study from the Vaughan site and excludes the Venice site monitoring data.

In conclusion, Chapter 5 synthesizes the findings of the dissertation and provides conclusions and recommendations for future research on BRCs in urban stormwater management. Additionally, it highlights the important insights from previous chapters and emphasizes the need for more research to improve the design, performance assessment, and real-world application of BRC systems in various urban settings under varied rainfall characteristics.

1.3 Research gaps

BRCs are a key component of integrated stormwater management by promoting infiltration, reducing pollutant loads, and contributing to mimicking pre-development hydrology, whether they function as standalone systems or in combination with grey infrastructure and other LID practices. In spite of thorough research, several research gaps remain, hindering the improving and widespread implementation of BRCs. In this Ph.D. dissertation, the research gaps, separated into three sections and are highlighted below.

1.3.1 Variability in the hydrologic and quality effectiveness of BRC

Despite extensive research, BRC performance remains highly variable, particularly regarding hydrologic and pollutant removal efficiency across different environmental conditions, climatic regimes, and system configurations. Hydrologic performance, typically assessed through volume reduction (VR) and peak flow reduction (PR), has shown discrepancies across field and laboratory studies due to differences in design, scale, climate, and contributing drainage area (CDA). For instance, Spraakman et al., (2020) reported that a BRC implemented in a parking lot with Area $_{BRC}$/CDA of 12% obtained an average VR of 93% and PR of 95%. In comparison, Hečková et al., (2022) observed a BRC with an Area $_{BRC}$/CDA = 25% managing stormwater from a rooftop, reporting a VR of under 13%, but obtaining an average PR of 88%. Similarly, J. Li et al., (2021), in a laboratory study, reported a 24% VR and a 54% PR, while the same media amended with 5% biochar resulted in a 51% VR and an 86%

PR. Additionally, a study conducted by Mai & Huang, (2021) demonstrated that an increase of 20 cm in internal water storage (IWS), volume can result in a change in average VR from 13% to 23%.

In addition to hydrologic performance, many studies have examined BRCs' effectiveness to reduce urban stormwater pollution with significant variations. While studies showed high TSS reduction performance, there are noticeable variances in reducing the other pollutants. For instance, Gilbreath et al., (2019) monitored a BRC over three years, from 2012 to 2017 and Area $_{BRC}$/CDA = 0.15%. The average TSS decrease ranged from 79% in 2012 to 97% in 2017. In a study conducted by Søberg et al., (2020), IWS improved TSS removal of BRC with a mean removal rate of 98%, while 90% for the BRC without IWS. Notably, the performance discrepancies are more evident in nutrient removal. In the study performed by Hsieh & Davis, (2005), a wide range of total phosphorus (TP) removal efficiencies (4–99%) was observed; however, Kandel et al., (2017) demonstrated that a 5% fly ash amendment in media led to TP reductions ranging from 64% to 75% in different land uses (residential to commercial, respectively). Furthermore, the efficacy of nitrogen oxides (NO_x), which include nitrate (NO_3^-) and nitrite (NO_2^-) oxide (NO), removal shows considerable variation, as Lopez-Ponnada et al., (2020) reported an 81% removal rate in BRCs utilizing 30 cm of IWS, in contrast to a mere 29% in designs lacking IWS. These discrepancies highlight the need for analysing the performance of the BRCs carefully to understand if BRCs are effective practices for urban stormwater management. Chapter 2 of this Ph.D. dissertation will focus on this research gap.

1.3.2 Selection of the optimal footprint of BRC at urban residential setting

The majority of research mainly evaluates the performance of BRCs at either the site scale or within controlled laboratory environments, specifically analysing the inflow and outflow dynamics of these systems (Li et al., 2017). However, there exists a noticeable gap in the understanding of how BRCs can effectively contribute to sustainable urban stormwater management at the scale of urban residential areas (Tameh et al., 2024; Walsh et al., 2015). Additionally, most of the previous studies are carried out on how BRCs can enhance urban stormwater management evaluating common hydrologic metrics (VR, PR, time lag, runoff coefficient and etc); however, the effect of the BRCs on the drainage network and flood prevention (hydraulic metrics) are still limited in literatures (Tameh et al., 2024).

In addition to the noted research gaps, a critical concern in BRC implementation is the lack of standardized guidelines for their design and installation in urban areas. While certain studies have suggested key design principles—such as multi-functionality, connectivity, and long-term planning—there remains an absence of clear, universally recognized frameworks for optimizing BRC placement and configuration at urban residential setting, considering not only the hydrologic metrics, but also hydraulic metrics as well as economic factors. Multi-Criteria Decision-Making (MCDM) approaches can be an effective method for assessing BRC performance across various urban contexts (Yang & Zhang, 2021). Additional research is required to develop comprehensive decision-support tools that enable informed planning and implementation of BRCs in urban stormwater management. Chapter 3 will be dedicated to this research gap.

1.3.3 The need for compact BRCs in space-constrained urban environments

Spatial limitations in densely populated urban environments present a considerable challenge to conventional BRC designs, which generally necessitate between 5% and 20% of the CDA (Nazarpour et al., 2023). In response to this challenge, compact BRC systems have been designed, providing a small footprint less than 1% of CDA. In this Ph.D. dissertation, one of the trademarked compact BRCs, which is called Filterra® (Terry Lee Siviter, 2008), have been investigated.

While research on compact BRCs remains limited, preliminary studies suggest encouraging outcomes, particularly regarding enhancements in water quality. Gilbreath et al., (2019) reported a 94% TSS removal using a semi-exfiltration compact BRC design with sandy loam media and an $Area_{BRC}$/CDA ratio of just 0.15%, showing the capacity of the BRC to treat highly impervious roadway runoff. In another study, Braswell et al. (2018) evaluated a combined system that integrated permeable pavement with Filterra as a secondary treatment in series. The standalone Filterra demonstrated limited efficacy in volume and peak flow reductions, achieving 1% and 14%, respectively, while successfully achieving a 96% reduction in TSS. However, the effectiveness of compact BRCs across various climatic and land use conditions has not been thoroughly assessed. Additionally, further verification is required to establish a connection between site-specific water quality and quantity outcomes and well-established laboratory-derived media properties, including the soil water retention curve and hydraulic conductivity. This is important to enhance the accuracy of modelling. Additionally,

designers face a challenge in improving compact BRCs for site-specific conditions, refining their designs, and scaling their impacts from individual installations to the catchment scale due to the lack of validated models (Lisenbee et al., 2020).

The practicability of compact BRCs as space-efficient stormwater solutions in densely urbanized areas may be improved by addressing these research gaps through monitoring, numerical, laboratory experiments, and modelling efforts. This research gap will be addressed in Chapter 4.

1.4 Research objectives

This Ph.D. study aims to conduct a comprehensive evaluation of the effectiveness of BRCs, as one of the essential LID practices, in improving hydrologic processes and stormwater quality for the purpose of sustainable urban stormwater management. The objectives of this dissertation, which are established based on the research gaps presented in section 1.2, are listed in accordance with the format of the following chapters.

1. Evaluation of the variability in the effectiveness of BRCs for urban stormwater management (*address research gap 1.2.1*)
    - Hydrologic performance: Assess the extent to which BRCs mimic key component of natural hydrologic processes in urban catchments (e.g., runoff volume reduction, peak flow attenuation) relative to undeveloped conditions.
    - Water quality performance: Assess the effectiveness of BRCs in improving the quality of stormwater through pollutant load reductions stormwater
2. Assessment of the hydrologic performance of BRCs in urban residential settings (*address research gap 1.2.2*)
    - Evaluate the effectiveness of BRCs when implemented across urban residential area.
    - Examine how varying rainfall characteristics, degrees of imperviousness, and different BRC configurations affect performance.
    - Identify the optimal BRC footprint using a MCDM framework that integrates hydrologic, hydraulic, and economic metrics for urban flood mitigation.

3. Investigation of the capability of Storm Water Management Model (SWMM) in simulating the hydraulic and TSS transport behaviour of a compact BRC. (*address research gap 1.2.3*).

    - Conduct laboratory experiments to gain better insights into the engineered media of Filterra, including water retention properties and saturated hydraulic conductivity, to support site-specific model validation
    - Develop a systematic calibration and validation procedure for SWMM to reproduce the inflow-outflow dynamic and TSS performance of Filterra, under data-limited conditions.
    - Establish a set of model parameters applicable to similar urban context to evaluate the performance of Filterra® in reducing TSS and regulating stormwater quality.

1.5 Significance and Contribution

This Ph.D. dissertation aims to contribute to sustainable urban stormwater management by addressing critical research gaps in improved design, effectiveness, and placement strategies of BRCs. Systematic reviews of existing research studies, including laboratory tests, field measurements, and numerical modelling provide evidence that BRCs can decrease urban stormwater volumes and peak flows, while also enhancing load reduction. These findings present a methodological framework for improving the design and placement of BRCs and offer insights into the implementation of compact BRCs.

Specifically, the dissertation presents an integrated framework that combines numerical modelling (SWMM) with various configurations of BRCs in an urban residential setting, using a MCDM method. This approach assesses BRC performance employing hydrologic, hydraulic, and economic metrics under diverse imperviousness and rainfall events, providing a decision-support tool for urban planners and policymakers. Additionally, the investigation of the Filterra system illustrates the properties of its engineered media, monitoring setup design, calibration-validation procedure with limited data, and a model applicable to similar urban contexts. This research establishes a framework for the implementation of more BRCs and the improvement of sustainable urban stormwater management in the context of increasing urbanization.

Chapter 2

Evaluating the Effectiveness of Bioretention Cells for Urban Stormwater Management: A Systematic Review

This chapter is based on the paper published of Nazarpour et al., 2023. It analyses the hydrologic and water quality performance of the bioretention cells, identifies important design issues, and indicates research gaps.

2.1 Abstract

Bioretention cells (BRCs) are a promising low-impact development (LID) practice that are commonly used in urban settings to improve the water quality and mitigate the hydrological impacts of stormwater. BRCs have been the subject of extensive research to better comprehend their function and improve their effectiveness. However, BRC performance differs greatly among regions in terms of hydrologic performance and quality enhancement. Due to this variance in BRC effectiveness, the current study conducted a comprehensive systematic review to answer the question, "Are BRCs an effective LID method for urban catchment stormwater management?". This review study analysed the effectiveness of BRCs in mitigating hydrologic impacts and enhancing the quality of stormwater in urban catchments. A review of 114 field, laboratory, and modelling studies on BRCs found that the promising BRCs may be one of the most successful approaches to restore urban hydrology cycle and improve stormwater water quality. With further development of BRCs, their performance in terms of quantity and quality will become more reliable, helping to develop long-term solutions to stormwater urban drainage issues. At the end of this review, the knowledge gaps and future prospects for BRC research are presented. In addition to providing a foundational grasp of BRC, this review study outlines the key design recommendations for BRC implementation to address the issues raised by certain BRC design errors.

2.2 Introduction

2.2.1 Background

The most significant effects of the rapid urbanization are the dramatic changes in land use, rising imperviousness, and the increase in pollutant load build up on urban surfaces (Walsh et al., 2005). The transformation of natural permeable surfaces to impermeable

surfaces has a concerning impact on the hydrology response of a catchment. As a result, runoff (both in terms of volume and peak flow rate) has increased, while infiltration and evapotranspiration have decreased, thus increasing the occurrence of flash floods and decreasing the recharge of groundwater supplies, as well as increasing nonpoint source contaminants(Hatt et al., 2004; Roy et al., 2008). At the same time, climate change exacerbates the negative consequences. The quantity and quality of urban stormwater may be impacted by climate change-related alterations such as changes in the distribution of rainfall events on an annual basis, which will make dry regions drier and wet regions wetter, as well as increasing the frequency of intense rainfall events (Madsen et al., 2014).

Historically, urban drainage systems have been designed to collect and convey stormwater and eventually its mixture with sewage (combined or separate approach) directly to the receiving water bodies (Chocat et al., 2007). In Europe, the standard conventional approach (known as grey infrastructure) for controlling stormwater and limit the occurrence of floods in urban areas includes (other than the drainage of stormwater as fast as possible through a network of channels and pipes) the construction of detention storage volume and structural defences to protect exposed locations (Grand-clement marie, 2017). In response to the above-mentioned effects of urbanization and climate change, the European Union (EU) focused on both surface and groundwater bodies in 2000 by introducing the Water Framework Directive (WFD) to improve their quality and protect aquatic environments (Bennion & Battarbee, 2007). Consequently, the conveyance approach has been gradually replaced by source control approaches that emphasize esthetic value, recreational value, ecological preservation, and other beneficial values over quantity and quality control (Chocat et al., 2007; Stahre, 2006). Indeed, conventional drainage systems are unable to effectively manage the continuous and significant increase in stormwater because of urbanization and/or climate change; additionally, there is a clear need to promote environmental protection policies and practices to minimize the impact of stormwater discharges on aquatic ecosystems. In this framework, low-impact development (LID) has been widely considered to deal with these issues. LID is an ecological engineering practice that aims to not only maintain or recreate natural hydrologic conditions in a developed area, but also to enhance the quality of runoff, promote evapotranspiration (ET), and provide a variety of other benefits (Oral et al., 2021). The concept rests on four key activities: (1) minimizing impervious areas, (2)

implementing on-site stormwater management systems, (3) routing stormwater through the watershed to mimic pre-development concentrations, and (4) educating the public on pollution prevention and on the maintenance of stormwater management systems (Cheng et al., 2001; Jia et al., 2013). It is noteworthy to mention that several similar concepts have also emerged in other developed countries (which is explored comprehensively in the Chapter 1), such as sustainable urban drainage systems (SUDS), green infrastructures (GI), blue-green infrastructures, best management practices (BMPs), and water sensitive urban design (WSUD) (Fletcher et al., 2015). There are various well-known LID practices, such as bioretention cells (BRCs), rainwater harvesting systems, vegetated open channels, downspout disconnection, permeable pavements, and green roofs (Hsieh & Davis, 2005; Palla et al., 2018; Vijayaraghavan, 2016). This review study focuses on BRCs, a kind of structural, vegetated LID that has attracted significant interest in recent years.

Bioretention systems are one of the source control LID practices that were first introduced in Prince George's County, Maryland, in the 1990s (Prince & County, 1999). Since then, they have grown to be one of the most promising among LIDs (Dagenais et al., 2018). The promising BRCs rely on the ecological functions of a terrestrial system (upland-based as opposed to wetland-based) of soil, plants, and microbes to retain and treat stormwater. Bioretention systems consist of a small area which are excavated and backfilled with a mixture of high-permeability soil and organic matter designed to maximize infiltration and vegetative growth and are covered with native terrestrial vegetation (Roy-Poirier et al., 2010). A schematic representation of a BRC is illustrated in Figure 2.1. The distinctive advantages of bioretention include enhanced runoff quality (Li & Davis, 2016), decreased runoff volume and peak flow (YYang & Chui, 2018), adaptable integration into urban landscapes (Ellis, 2013), improved biodiversity and esthetics (Kazemi et al., 2009), and the mitigation of urban heat island (UHI) effects (Livesley et al., 2016). Extensive research has been conducted on BRCs in an effort to comprehend their functions, improve their performance, and extend their lifespan (Liu et al., 2014), but the real data on the performance of these system components over an extended period of operation in the field are insufficient and most of the studies have

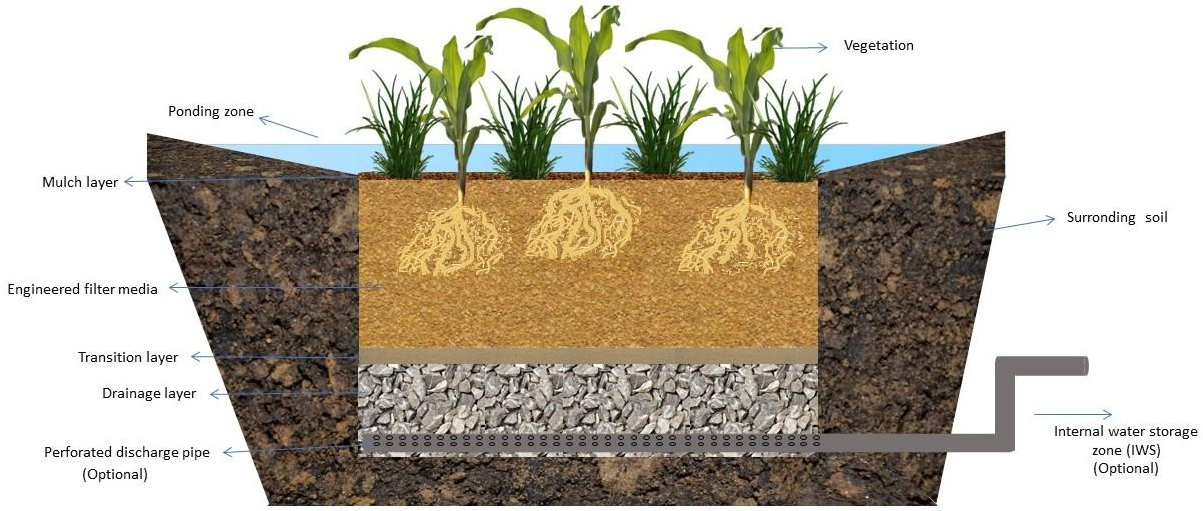

Figure 2. 1 Schematic representation of a bioretention cell.

been conducted in the laboratory, using prototypes, synthetic inflow, and numerical studies (Muerdter et al., 2020). Because of this knowledge gap, bioretention designers and city planners are often unfamiliar with the different bioretention design options, such as the selection of vegetation to be utilized at a given site and the selection of substrates to be considered for certain goals of a BRC, such as the removal of inorganic or organic contaminants (Cosgrove & Bergstrom, 2003). Although some developed countries have established regional guidelines to address this problem, these regulations tend to apply exclusively to specific regions (Roy-Poirier et al., 2010). In retrospect, it is possible to attribute some of BRCs' failures to the fact that these guidelines were adopted without considering local infrastructure and climate conditions (Wang et al., 2017).

2.2.2 Previous Literature Reviews

Over the last five years, various review papers on BRCs have been published (Biswal et al., 2022; Muerdter et al., 2018; Osman et al., 2019; Skorobogatov et al., 2020; Spraakman et al., 2020). The effects of vegetation on the hydrologic and pollution mitigation performance of BRCs are underlined in the study conducted by Muerdter et al., (2018). Plants improve water infiltration, decrease media clogging, and allow water to evapotranspirate while reducing BRC surface erosion. The effect of plants on the removal of total suspended solids (TSS), phosphate, hydrocarbons, and pathogens are modest, but their effect on nitrogen removal is considerable. This is especially true when the broad range of nitrogen removal capacity among plant species is considered. In the study of Muerdter et al., (2020) provides an overview of the relevance of vegetation in BRCs in terms of pollution removal and other

advantages such as better esthetics, providing of urban micro-habitats, higher resilience to climate change, and the possibilities of enhancing air quality, biomass generation, and/or food production. Moreover, this research emphasizes the dearth of long-term field and continuous modelling investigations. In another study by Biswal et al., (2022), a critical review of evaluation of the effectiveness of BRCs based on biochar for the removal of chemical and microbiological contaminants existed in urban stormwater was introduced. To enhance the long-term effectiveness of BRCs, Skorobogatov et al., (2020) emphasizes the need for comprehending the media–vegetation interactions and maximizing these interactive interactions. Additionally, Osman et al., (2019) highlights the cutting-edge innovations in BRCs and provides a summary of research on nitrogen removal for urban stormwater. However, most of the previous review studies on BRCs in urban catchments were almost all narrative reviews that lacked a comprehensive and detailed analysis of the effectiveness of bioretention systems. The latest scoping review performed by Spraakman et al., (2020) investigated the methodology and metrics for the performance of BRCs in field studies. However, the effectiveness of BRCs was not reviewed and laboratory investigations were not included in this review study.

The purpose of this systematic review article is to examine the effectiveness of BRCs in mitigating the alteration of the natural hydrological cycle and improving the quality of storm water runoff in urban catchments. The present review study concentrates on recently published publications encompassing field, laboratory, and numerical modelling research, and evaluates several factors that contribute to the performance of BRCs.

This systematic review study aims to answer the principal research question of whether BRCs are an effective practice for managing stormwater in urban catchments in terms of both quantity and quality issues. Additionally, the present review study tried to compile the most recent knowledge on the use and design of BRCs in a variety of climatic conditions, applications, and local infrastructures to assist researchers, operators, and regulators in avoiding specific design errors. Finally, this systematic review paper tries to identify knowledge gaps and future prospects for BRC research and present the key design recommendations for BRC implementation.

2.3 Materials and Methods

The research articles used in this study were from Scopus, one of the most prominent and comprehensive bibliographic abstract and citation databases currently accessible (Baas et al., 2020). The time frame spans from the database records in 2017 through to the end of September 2022. The selection of this time frame is since, according to Scopus data, BRCs have recently gained increasing global attention in urban catchments for stormwater management, regarding both quantity and quality. Furthermore, the number of countries contributing to BRC research has increased during this time frame has presented a greater variety of environmental and architectural aspects to evaluate. Consequently, the present review study aimed to assess the most recent developments and studies conducted regarding BRCs in urban catchments for the management of stormwater from a quantity and quality perspective.

The approach for this systematic review was based on the framework established by Arksey and O'Malley (Arksey & O'Malley, 2005). An outline of the five stages of this research paradigm is provided below.

- Phase 1: Choosing the research questions: What are the research questions and what domain must be investigated?
- Phase 2: Identification: Finding relevant studies.
- Phase 3: Selection: Choosing studies that are pertinent to the question(s) using set inclusion/exclusion criteria.
- Phase 4: Data extraction: Arranging the data from the relevant selected studies.
- Phase 5: Collating: Reporting and summarizing the findings.

2.3.1 Research Questions

In terms of the quality and quantity of urban stormwater management, BRC research continues to be active despite its widespread implementation and development. It should be highlighted, however, that the performance of BRCs in terms of hydrologic effects and quality improvement varies considerably from one region to another. This discrepancy in results is attributable to several factors, such as design flaws in BRCs or the disregard of regional climate and site-specific hydrologic responses and runoff quality characteristics. As a result of this discrepancy in BRC performance, the purpose of this review study is to investigate the

reliability of BRCs in urban catchments for urban stormwater management in terms of quantity and quality. Therefore, the fundamental research question of this systematic review study is "Are BRCs an effective LID practice for urban catchment stormwater management?". This fundamental research question is broken down into two more specific questions, which are as follows:

a) Are BRCs an effective practice for implementation in urban catchments with the objective of mimicking the key components of natural hydrological processes?

b) Are BRCs an effective practice for implementation in urban catchment areas with the purpose of improving the load reduction of stormwater?

In this study, the authors describe a systematic review as a sort of research synthesis that maps the literature on a certain topic or research area and allows for the identification of key concepts, research gaps, and evidence types that may be used to inform practice and future studies (Khan et al., 2003). In order to comprehend the effectiveness of BRCs in terms of improving load reduction and quantity management for urban stormwater, an assessment of several BRC studies was conducted using a large database of field, laboratory, and numerical modelling investigations.

2.3.2 Identification and selection of relevant studies

This section outlines the second and third phases of the research paradigm. The PRISMA (Preferred Reporting Items for Systematic and Meta-Analysis) 2020 flow diagram (Page et al., 2021) visually summarizes the screening process. It first shows how many publications with a specific set of keywords are available in Scopus, and then it streamlines the selection process by outlining the decisions made throughout the systematic review. Figure 2.2 shows a sequence of steps beginning with the identification of relevant studies and concluding with their ultimate inclusion.

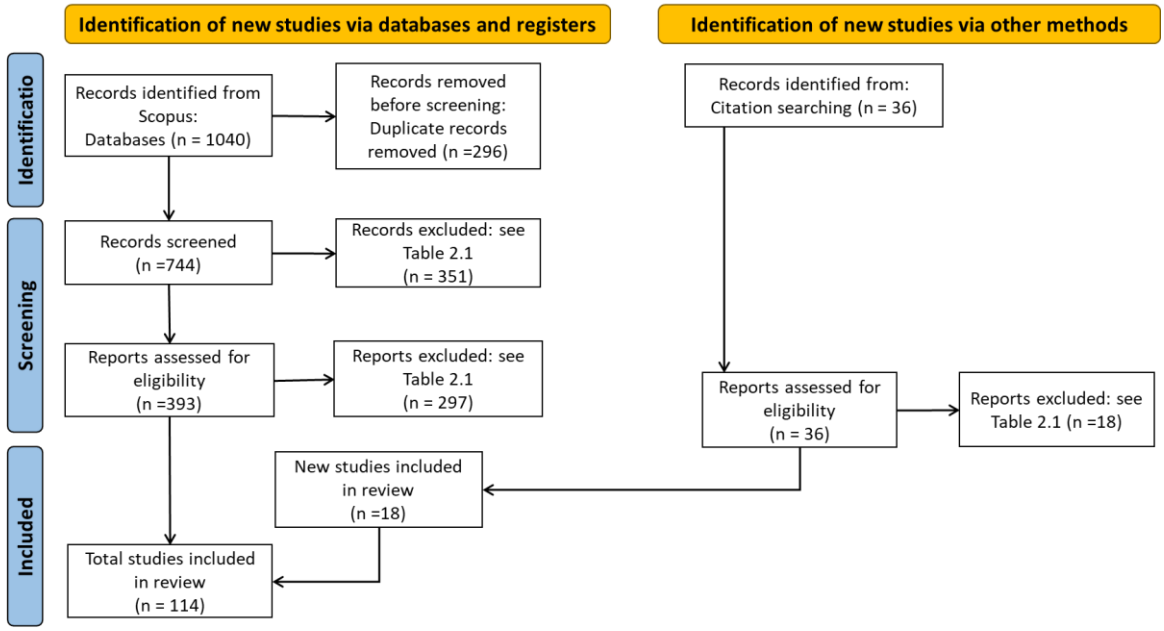

Figure 2. 2 PRISMA 2020 diagram of study selection procedure.

Scopus was used as the bibliometric database to extract the peer-reviewed literature, book chapters, and proceedings of indexed conferences. The studies in this systematic review range in chronological order from 2017 to the end of September 2022. The following is a list of the key terms and their various combinations that were used in our review study: “bioretention”, “biofiltration”, “raingarden”, “urban catchment”, and “stormwater”.

In the primary search, 1040 citations were downloaded from the Scopus database for various combinations of the keywords. After running them through Endnote’s deduplication tool (Bramer et al., 2016), 296 were dropped. Then, a set of inclusion and exclusion indicators reported in Table 2.1 was provided, based on a modified version of adapted from study conducted by (Spraakman et al., 2020), to verify that the study selection process was performed correctly and that all studies contribute to answering the two sub-questions. The studies were chosen based on the complete design and description of the BRC (see Figure 2.1 and Section 2.5.1.1 for more details). Studies in which a BRC was combined with other stormwater management practices were included. Another significant indicator is inflow type. Studies must investigate stormwater in urban catchments and the properties of urban stormwater in terms of quantity and quality impacts, whereas other types of inflows (i.e., wastewater) are not included in this review. In addition, the enhancement in social and environmental values by BRCs, life cycle analysis (LCA), economic background, and only maintenance recommendations for bioretention systems are not included.

Table 2. 1 Inclusion and exclusion indicators adopted to select relevant studies

Indicator	**Inclusion**	**Exclusion**
Definition of BRC	Definition of a BRC as it is mentioned (refer to section 2.5.1.1)	Any stormwater management approach without full BRC defining elements and proprieties
Type of inflow in BRC	The runoff entered BRCs must be generated by stormwater in urban catchments, or the properties of the urban runoff must be included	Any type of wastewater other than urban stormwater
Type of study	Studies that evaluate the quantity and quality effectiveness of BRCs in field, laboratory, and numerical modelling settings	Studies regarding evaluation of economic, LCA, or other indicators but did not include quality and hydrologic metrics
Type of publication	Peer reviews, conference proceedings, and book chapters	Review articles and theses
Language	English	Other languages
Chronological order	Studies between 2017 and September 2022	Other studies outside of 2017 and September 2022

Selecting the appropriate studies requires careful consideration; hence, two stages of screening (based on the indicators in Table 2.1) were performed when the duplicates were excluded. In the first stage of screening, the titles and abstracts (in some cases, the complete text was reviewed to find unrelated studies) of the studies were evaluated for eligibility. In this stage, 351 studies, including 45 reviews, were discarded. In the second stage, the full texts of the studies that had been identified in the first screening were re-evaluated using the indicators reported in Table 2.1. This resulted in the elimination of 297 studies from the remaining 393. The overall number of remaining relevant papers was 96; however, to increase the comprehensiveness of the review study, other articles were included through the investigation of remaining study references. With this aim, the referenced papers of these 96 articles were considered. Consequently, an additional 36 papers were considered in our screening pool, from which 18 were selected for inclusion. Finally, 114 articles were reviewed that seemed sufficient for reaching an adequate conclusion.

2.3.3 Data Extraction/Chart

Following the identification and selection of relevant studies, the full texts of all relevant studies were analysed to obtain the required data. General and specific data were collected based on the following criteria:

- General information: Author(s), publication year, and country of origin.
- Watershed features: Location, land use category, contribution drainage area (CDA), and percentage of imperviousness.
- BRC technical design characteristics: Media composition, media depth, ponding zone depth, A_{BRC}/CDA, and internal water storage (IWS) depth.
- Results from BRC quantity and quality performance.
- Type of modelling, simulation type, hydrology and quality metrics for modelling, and calibration status.

Each Excel spreadsheet contained a different combination of the above items to reduce the possibility of bias and provide more reliable data from which conclusions and choices may be derived. Although every effort was made to follow the same procedure to extract the essential information from each of the 114 papers included in this review, this was not always possible due to the absence of key details in certain studies. Data are not always presented in the most user-friendly way, as has been noted by (Badger et al., 2000).

2.3.4 Collating

Following the extraction of data from the 114 studies, the purpose was to provide an overview of all data analysed and, as a result, address questions regarding the quality and quantity of BRC effectiveness in urban catchments. There are two distinct ways to show the results. To begin, an initial mapping was performed, including the main components of BRC and the possible mechanisms that occur in BRCs, such as physical, biochemical/chemical, and biological mechanisms (see Figure 2.3 for more details), as well as the geographical distribution of the research studies, the number of studies conducted over the time frame covered by the review study, and the number of studies classified into each of the three categories (field, laboratory, and numerical modelling studies).

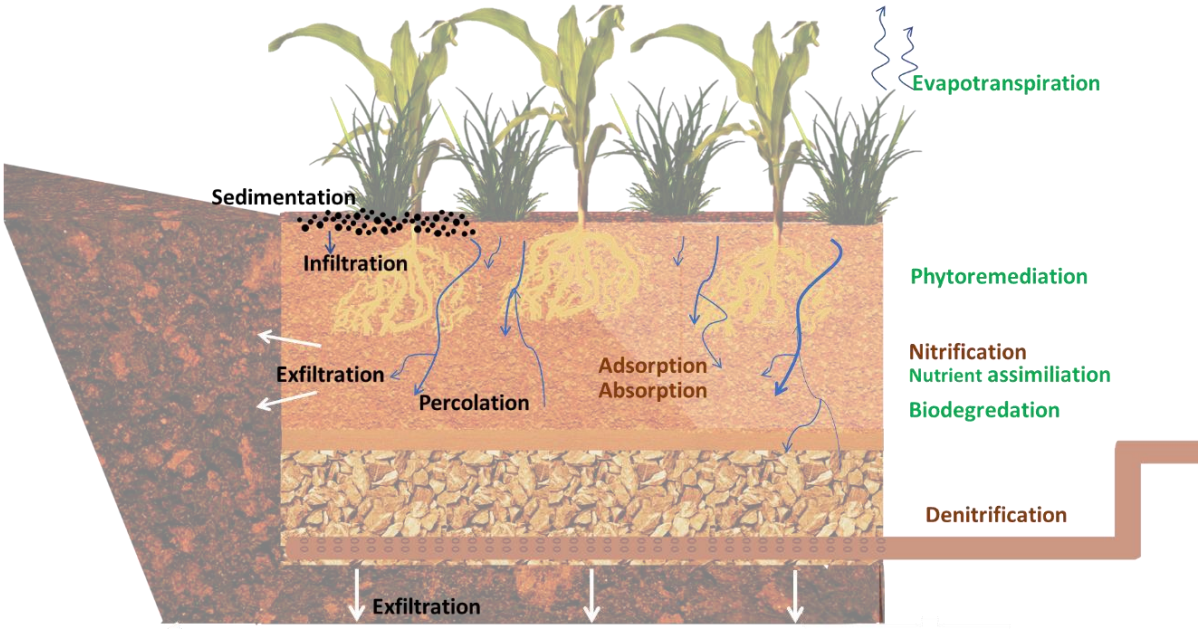

Figure 2. 3 Fundamental physical (black label), biochemical/chemical (brown label), and biological (green label) mechanisms that occur in BRCs. Infiltration/percolation (blue arrows) and exfiltration (white arrows) are illustrated.

The performance of BRCs in terms of quantity was classified into three categories: volume reduction, peak flow reduction, and capture of runoff (is evaluated as the percentage of the number of events for which the inlet is completely captured). Additionally, the effectiveness of BRCs for reducing certain contaminants that are found in excessive amounts in urban stormwater can be classified into the following five groups: total suspended solids (TSS), nutrients (N species and P species), heavy metals (Zn, Cu, and Pb), pathogen microorganisms and COD/BOD_5, and microplastics (MP). The category of model studies included data on the models employed, temporal scale analysis, calibration and validation settings, and quantity and/or quality metrics.

2.4 Results

2.4.1 Initial Mapping

This section will outline an overview of BRCs, including their fundamental components, the various BRC designs, and the underlying natural mechanisms involved in BRCs. A chronological and geographical analysis of BRC research studies throughout the review period will also be included in this section,

2.4.1.1 BRC Overview

The selection of BRC components is significantly impacted by the local climatic variables (such as precipitation intensity, evaporation rates, and antecedent moisture

conditions), the hydrologic and hydraulic characteristics of the site, the characteristics of the pollutant load associated with runoff, the required water quality standards of effluents, and the local availability of BRC components such as vegetation, soil media, and substrates. It is important to note that, for instance, in temperate countries, BRCs are designed to capture the first flush of runoff. In tropical climates, however, where rainfall is often heavy and frequent, the impact of the first flush may not be as significant as in temperate climates (Wang et al., 2017). Furthermore, a comprehensive review of 40 years' worth of data for more than 60 cities throughout the world revealed that urban runoff and nutrient content in tropical regions differ from those in temperate regions (Duncan & others, 1999). Additionally, countries in the temperate zone, such as Australia, the United Kingdom, and the United States, receive around 800 mm of precipitation annually, whereas those in the tropics, such as Singapore and Malaysia, receive around 2500 mm (Goh et al., 2017). These tropical nations frequently experience short, intense thunderstorms, which are less frequent in temperate countries. Hence, it is crucial to account for the rainfall characteristics in designing BRCs to avoid under-sizing of the system, thus leading to runoff bypassing the system (Wang et al., 2017).

BRCs employ excavated areas to form depressed planting beds to collect and treat stormwater. As illustrated in Figure 2.1, BRC generally includes the following layers, starting from the top: a surface ponding area, plants, a layer of mulch, an engineered filter medium, a transition layer, and an underlying drainage layer. The system optionally includes an underdrain that links to the main urban drainage system (eventually with reuse purposes) and the outlet section may be raised to determine the internal water storage (IWS) (Macedo et al., 2019; Spraakman et al., 2020). The latter is typically constructed by adding a 90-degree elbow to the underdrains in the BRC. It is important to mention that the presence of an underdrain depends on the implementation goal of the BRC as well as the characteristics of the soil surrounding the BRC, such as the rate of infiltration and pollutant concentration.

The effectiveness of each design varies greatly because different BRC designs lead to different hydrological and quality responses, especially when it comes to nutrient contaminants (Ketabchy et al., 2019). The BRCs may be constructed without an underdrain for complete exfiltration, with an underdrain (most preferred) for partial exfiltration, or with an impermeable liner and underdrain for no exfiltration (as it is defined in Chapter 1). Typically, based on the discharge configuration, BRCs may be divided into two categories: BRCs with a

conventional drainage design and BRCs with an IWS. BRCs mainly act as a source of aerobic substrates, organic material, and microorganisms for the nitrification of produced ammonium and mineralization of incoming organic nitrogen. Raising the underdrain outlet to create an IWS zone will result in anaerobic conditions (Hoppmann et al., 2011; Wang et al., 2018; Willard et al., 2017). As result of incorporating IWS into BRCs, the system has improved nitrogen removal, due to the comparatively higher denitrification, because of the anaerobic environment in the submerged zone. In addition to the advantage of nitrogen removal, an IWS zone may have a considerable hydrologic influence on runoff reduction (Jiang et al., 2019; Passeport et al., 2009; Willard et al., 2017). Another classification of BRC designs is related to the overflow design. BRCs can be designed to be offline and online. In contrast to offline BRC, which only permits the amount of storm runoff storage determined by design to enter the BRC, online bioretention captures all flow from the drainage area and conveys large event flows to an overflow outlet.

Stormwater can be managed in terms of quantity and quality near to where it originates by implementing BRCs into a site's infrastructure. The majority of possible natural mechanisms that can occur in BRCs are illustrated in Figure 2.3. These mechanisms are divided into three categories: physical/hydrological, biochemical/chemical, and biological (Fletcher et al., 2015; Wang et al., 2018). The physical processes consist of exfiltration, infiltration, percolation, and sedimentation. In BRCs, chemical and biological classifications are challenging processes. Absorption and adsorption are chemical processes that commonly occur in soil and plant components. Nitrification and denitrification processes, occur mostly in the soil profile, plant roots, and IWS zone. Figure 2.3 shows that biodegradation, nutrient assimilation, phytoremediation, and ET are all biological processes that occur in BRCs. The mechanisms involved in BRCs, as well as how they affect the quantity and effectiveness of treatment, will be examined in further detail.

One key feature of BRCs is their adaptability in practice (Davis, 2007). BRCs can be implemented in parking lot landscaping, alongside highways, and in open spaces close to impermeable surfaces

2.4.1.2 Chronological and Geographical Analysis of BRC

Numerous studies have been conducted to enhance BRC effectiveness and to construct cost-effective BRC designs under various climatic conditions since the advent of BRC

in the 1990s (Prince & County, 1999). As shown in Figure 2.4, in recent years, an increasing number of researchers from all over the world have been drawn to the utilization and effectiveness of BRCs in urban stormwater management. There were 744 publications found in this review research, with an annual average of 124 articles regarding BRCs in the field of urban stormwater management. Although there was a decline in publication trends in 2020—about 24% less than in 2019—the long-term average has increased by about 16% annually. The growing amount of the literature on urban stormwater management from 2017 highlights the significance of BRCs.

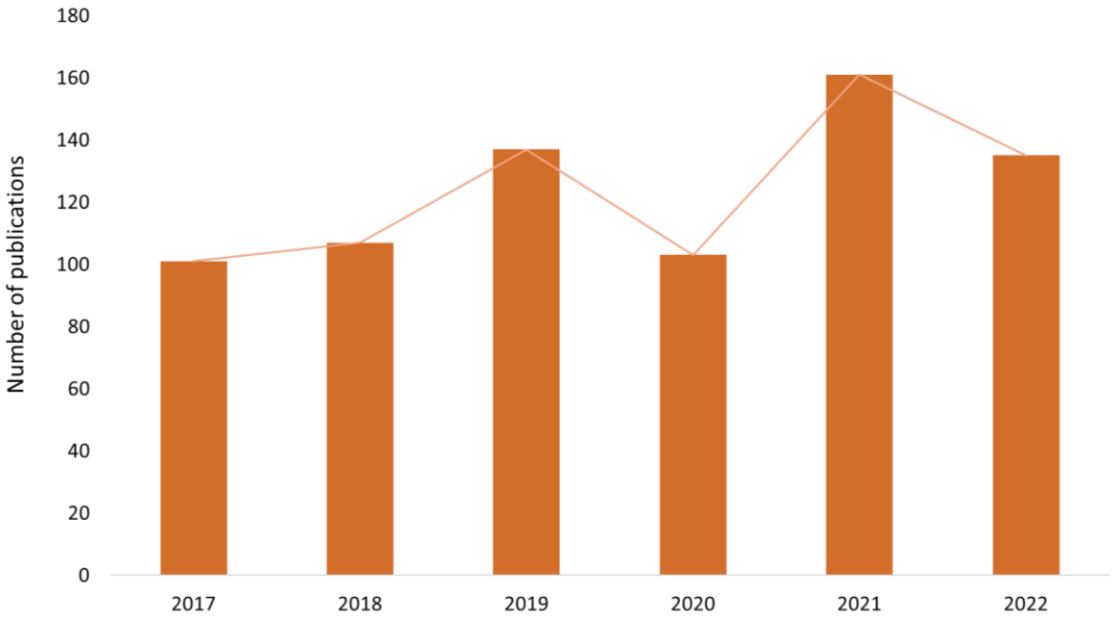

Figure 2. 4 Trend in the annual number of studies published, 2017–2022.

It is worth noting that throughout the time frame covered by this review study, laboratory research accounted for 45% of the total number of studies, while field and numerical modelling studies accounted for 24% and 31%, respectively. The fact that laboratory studies are so prevalent may be explained by the fact that they are preferred for obtaining essential information because of their ability to simplify full-scale systems and focus on improving specific qualities. Furthermore, by conducting laboratory investigations, the high expenses as well as the variety of constraints connected to field-scale research may be minimized.

According to Figure 2.5, this review study analysed BRC papers published within a specific time frame and by countries. Figure 2.5 illustrates that over the last five years, the United States and China have contributed the most publications on BRCs for urban

stormwater control, with 269 and 242 articles, respectively. Other noteworthy contributors besides those mentioned above were Australia (58), Canada (41), Hong Kong (18), Brazil (16), and Sweden (15).

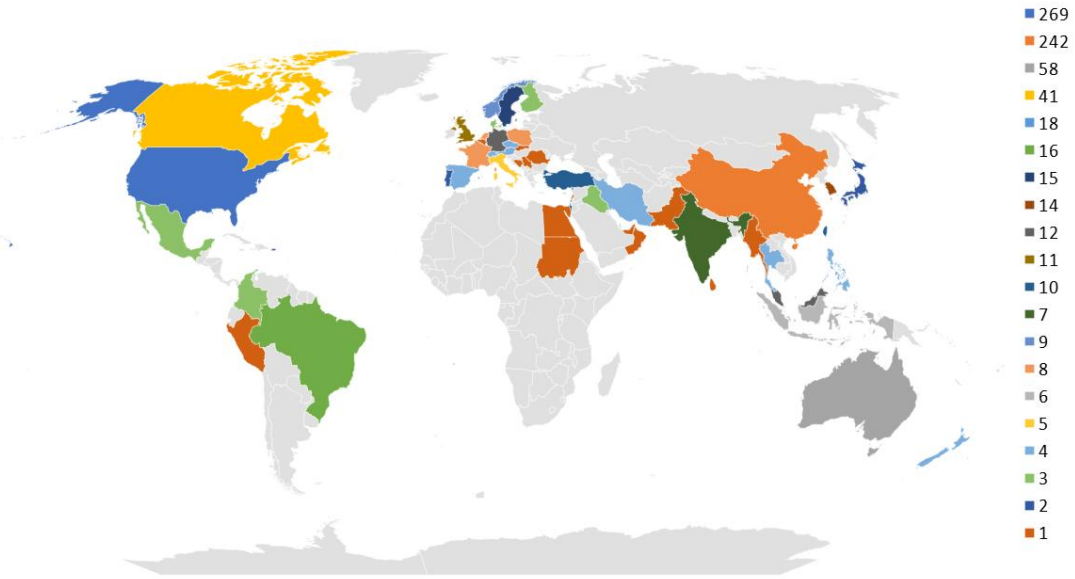

Figure 2. 5 Country-wise analysis of studies published on BRCs, 2017–2022.

Figure 2.6 shows the percentages of studies that belong into each of these three categories based on the countries that contributed the most. As previously stated, laboratory studies constitute most of the research, with China accounting for around 45% of all studies. On the other hand, the United States conducted 35% of all field studies, making it the top in this area. Furthermore, the United States and China made comparable contributions to the modelling studies, and other countries such as Hong Kong and Singapore made more contributions in comparison to the field and laboratory studies.

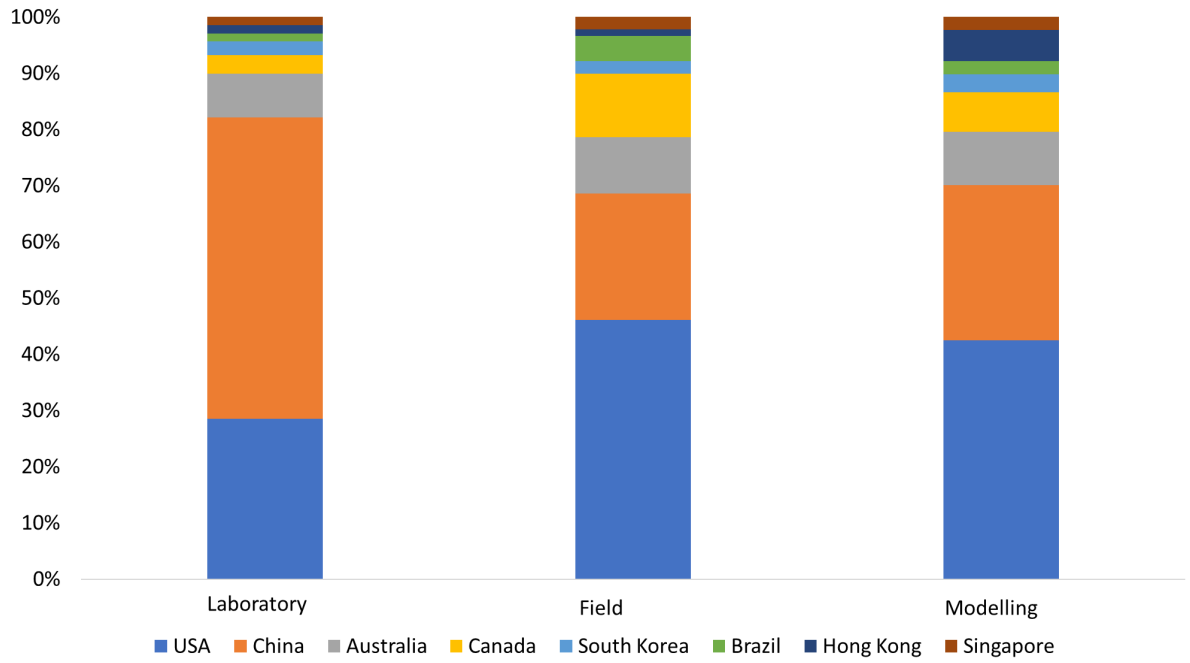

Figure 2. 6 Leading countries in laboratory, field, and modelling studies on urban stormwater management by BRC, published 2017–2022.

This bibliometric analysis demonstrates that only a limited number of nations have undertaken novel research on BRCs, while others have not yet initiated such comprehensive research. Given the current concern about global climate change, increasing urbanization, and the vast network of impervious road surfaces, it is necessary to do more research in a diverse range of geographical regions with varying precipitation regimes and local soil conditions. As a result, additional research can provide a more solid foundation for evaluating the effectiveness of BRCs.

2.4.2 Evaluation of BRC Effectiveness

The total effectiveness of BRCs in lessening the negative effects of urbanization is significantly influenced by their hydrologic performance (Clary et al., 2011; Davis et al., 2012; Willard et al., 2017). As a result of this, the present review begins with an assessment of BRCs' hydrological effectiveness. Subsequently, the quality performance of BRCs will be examined.

2.4.2.1 Quantity Effectiveness of BRC

According to a quantity performance, the primary function of a BRC is to reduce the volume of stormwater and to smooth the peak flow rate. The quantity effectiveness in lowering runoff volume and peak flow has been the topic of various research works in recent years, and efforts have been made to enhance the overall performance of BRCs.

There are several assessment indicators that can be used to assess the quantity effectiveness of BRCs that are collectively referred to as the hydrologic performance of BRCs. Common indicators include lag time, volume and peak flow reduction, runoff coefficient, and capture. The time elapsed from the start of a rainfall event until the start of BRC discharge is referred to as the lag time. The runoff coefficient represents the system's effectiveness at infiltrating precipitation into the soil and minimizing the quantity of runoff generated. In this systematic review, the hydrologic performance of BRCs is analysed based on three indicators: volume reduction (VR), peak flow reduction (PR), and capture. VR, in the context of BRC effectiveness, is evaluated as the relative percentage difference between the outlet (evaluated as the sum of the outflow and overflow volumes) and inlet volumes. Furthermore, PR is similarly evaluated as the absolute percentage difference between the overflow peak and inlet flow peak rates. The capture is evaluated as the percentage of the number of events for which the inlet is completely captured. Note that the captured volume by a BRC refers to the volume of runoff that is retained without any overflow, underdrain flow, and exfiltration.

Tables 2.2–2.4 report the VR, PR, and capture for the selected literature studies, respectively, in USA, Canada, and other countries (China, Brazil, Australia, Korea, and Czech Republic). For each study, the site characteristics, including CDA, imperviousness rate (Imp.Rate), and land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, ratio between the surface area of BRC and contribution drainage areas (A_{BRC}/CDA), and the IWS.

In BRCs, the volume of runoff can be reduced by a range of mechanisms. These mechanisms include infiltration, storage in the pores of the media compositions, percolation and lateral flow to surrounding soils, shallow interflow, evaporation or evapotranspiration to the atmosphere, and assimilation by plant roots. It should be noted that the treated water from BRCs (with underdrain) can be reused for irrigation and other non-potable purposes, such as toilet flushing (Jiang et al., 2019). Moreover, PR implies smoothing of the runoff hydrograph, which reduces erosion, scour, and sediment transportation into receiving water bodies. More specifically, BRC acts as a buffer to runoff peak flow by producing ponds on the surface, keeping runoff within the media and slowly releasing it (Davis, 2007). BRCs may continue to gradually release water downstream through the underdrain for several days after precipitation events (Li et al., 2021; Pan et al., 2022). Concerning the capture, the term

"Bioretention Abstraction Volume" (BAV) was developed in the study of Davis et al., (2012), which represent the volume captured by BRCs. This reduced or captured volume of runoff is supposed to be reduced or retained. It is important to point out that the term "retain," which refers to the mitigation of surface runoff, is gaining widespread acceptance within the field of stormwater management. It is important to recognize that stormwater that is evapotranspired, captured, utilized, or infiltrated is not actually stored; instead, it is merely prevented from flowing off the surface.

In accordance with all advancements in the most recent studies analysed in this review study, the findings show that BRC performance in terms of volume and peak flow reduction is appropriate for stating that BRCs can effectively contribute to mitigating the risk of floods, mimic pre-development conditions, and address the impacts of hydromodification on urban areas. In Tables 2–4, the VR are in the range of 50–98% for the field experimental studies, except for the site located at Grove (OK, USA), where an interaction with the groundwater table significantly limits the performance (Kandel et al., 2017). For laboratory experiments, the VR are lower with respect to the field studies (in the range of 11–71%) since the generated rainfall intensity reaches the 5-year return period. Similarly, the PR are in the range of 65–100% for the field sites and are reduced in the range of 10–98% for the laboratory experiments. As for the capture, it ranges from 19% to 84%, depending mainly on the rainfall characteristics of the site and on the age of the systems (see, e.g., Nissen et al., 2020; Shrestha et al., 2018; Spraakman et al., 2020).

Specifically for the age of the system, a study conducted by Spraakman, et al., (2020) analysed the BRC capture performance throughout two-time intervals (2013–2014 and 2017–2018). The rainfall depth and intensity, as well as antecedent dry weather period (ADWP), were comparable across the two periods. In this study, the BRC was able to catch 84% rainfall events in 2013–2014 and 51% in 2017–2018. Other long-term research undertaken by Goor et al., (2021) (from November 2018 to January 2020 with 124 rainfall events) indicated that the BRC performance in terms of capturing the rainfall was about 56%. It should be mentioned that, in these two investigations, the BRC was able to capture rainfall events that were less than or equal to 15 mm.

To improve the hydrologic performance of the BRC, recent research has focused on a variety of BRC-related elements, such as the general design, selection of the media

composition, and vegetation type (Cording et al., 2018). Notwithstanding, the BRC's fundamental elements, the local conditions linked to climate characteristics, and surrounding soil conditions (such as soil permeability, groundwater table, etc.) also affect the BRC's hydrologic efficiency, as mentioned in the previous section. As for climate-related conditions, there are several indicators influencing BRC hydrologic performance, such as rainfall intensity, rainfall depth, seasonality, and ADWP (Jiang et al., 2019; Macedo et al., 2019; P. Shrestha et al., 2018). For instance, in the study of Shrestha et al., (2018), eight BRCs were monitored under a variety of conditions including different rainfall intensities and a variety of plant types. The results were 75% for VR, 91% for smoothing the peak flow, and 31% for capturing. In addition, the significant sensitivity of PR to maximum inflow rate was discovered, whereas VR was contingent on inflow volume, peak inflow, and rainfall depth. Seasonality is another factor that should be considered significant for the BRC's performance. In the study of Goor et al., (2021), considering the high variability between individual events within each season, it was observed that a variation in the mean VR efficiency of the summer (85%) compared to other seasons is considerable (the mean VR of other seasons is approximately 70%). The precipitation amounts and intensity, as well as the antecedent moisture conditions, may explain this phenomenon (Davis et al., 2012). The relative importance of the various performance indicators varies depending on the time of year. For example, during dry weather periods, the antecedent soil moisture conditions and the rainfall intensity were found to be more important than the total precipitation depth, whereas, during the wet period, the hydrologic performance of BRCs was primarily influenced by the total rainfall depth and the maximum rainfall intensity (Jiang et al., 2019; Macedo et al., 2019). Additionally, this variation may be partially explained by a reduced water holding capacity and ET rate during the winter months compared to the summer months. According to H. Li et al., 2009, approximately 19% of VR in BRCs relies on ET (plants transpiration and abiotic evaporation). Reduced ET rates impact not just the BRC's internal water level, but also the surrounding high-water table. As Hunt et al., 2006 revealed that during winter, the exfiltration potential is reduced by elevated water tables, as the soil's capacity to absorb and store water is reduced in comparison to milder periods. This seasonal disparity emphasizes the necessity of include climatic and subsurface dynamics in the design and performance assessment of BRC.

Numerous BRC design characteristics influence the hydrologic performance of a BRC such as the composition and the depth of the filter media, the outflow configuration, the types of vegetation, and the construction and maintenance of the system (Li et al., 2021; Shrestha et al., 2018; Spraakman, et al., 2020; Willard et al., 2017). Most research studies suggest that the total potential advantages of BRCs are heavily reliant on the optimal selection of media substrates. The particle-size distribution (PSD), porosity, pore-size distribution, and saturated hydraulic conductivity (K_s) have a significant impact on the rate of infiltration, as well as an impact on the soil stability and compaction. All of these effects are dependent on choosing the right combination of media composition. This helps to partially explain why Nissen et al., 2020 concluded that the initial moist deficit (IMD) is crucial for BRCs to catch inflow runoff. In general, the ability to collect and store runoff increases as the IMD increases. In this study, BRCs with pumice sand compositions outperformed those with sand-based compositions, with 28% and 10% better capturing outcomes, respectively, because pumice has the potential to hold water inside its aggregate structure. Furthermore, Li et al., (2021) evaluated the effectiveness of various media compositions in cold climates with severe climatic conditions and found that media composition has a substantial impact on BRCs. In terms of PR, sandy loam media performed better than sand-based media. This study's outcome might be explained by the water-holding capacity of the media composition; indeed, sandy loam has more micropores compared to sandy soil, allowing it to hold more water. The performance of filter media has recently been the focus of several research efforts studying the effect of altering their constituent parts. Adding a certain number of suitable admixtures to the BRC media material might provide a solution. However, the admixtures must be affordable, conveniently accessible, beneficial to plant growth, long-lasting, and, most importantly, efficient in removing pollutants (Jeon et al., 2021; Joseph et al., 2021; Mai & Huang, 2021; Mohanty et al., 2018). On the whole, several changes can be made to media to affect their water-holding, adsorption, and infiltration capacities, and these can all be considered when evaluating BRC hydrologic performance. It was found that both organic and inorganic supplements may increase the hydrologic performance of BRCs (Jiang et al., 2019; J. Li et al., 2021). According to J. Li et al., (2021) assessment of the effectiveness of a water treatment residual (WTR) and biochar substrates in the columns with regards to quantity management, BRCs with biochar were more stable than BRCs with WTR regarding the water volume control effect, and both were superior to bioretention soil media (BSM). Regarding PR, the effect of

BRCs with biochar was very steady throughout a range of inflow circumstances, all of which were greater than 74%. In order to illustrate how biochar addition might alter the performance of filter media, the effect of biochar on the bulk density of the filter media could well be considered. In particular, the addition of biochar decreases the soil's bulk density, and increases the soil's overall porosity and the capillary force of the filter media. Furthermore, biochar's larger surface area and its micropores could explain its consistent efficacy in reducing peak flow. It should be noted that the high carbon content and biological origins of biochar make it a suitable substrate for microbial colonization; in turn, these microorganisms can contribute to additional runoff reduction (Joseph et al., 2021). The hydrologic performance of field-scale biochar-amended BRCs was examined with four rainfall return periods under varied biochar distributions in the study of Mai & Huang, (2021). When layered and uniform mixing of biochar distributions were compared, it was discovered that uniform mixing of biochar distributions may more effectively improve the soil water holding capacity, which in turn enhances the ability to regulate runoff. It is possible that uniform mixing distributes the biochar evenly throughout the soil, allowing for a more consistent improvement in the soil water holding capacity. This increased capacity can lead reduced runoff compared to layering, where the biochar may be concentrated in specific areas, leading to more variable results. It is crucial to highlight, however, that this is only one possible explanation; the performance of BRCs under various amended distributions should be explored further.

Recently, researchers have attempted to apply the IWS in BRCs for a variety of purposes, including hydrologic performance. The IWS is a subsurface part of the filter media that contributes to BRC storage capacity. The effects of the IWS on VR have been examined in several studies such as Jiang et al., (2019), which found that the IWS has the most significant importance for VR after the infiltration rate of the media. In addition, in the study of Mai & Huang, (2021), the effects of varying the IWS depth were studied. Comparing the impacts of three different IWS heights, it was discovered that the volume reduction pattern increased with increasing IWS depth, from the range of 11.4–16.2% with no IWS to 38.4–59.8% with a 40 cm IWS. The VR achieved by a 20 cm IWS was 16.3–29.6%. This was because the increase in the IWS zone height led to an increase in the internal storage water capacity and a decrease in outflow (Brown & Hunt III, 2011).

One of the most essential design variables is the size of the BRC surface, which should be selected based on the loading and target performance, as well as on local regulations and spatial and economic constraints. Local regulations generally define both runoff volume and water quality discharge limits that need to be addressed. Based on results examined in the present review, the A_{BRC}/CDA ratio between 5 and 25% is recommended (Prince & County, 1999; Spraakman et al., 2020; Willard et al., 2017). The specific size may vary depending on land use, rainfall patterns, targeted volume management, and pollution treatment effectiveness. For instance, Nissen et al 2020 showed that the BRCs with higher surface area had higher stormwater capturing percentage.in their study, a BRC with 12% A_{BRC}/CDA achieved 56% of capturing, while the BRC with 5% of surface area had only 19%.

Another vital point is to keep an appropriate distance between the bottom of the BRC and the seasonal high groundwater table. Various bioretention manual guidelines recommend between 30 and 60 cm for this distance. For instance, Kandel et al., (2017) observed that two BRCs had groundwater seepage had a detrimental effect on their ability to VR. In this study, the VR performances of the two BRCs were substantially negative. In this investigation, as shown in Table 2.2, the underdrain flow of one BRC was 200% more than the influent flow.

The vegetation or the plant zones are components which differentiate BRCs from other LIDs. The ability of plants to intercept and hold runoff and to decrease water flow with stalks, stems, branches, and foliage is one of the better recognized functions of vegetation (Shaw, 2003). Vegetation maintains the soil, and media porosity allows for infiltration, temporary storage, and then exfiltration through the subsoil, all of which act to attenuate the peak flow (Shrestha et al., 2018). Despite the fact that several manuals emphasize the role played by vegetation in achieving various hydraulic, hydrologic, and treatment goals, the topic of the beneficial contribution of plants in hydraulic or pollutant removal is not trivial, and yet the role of vegetation and roots in the context of BRC has not been thoroughly researched. Shrestha et al., (2018) examined the effectiveness of a high and low diversity (low-diversity treatment (VL) contains two species, and the high-diversity treatment (VH) contains seven species) of vegetation and found that VL effects on peak flow were not negligible. Moreover, appropriate plant species, for example, ones that reach maturity faster alongside occupying a greater soil area and accumulating a larger above-ground and below-ground biomass while tolerating changing environmental conditions, should be considered for bioretention in cold

climate regions. In the study of Nasrollahpour et al., (2022), the influence of media–vegetation interactions on ET were determined by observing 24 mesocosms containing various types of vegetation. The impacts of the vegetation, which became more prominent over time, were also observed. This study uncovered the impacts of vegetation and media on ET, which, in turn, impacted the performance of BRCs.

The ponding depth is another important design feature to consider. Ponding depth allows for the temporary storage of rainwater prior to filtering it through the BRC, the storage of excess runoff, and the settling of particles and evaporation of surplus water. This design feature is critical for estimating the hydraulic loading of treatable surface runoff (Clar et al., 2008; Prince & County, 1999). The ponding zone is typically determined by local guidelines; however, McLemore et al., (2017) suggests that the ponding depth should be more than the product of the infiltration rate and 24 h. In addition, to provide for the appropriate drainage and to avoid stagnant water, a slope of 1% is often suggested. Therefore, the maximum ponding depth is determined by the fact that standing water drains in less than twenty-four hours, which is less than the time required for one mosquito breeding cycle.

Table 2. 2 The hydrologic performance, volume reduction (VR), peak flow reduction (PR), and capture of the BRC literature studies in the USA. For each study, the site characteristics, including the contribution drainage area (CDA), the imperviousness rate (Imp.Rate), and the land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas (A_{BRC}/CDA), and the internal water storage (IWS).

Reference	Site	CDA [ha]	Imp.Rate [%]	Land Use category	Media Depth [cm]	Media compositions	A_{BRC}/CDA [%]	IWS [cm]	VR [%]	PR [%]	Capture [%]
Kandel et al., (2017)	Grove (OK)	0.26 0.76 0.25	90 36 100	Residential area Parking area Parking area	60	95% sand, 5%fly- ash	5.7 2.2 2.5	**	13 -200 72	-	-
Willard et al., (2017) [1]	Blacks-burg (VA)	0.16	N/A	Parking area	60	88% washed sand, 8% clay and silt fines, 4% leaf com-post	2	30	98 84	91 82	
Mahmoud et al., (2019)	Weslaco (TX)	0.16	N/A	Parking area	76	Sandy	3	**	82	-	-
Nissen et al., (2020)	Hobo-ken (NJ)	0.0142 0.0109 0.0054 0.0098	100	Roof area	55.9	88% pumice sand, 12% compost	5 6 12 7	**	-	-	19 45 56 24
Shrestha et al (2018) [2]	Burling-ton (VT)	0.003–0.012	N/A	Roadway	61	60% sand, 40% compost	7.7	**	75	91	31[3]

*Note: "-" is not evaluated, "**" is not included, and "N/A" is not available in the study. [1] This study is an evaluation of the maturation of the BRC's effectiveness (2007–2008 (first row) and 2013–2014 (second row)). [2] The study site consists of eight bioretention cells, the results are the average across all. [3] The value refers to the number of events that are completely captured with respect to the overall monitored event.*

Table 2. 3 The hydrologic performance, volume reduction (VR), peak flow reduction (PR), and capture of the BRC literature studies in Canada. For each study, the site characteristics, including location, contribution drainage area (CDA), imperviousness rate (Imp. Rate), and land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas (A_{BRC}/CDA) and the internal water storage (IWS).

Reference	**Site**	**CDA [ha]**	**Imp.Rate [%]**	**Land Use category**	**Media Depth [cm]**	**Media compositions**	**A_{BRC}/CDA [%]**	**IWS [cm]**	**VR [%]**	**PR [%]**	**Capture [%]**
Goor et al., (2021)	London (ON)	0.13	N/A	Roadway	100	91% sand, 9% fine soil, 3% organic matter	4	**	73	-	56
Li et al., (2021)[1]	Edmonton (AB)	N/A	N/A	Lab.Exp	86 84.9 85.8 86.4	50.8% sand, 29.4% silt, 19.8% clay 67.2% sand, 19.6% silt, and 13.2% clay 48% sand, 27.7% silt, 18.7% clay, 0.5%steel wool, 5 % woodchips 63.5% sand, 18.5% silt, 12.4 % clay, 0.5%steel wool, 5 %woodchips	10	0 0 20 20	-	80 39 82 67.5	-
Spraakman et al., (2020)[2]	Vaughan (ON)	0,02	N/A	Parking area	40	3–99% sand, 1–7% silt, clay	12	**	98 93	- 95	84 51

*Note: "-" is not evaluated, "**" is not included, and "N/A" is not available in the study. [1] The results of peak flow reduction are the average. [2] This study is an evaluation of the maturation of the BRC's effectiveness (2013–2014 (first row) and 2017–2018 (second row)).*

Table 2. 4 The hydrologic performance, volume reduction (VR), peak flow reduction (PR), and capture of the BRC literature studies in China, Brazil, Australia, South Korea, and Czech Republic. For each study, the site characteristics, including the contribution drainage area (CDA), imperviousness rate (Imp. Rate), and land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas (A_{BRC}/CDA), and the internal water storage (IWS).

Reference	Site	CDA [ha]	Imp.Rate [%]	Land Use category	Media Depth [cm]	Media compositions	A_{BRC}/CDA [%]	IWS [cm]	VR [%]	PR [%]	Capture [%]
Jiang et al., (2017)	Xi'an Xianyang China	0.028	N/A	Residential	50	80% silt, 11.3% sand, 9% clay	8	**	54.08	-	-
Macedo et al., (2018)	São Carlos (SP) Brazil	2.3 N/A	N/A	Roadway sidewalk Lab.Exp	32 100	Sandy Sandy	0.3 N/A	**	100 99	100 -	- -
Jeon et al., (2021)	Cheonan S. Korea	0.047	100	Parking area	80	Sand, soil, ash	1	**	88	-	-
Liu et al., (2022)	Gold Coast City Australia	6.58	32	Residential area	80	N/A	0.4	**	49.5	94.2	-
Mai & Huang, (2021)[1]	Guangzhou China	0.01	N/A	Lab. Exp	55	BSM, different biochar distribution	8	0 20 40	11.4–16.2 16.3–29.6 38.4–59.8	7.4-49.4 8.6-44 10-50	-
Hečková et al., (2022)[2]	Buštehrad Czech Republic	0.0038	N/A	Roof area Lab.Exp	30	50% sand,30% compost, 20% topsoil	25 N/A	**	13 14	75-97 13-34	-
J. Li et al., (2021)[3]	Shaanxi China	20.025	N/A	Lab. Exp	70	BSM BSM, 5% biochar BSM, 5% WTR	5	-	12.6-33.9 29-70.5 32.4-61.7	20-88.4 74.6-97.1 46-87.5	-

*Note: "-" is not evaluated, "**" is not included, and "N/A" is not available in the study. WTR: water treatment residue, BSM: bioretention soil media.[1] The hydrologic performance was assessed for an artificial rainfall event, the performance was assessed for rainfall intensities in the 2-year to 0.2-year return period. [2] The results of the first row refer to natural rainfall characterized by variable intensity and duration typical of the local climate while those in the second row refer to a ponding experiment with an influx corresponding to a 5-year return period.[3] The hydrologic performance was assessed for an artificial rainfall event, the performance was assessed for rainfall intensities in the 3-year- to 0.5- year return period for two rainfall durations of 2 and 6 h.*

2.4.2.2 Quality Effectiveness of BRC

The potential of BRCs to reduce pollutant concentrations and/or loads provides a measure of their effectiveness in improving urban stormwater quality. The quality of BRC outflow is highly reliant on all the parameters that influence BRC hydrologic performance. Furthermore, the concentration of contaminants in the inflow is another factor that can affect the BRC's quality efficiency (He et al., 2022; Spraakman et al., 2020). The previous section of this review study provided in-depth information concerning BRC hydrological performance and the criteria that influence that effectiveness. Hence, the mechanism and efficiency of BRC performance in reducing the contaminants in urban runoff will be discussed in the following sections.

In order to address the second research question, BRC's load reduction performance will be divided into five subgroups: total suspended solids (TSS), nutrients (N and P species), total heavy metals (Zn, Cu, and Pb), oxygen-demanding substances (COD and BOD_5), and microplastics (MP). The selected pollutant constituents represent the pollutants typically associated with urban stormwater.

Each section aims to outline information on the pollutant sources, the BRC mechanisms involved in treating the pollutant, and the effectiveness of pollutant removal. The load reduction performances of BRCs, as shown in Table 2.5-2.7, demonstrate that they have the potential to be one of the most effective LIDs for pollutant removal from urban runoff. It should be mentioned that the water quality data are presented as relative values (i.e., the percentage of reduction rate) and not as absolute values (i.e., the concentration/mass values), considering the differences both in the monitoring programme adopted to collect water quality data, as well as the analytical methods used to detect the pollutant constituents.

Total suspended solids

TSS include a wide range of organic and inorganic materials, such as silt, decomposing organic matter, fallen leaves, and debris. The removal of TSS by BRCs is accomplished by the mechanisms of physical filtration of the particulates and colloids during percolation through the soil profile (Davis, 2007; He et al., 2022; Lim et al., 2021; Shrestha et al., 2018).

BRCs are consistently effective in TSS removal, as illustrated Table 2.5, with the removal rate generally exceeding 78% on average. Table 2.5 summarizes the findings from field and laboratory studies across different climates and land uses, providing a comparative

overview of TSS removal performance in different BRC systems. Notably, TSS removal is more effective in mature BRCs (Gilbreath et al., 2019; Spraakman, et al., 2020). In this review study, a BRC is assumed to be a mature system when it has been operating for several years. Gilbreath et al., (2019) monitored a BRC managing runoff from a roadway with 0.1% footprint (A_{BRC}/CDA) and sandy loam media for three years within the 2012-2017 timeframe to assess the efficiency of the mature BRC; the average TSS reduction varied from 79% in 2012 to 97% in 2017. Settling and compaction occur naturally during system maturity; therefore, this may explain why TSS removal rates tend to rise with time (Jia et al., 2015). Similarly, Spraakman, et al., (2020) demonstrated that evaluating the quality performance of a BRC after 5 years of construction, provided a reliable result, as the soil media is settled, and vegetation is developed (typically two years post-construction). However, it is critical to recognize that the TSS may cause a clogging problem, which in turn impairs the BRC hydrologic performance. Kratky et al., (2021) investigated TSS removal by examining four BRC mesocosms with varying media compositions and temperatures (ranging from −20 to +20). According to this study, the efficiency of loam and sandy loam to remove TSS was comparable, which is approximately 97%. Notably, although the results of TSS removal in this study between two types of filter media were equivalent, the media composition in BRCs plays a vital role in TSS removal. However, this performance decreased to 72% for the media composition amended with steel wool and woodchips. Several factors, including porosity and compaction, can explain the influence of the media's composition on TSS removal. In addition, contrary to expectations, Kratky et al., (2021) showed that the freeze–thaw cycle did not inhibit TSS removal, since TSS removal is primarily a physical treatment mechanism.

BRCs are highly reliable at removing TSS regardless of rainfall depth, ADWP, and influent load quantities according to Shrestha et al., (2018). Similarly, He, et al., (2022) stated that the intensity of rainfall has a negligible effect on the TSS removal by BRCs. An increase in rainfall intensity causes a higher runoff rate conveyed towards BRCs, resulting in a shorter hydraulic detention time, whereas TSS removal is based on physical mechanisms, such as filtering and sedimentation, which are not significantly influenced by a change in hydraulic detention time. It is essential to note that outflow configurations can impact TSS reduction. In the study conducted by Søberg et al., (2020), IWS improved TSS removal with a mean removal rate of 98%, while TSS was effectively retained in the BRC without IWS, with a mean removal

rate of 90%. It has been found that the reduction in TSS was increased by roughly 8% when IWS was used. There are several causes for this, including decreased macropore development in BRCs with IWS and decreased fine re-suspension, which results in fewer preferred flow paths allowing particles to pass through the filter (Li et al., 2014; Søberg et al., 2020). Similarly, Kratky et al. (2021) studied TSS removal in a cold-climate laboratory column and revealed that the presence of IWS affected performance. The TSS removal rate of columns without IWS were on average higher (~97%) than those with IWS (~82%). The lower performance in IWS-equipped columns was most noticeable during the first period due to fine material washout from altered media; however, removal efficiency increased considerably over time. These findings indicated that although IWS can positively impact TSS removal, its efficacy may be initially influenced by media composition and system maturity.

Table 2. 5 The total suspended solids (TSS) reduction performance, volume reduction (VR), peak flow reduction (PR), and capture of the BRC literature studies. For each study, the site characteristics, including the land use category, together with the system characteristics, including media depth and composition, fraction between the BRC and contribution drainage areas (A_{BRC}/CDA), and the internal water storage (IWS).

Reference	Site	Land Use category	Media composition	Media Depth [cm]	A_{BRC}/CDA [%]	IWS [cm]	TSS [%]
Spraakman et al., (2020)	Vaughan (Canada)	Parking area	99–93% sand, 1–7% silt, clay	40	11	**	63
Shrestha et al., (2018)	Burlington (USA)	Roadway	60% sand and 40% compost Industrial filter media consists of fine granules of Fe, Al oxide	61	3 12	**	92 97
Willard et al., (2017)[1,2]	Virginia (USA)	Parking area	88% washed sand, 8% clay and silt fines, 4% leaf compost	60	2	30	100 96
Gilbreath et al., (2019)[3]	California (USA)	Roadway	70% sandy loam, 10% clay, 20% compost	46	0.15	**	79 86 86 97
Jiang et al., (2017)	Xianyang (Cina)	Residential	79.9% silt, 11.31%, sand,8.8% clay	50	8	**	51.8
Mahmoud et al. (2019)	Texas (USA)	Parking area	Sandy	76	3	**	96
Li.Qian et al., (2022)	Tianjin (Cina)	Roadway	30% soil,24% river sand,6% peat soil, 20% WTR, 10% vermiculite, 10% zeolite	65	10	**	64.4
Lim et al. (2021)	Singapore	Roof area	Sand, soil, coconut fibres, WTR	100	4	**	44
Jeon et al., (2021)[4]	Cheonan (South Ko-rea)	Roadway and Parking area	Sandy	80	10	**	85
Kandel et al., (2017)	Grove (USA)	Public Public Commercial	95% sand, 5% fly- ash	60	2.2 5.7 2.5	**	70 59 61
He et al., (2022)	China	Lab.Exp	sand-based sand-based, 10%Volcaninc rock sand-based, 10% Zeolite	50	10	**	97 99 99

			sand-based, 10% coal slag sand-based, 5% vermiculite sand-based, 5% perlite				98.5 98 97.5
Takaijudin et al., (2021)[5]	Malaysia	Lab.Exp	Engineered media: 60% sand, 30% soil 10% compost	29	N/A	**	83 89
Kratky et al., (2021)	Edmonton (Canada)	Lab.Exp	50.8% sand, 29.4% silt, 19.8% clay 67.2% sand, 19.6% silt, 13.2% clay 48% sand, 27.7% silt, 18.7% clay, 0.5%steel wool, 5 % wood chips 63.5% sand, 18.5% silt, 12.4 % clay, 0.5%steel wool, 5 %wood chips	86 84.9 85.8 86.4	N/A	0 0 20 20	97.9 97.28 72 91.2

*Note: "-" not evaluated, "**" not included. CDA: Contribution drainage area, IWS: Internal water storage, BRC: Bioretention cell. [1] The efficiency is based on mass reduction. [2] This study is an evaluation of the Maturation of the BRC's effectiveness ((2007-2008) (first bullet) (2013-2014) (second bullet)). [3] the results were in 4 years of 2021, 2014, 2015, and 2017. [4] This study is an evaluation of the maturation of the BRC's effectiveness (2014 to 2018): the results recorded are the average of the 5 years. [5] The comparison of the different vegetations: Ixora Padulosa sp. (first row) and Hisbiscus Rosa-Sinensis sp. (second row).*

Nutrients

Nutrients pose significant issues in urban stormwater (Fairbairn et al., 2018). Stormwater management primarily targets the reduction of nitrogen (N) and phosphorus (P), as elevated levels of both lead to ecological consequences such as eutrophication, harmful algal blooms, and aquatic fatalities (Kandel et al., 2017). Nutrients in urban stormwater primarily originate from the wash off impervious surfaces, as well as the atmospheric wet and dry deposition. Overall, natural (e.g., atmospheric deposition), anthropogenic, and biogenic (e.g., leaf litter and grass clippings) components collectively influence the amount of N and P concentrations in urban settings (Brett et al., 2005).

The studies analysed for this review study showed that the ability of BRCs to remove N and P species differs significantly, as shown in Table 2.6. Recent advancements in BRC design, on the other hand, have served to lessen this uncertainty. Based on these findings, this review study can infer that the efficiency of BRCs in reducing nutrients has improved, albeit that more study is still needed. The primary P removal mechanisms within the BRC are precipitation, adsorption, filtration, and plant uptake. P ions can be readily absorbed by several types of soil via ion exchange or ligand substitution (Goldberg, 2005; Søberg et al., 2020). Filtration allows particulate P to be retained in BRC media (Roy-Poirier et al., 2010). For plant uptake, soluble PO_4 is the most easily accessible P species (Schachtman et al., 1998). The rate of P uptake by plants is a function of several interrelated factors, including the age of the plant and its root system, the prevailing soil temperature and acidity, and the composition of the filtration media (Barber, 1995).

Based on the above considerations, it emerges that the main factors affecting P removal include the filter media composition and the plant characteristics. In terms of the media composition, Shrestha et al., (2018) demonstrates that BRCs with granules of Fe and Al oxide has a significantly enhanced P adsorption ability. According to Chen et al., (2020), pyrite was more effective than zeolite at removing TP by 81.6% compared to 47.5%; furthermore, the stability of pyrite was confirmed after 8 months of monitoring (it is a laboratory experiment). According to Xiong et al., (2019), the highest treatment performance for TP (93.7%) was found in iron-coated biochar-amended media, according to the evaluation of various BRC filter media. In the research conducted by Kandel et al., (2017), 5% of fly ash amendment in BRC filter media resulted in a TP removal rate ranging from 64% (from a public

urban area) to 75% (from a commercial area) after 7 years of construction. In field studies, TP removal rates exceeding 90% were also observed, as demonstrated by Willard et al. (2017) and Spraakman et al. (2020), where sandy-based media configurations obtained up to 100% and 92% TP reduction, respectively. Jiang et al. (2017) provided additional field evidence that demonstrated a moderate TP removal rate of 57% in a silt-dominant filter media in an urban BRC. The influence of media type was underscored by Lim et al. (2021), who reported a 32% eradication of TP in a roof discharge BRC using coconut fibre-based media. The lab-scale study by Chai et al. (2022) demonstrated that alternative soils composed of coal and volcanic rock can achieve TP removal rates of up to 86%.

In terms of plants, vegetation plays a key role in determining preferential flow pathways, indeed, Hsieh & Davis, (2005) showed that the preferential flow patterns observed during the laboratory phase implied a wide range of variation in TP removal efficiency from 4% to 99%. Considering that TSS removal implies particle bound P, BRCs equipped with IWS have a consequent impact on TP removal. This relationship is evident in the study of Mai & Huang, (2021), where the performance of BRC mesocosm with diverse IWS depths equal to 40, 20, and 0 cm showed TSS removal rates of 93.9%, 81.1%, and 70%, respectively. Correspondingly, the TP removal was equal to 59.5%, 46.6%, and 40.2%.

N treatment in BRCs includes many key processes: ammonification, volatilization, nitrification, denitrification, and plant assimilation. Ammonification is the transformation of organic N molecules into ammonium (NH_4^+). The loss of nitrogen from ammonium to ammonia gas is referred to as volatilization. It must be noted that volatilization at an alkaline pH (basic); however, the majority of BRC filter media are characterized by pH values below 7.5 or 8 (Wang et al., 2023). Nitrification is a microbial process that sequentially oxidizes ammonium to nitrite (NO_2^-) and nitrate (NO_3^-) (Hunt et al., 2006). This process, governed by autotrophic bacteria, is most efficient at a pH of 6–8 and dissolved oxygen levels of 0.5–5 mg/L (Le et al., 2019; Stenstrom & Poduska, 1980), typically occurring in moist, oxygen-rich environments such as those surrounding plant roots (Hunt, 2003; Willard et al., 2017). Under anaerobic conditions, bacteria convert NO_3 to N_2 gas by a mechanism known as denitrification. The root systems of plants are responsible for taking up NH_4^+ and NO_3 from the soil and using them in the plant's physiological processes.

Similarly to P removal, N removal is greatly influenced by various factors such as media composition and plant features. In terms of BRC media, amendments such as zeolites, coal slag, vermiculite, and perlite reduce the ammonium concentration by adsorbing NH_4^+ through ion exchange processes. Zeolites have a negative framework that attracts positive ammonium ions. Coal slag and vermiculite bond with ammonium ions chemically, and perlite has a large surface area for physical adsorption of ammonium ions. For instance, in a study conducted by He et al. (2022), sand-based media that were amended with zeolite, coal slag, vermiculite, and perlite achieved ammonium reduction rates of 94%, 75%, 87%, and 88%, respectively. In another study performed by Shrestha et al., (2018), boosting the BRC media with the addition of granular Fe and Al significantly increased the performance of the BRC for NO_x reduction. As illustrated in Table 2.6, the standard sand and compost media of a BRC resulted in an average 2% NO_x removal rate, while the media that was amended with Fe and Al oxide amendments obtained a 23% removal rate. Indeed, Fe and Al can act as adsorbents for nitrogen oxides. Furthermore, carbon source additions such as newspapers, woodchips, compost, biochar, and coconut husk have been widely used to promote N reduction (Goh et al., 2017; Kratky et al., 2021; Wang et al., 2017). Soil media qualities, absorption, infiltration, retention, and maintaining a proper plant development all contribute to N removal, which may be accomplished by using carbon amendments (Iqbal et al., 2015). Another important note, these amendments to media can form tiny anoxic zones for additional nitrification (Goh et al., 2017).

The denitrification process, important for nitrate removal, requires a prolonged retention period. With this aim, BRCs equipped with IWS layer increase retention time, consequently impacting TN removal (Lopez-Ponnada et al., 2020; Wang et al., 2018; Willard et al., 2017). For instance, according to studies of Kratky et al., (2021) and Wang et al., (2018) a deeper IWS has the potential to greatly enhance the removal rates of NO_3, while the removal rate of NH_4 did not increase significantly, since NH_4 removal occurs primarily under aerobic conditions through soil adsorption processes (Hunt et al., 2006). In the study of Wang et al., (2018) the change of IWS from 20 cm to 60 cm made an increased rate of NO_3^- from 0% to 62% while NH_4^+ decreased from 88% to 75%. The long-term effects of IWS and a conventional outflow configuration has been evaluated in the study of Lopez-Ponnada et al., (2020), where the NO_x removal was 81% in BRC with 30 cm IWS, while in BRC without IWS, the removal rate was only 29%. Notably, the presence of organic matter, which serves as a source of energy for

the bacteria, and a low-oxygen environment promotes the removal of nitrates from the water and a prolonged retention time, which is present in the IWS zone of BRC. By providing a deeper IWS, BRC can lengthen the retention time for denitrification, resulting in an increase in nitrate removal. In this framework, it may be beneficial to add carbon sources as a source of organic matter to promote bacterial growth in the IWS zone and improve plant growth, thus reducing the leaching of N. It is important to note that the amount of carbon sources in the IWS zone should be limited to avoid any clogging effects in BRC media; some research has suggested incorporating between 1% and 5% biochar by volume into the IWS layer (Wang et al., 2018).

However, it is important to acknowledge that BRCs may function as sources of nitrate rather than treating it under specific circumstances. This usually happens when ammonium is successfully nitrified but the system lacks the required conditions—such as enough carbon or anaerobic zones—for complete denitrification. Kratky et al. (2021) reported negative NO_x removal efficiencies of −101.5% and −116.5% in systems amended with woodchips and steel wool, suggesting substantial nitrate leaching. Qian et al. (2022) observed a −140% NO_3^- removal efficiency in one of their bioretention configurations, while achieving an NH_3-N removal efficiency exceeding 70%. The findings indicate a significant limitation in certain BRC designs, especially those without an IWS zone or an accessible carbon source. Thus, careful design considerations, including the integration of deeper IWS zones and suitable organic amendments, are crucial for achieving effective nitrate control in BRC.

The hydrologic and hydraulic factors in BRCs are essential for nitrogen transformation and the overall removal N species. During ADWPs, these processes facilitate the denitrification of NO_3^- and the mineralization of organic nitrogen, thereby contributing to the removal of total nitrogen from stored runoff. In rainfall, BRC media absorb NH_4^+, which is subsequently nitrified or metabolized by microorganisms during dry periods, leading to minimal net NH_4^+ leaching. Shrestha et al. (2018) highlighted that rainfall depth and peak flow rates are critical determining factor of nutrient removal efficiency. In this study it was demonstrated that for each additional millimetre of total rainfall depth, the NO_x removal efficiency decreased by 11.7%, while an increase of 2.48% was observed for each L/min rise in peak inflow rate. In mainly sandy media, nutrients can bypass the adsorption layer (Spraakman et al., 2020) and leach out, thereby impacting performance. Influence of the influent nitrogen concentration on removal rates is significant. Wang et al. (2017) observed a NO_3^- removal efficiency of 20.5%

at influent levels ranging from 6.15 to 9.61 mg/L. In contrast, He et al. (2022) reported a mere 15% removal at influent total nitrogen concentrations of 10.23 to 14.11 mg/L. Higher input loads can initially improve adsorption until the saturation of fillers occurs; however, this also results in reduced denitrification efficiency (He et al., 2022; Shrestha et al., 2018).

Several studies have shown that the presence of vegetation improves N removal (Glaister et al., 2017; Shrestha et al., 2018). It is worth mentioning that some plant species may accelerate the rate of N species decomposition. For instance, the variability of plants in nutrient removal was studied in the study of Shrestha et al., (2018). In this study it is reported that diversity in nutrient removal among species, demonstrating that plant absorption of dissolved nitrogen (NH_4^+ and NO_3^-) varies by species. The Research has shown that in plantings with a high diversity of species, such as New England Aster and Butterfly Milkweed, there is a 20-25% increase in nitrogen uptake compared to systems with low diversity, where Daylilies and Switchgrass predominate. Recent studies conducted in BRC mesocosms showed that high-biomass plant species, in particular those with deep root systems, may be capable of reducing a significant amount of N from stormwater (Glaister et al., 2017; Willard et al., 2017).

The maturity of a BRC can affect the removal of N-containing species. Over time, the BRC filter medium is likely to accumulate carbon from plant growth, death, and decay; this carbon acts as a catalyst for denitrification (Johnson & Hunt, 2019; Willard et al., 2017). In addition, it is a reasonable point to make that mature vegetation will have a larger root mass than when it was first planted, which may lead to an increase in N removal owing to a larger surface area for nutrient uptake and microbial communities (Read et al., 2008). Seasonal cycling of decaying plant matter into the soil media also provides an optimal environment for nitrogen-fixing microbes (Chen et al., 2020), on the other hand, it contributes to enriching the media in nutrients.

Table 2. 6 The nutrients reduction performance, including total phosphorous (TP), ammonium nitrogen ($NH_{3,4}$-N), total nitrogen (TN), nitrate-nitrite (NO_x) of the BRC literature studies. For each study, the site characteristics, including the land use category, together with the system characteristics, including media depth and composition, fraction between the BRC and contribution drainage areas (A_{BRC}/CDA), and the internal water storage (IWS).

Reference	**Site**	**Land Use category**	**Media Depth [cm]**	**Media compositions**	**A_{BRC}/CDA [%]**	**IWS [cm]**	**TP [%]**	**$NH_{3,4}$-N [%]**	**TN [%]**	**NOx [%]**
Spraakman et al., (2020)	Vaughan (Canada)	Parking area	40	99–93% sand, 1–7% silt, clay	11	**	92 [1]	56	24	80
Shrestha et al., (2018)	Burling-ton (USA)	Roadway	61	60% sand, 40% compost Industrial filter media consists of fine granules of Fe and Al oxide	3 12	**	-288 94	-	45 57	2 23
Lopez-Pon-nada et al., (2020)	Florida (USA)	Urban area	35	Sandy	N/A	0 30	-	74 83	44 77	29 81
Willard et al., (2017)[1,2]	Virginia (USA)	Parking area	60	88% washed sand, 8% clay and silt fines, 4% leaf compost by volume	2	30	100 95	-	100 96	-
Jiang Ch. et al., (2017)	Xianyang (Cina)	Urba area	50	79.9% silt, 11.31%, sand, 8.8% clay	8	**	57	60	56.8	49.8
Mahmoud et al., (2019)	Texas (USA)	Parking area	76	Sandy	3	**	83	-	-	-
Li.Qian et al., (2022)	Tianjin (Cina)	Roadway	65	30% soil,24% river sand,6% peat soil, 20% WTR, 10%vermiculite, 10% zeolite	10	**	70.3	75.2	55	-140
Lim et al., (2021)	Singa-pore	Roof area	100	Sand, soil, coconut fibres, WTR	4	**	32	-	46	-
Ding et al., (2022)[1]	Shenzhen (China)	Parking area	55	60% sand, 31% silt, 9% clay	10	30	-	63.8	-	43.6
Wan et al., (2018)	Shanghai (China)	Roadway	90	80 % sand, 15% soil, 5% wood chips	5	**	-	-10	34	19
Jeon et al., (2021)[3]	Cheonan (South Korea)	Roadway and Park-ing area	80	Sandy	10	**	74	-	74	-

Kandel et al., (2017)	Grove (USA)	Public Public Commeri-cal	60	95% sand, 5% fly- ash	2.2 5.7 2.5	**	64 67 75	-	-	-
Johnson and Hunt (2019)[4]	North Carolina (USA)	Parking area	120	Clay, clay loam, silty clay	15 8	**	-21.4 39.3	-	-38 26	-20 67.4
Chen et al., (2020)	China	Lab.Exp	65	Sand, soil, ceramist, quartz, pyrite Sand, soil, ceramist, quartz, zeolite	N/A	40	81.6 47.5	87.6 98.7	89.3 47.1	-
Fan et al., (2019)[5]	China	Lab.Exp	60	80% fine sand, 20% red soil	N/A		-	95 96	76 71	61 66
He et al., (2022)	China	Lab.Exp	50	sand-based sand-based, 10%Volcaninc rock sand-based, 10% Zeolite sand-based, 10% coal slag sand-based, 5% vermiculite sand-based, 5% perlite	10%	**	99 95 78 87 85 88	34 67 94 75 87 88	32 42 46 35 45 32	-
Takaijudin et al., (2021)[5]	Malaysia	Lab.Exp	29	Engineered media: 60% sand, 30% soil 10% compost	N/A	**	-	81 82	-	-
Wang Chu. et al., (2018)	China	Lab.Exp	45	sandy loam	5%	0 20 30 40 50 60	-	80 88 80 75 80 75	35 45 50 55 58 73	-23 0 10 20 35 62
Chai et al., (2022)[1]	China	Lab.Exp	78	75% topsoil, 25% sand 37.5% topsoil, 12.5%sand, 50% coal 22% topsoil, 12% sand, 33% lava rock, 33% coal	10%	**	82 84 86	-	78 87 86	-

Kratky et al., (2021)	Edmon-ton (Can-ada)	Lab.Exp	86 84.9 85.8 86.4	50.8% sand, 29.4% silt, 19.8% clay 67.2% sand, 19.6% silt, 13.2% clay 48% sand, 27.7% silt, 18.7% clay, 0.5%steel wool, 5 % woodchips 63.5% sand, 18.5% silt, 12.4 % clay, 0.5% steel wool, 5% woodchips	N/A	0 0 20 20	-	94.2 97.8 58.9 73.6	-	-101.5 -116.5 83 73

*Note: "-" not evaluated, "**" not included. CDA: Contribution drainage area, IWS: Internal water storage, BRC: Bioretention cell. [1] The efficiency is based on mass reduction. [2] This study is an evaluation of the Maturation of the BRC's effectiveness ((2007-2008) (first row) (2013-2014) (second row)). [3] This study is an evaluation of the maturation of the BRC's effectiveness (2014 to 2018): the results recorded are the average of the 5 years.[4] This study is an evaluation of the maturation of the BRC's effectiveness ((June 2002–April 2003 (second row), and February 2017–March 2018 (first row)). [5] IWS is 20 cm (down - up: U-type flow regime design) for first row and 20cm (down - up - down -up: W-type flow regime design) for second row. [5]The comparison of the different vegetations: Ixora Padulosa sp. (first row) and Hisbiscus Rosa-Sinensis sp. (second row).*

Heavy Metals

Heavy metals can be found in large amounts in urban stormwater. Most of these metals come from traffic-related sources such as worn tires, brake linings, engine and vehicle body wear (sources of copper and zinc), atmospheric deposition (sources of copper, cadmium, and lead), and building claddings (sources of copper, zinc, lead, and cadmium) (Davis, 2007; Müller et al., 2020). Although low concentrations of some heavy metals such as copper (Cu) and zinc (Zn) are essential to plants, humans, and animals, high heavy metal concentrations are toxic (Nadella et al., 2009). In contrast, even low concentrations of lead (Pb) may have detrimental consequences (Srivastava et al., 2005).

Metals in stormwater may be found in dissolved or particle-bound forms (Sakson et al., 2018), and their partitioning and average concentration values vary greatly from one location to another (Sansalone & Buchberger, 1997). However, a variety of factors, including the pH, temperature, and urban impervious surface type may influence their partitioning and speciation (Gnecco et al., 2019). Heavy metal removal mechanisms in BRCs include sedimentation, filtration, adsorption, and vegetation assimilation (Costello et al., 2020; He et al., 2022). Sedimentation and filtration are effective methods for removing heavy metals in their particle forms, while dissolved form of heavy metals are removed through adsorption onto clay and filter media amendments. In this research, Cu, Pb, and Zn were examined to assess the effectiveness of heavy metal removal by BRCs (Table 2.7).

Using a variety of filter media and amendments, six sand-based BRCs with different amendments in a laboratory study of He et al., (2022) were able to remove Cu, Pb, and Zn, with more than 90% removal rates. In this study, 6 BRC columns were constructed using different amendments which was controlled with no amendments (only sand). five treatments with 10% volcanic rock, 10% zeolite, 10% coal slag, 5% vermiculite, and 5% perlite. All systems achieved removal efficiencies for Cu, Pb, and Zn between 90 and 100%, with some treatments completely removing Zn and Pb. Likewise, Xiong et al., (2021) demonstrated that BRC enhanced with biochar obtained remarkable heavy metal removal effectiveness, exceeding 97% for Cu, Pb, and Zn. Furthermore, in contrast with typical sand-based fillers, the biochar amendment decreased effluent concentrations by 55% for Cu, 61% for Zn, and 19.66% for Pb, highlighting its efficacy in improving adsorption capacity and reducing heavy metal migration in stormwater. Notably, when influent heavy metal concentrations increased, the

media with biochar functioned significantly better. This improved performance is most likely due to biochar's ability to raise the pH of the solution, lowering metal solubility and promoting precipitation, as well as its abundance of anions (e.g., carbonate, phosphate, and hydroxide), which facilitate metal removal through ion exchange, chemical precipitation, and complexation with negatively charged functional groups on its surface.

BRCs are more successful in removing heavy metals from the top filler layer (10–20 cm), according to several research studies (Costello et al., 2020; He et al., 2022; Xiong et al., 2021). This is a result of the quick absorption of heavy metals by the filler and the considerable quantity of TSS retained in the filler's top layer. It is worth noting that the elimination of TSS has a clear correlation with the elimination of heavy metals in BRCs. Additionally, the presence of vegetation can impact heavy metal removal, although this is often secondary to the physical-chemical properties of the soil matrix. Studies (Jeon et al., 2021; Xiong et al., 2021) show that plant species, soil composition, and environmental conditions affect the water-holding capacity and nutrients availability of plant roots, hence influencing heavy metal removal. Notably, Xiong et al. (2021) showed that introducing biochar into medium boosted adsorption capacity while also inhibiting heavy metal downward migration, substantially lowering their transportation into the effluent. These data highlight that, whereas TSS removal and vegetation both contribute to heavy metal sequestration in BRCs, adjusting the media with amendments like as biochar may be critical to improving overall decontamination efficacy.

Oxygen Demanding Contaminants

Two common load reduction criteria may be used to quantify the amounts of organic compounds in stormwater: chemical oxygen demand (COD) and biological oxygen demand (BOD_5). In most cases, the depletion of dissolved oxygen (DO) in streams may be related to anthropogenic sources of organic matter that increase oxygen demand. Common sources include Leaf and other yard wastes, pet and animal wastes, fertilizer, sediment containing organic matter (such as topsoil), and hydrocarbons (e.g., oil) (Davis, 2007; Dickenson & Sansalone, 2022).

The four most common mechanisms for removing the COD in BRCs are adsorption, filtration, microbial degradation, and plant uptake (He et al., 2022; Mahmoud et al., 2019). In particular, the adsorption mechanism is crucial because it acts as a fast capture mechanism

and short-term storage reservoir, paving the way for longer-lasting processes such as biodegradation and plant uptake (Jhonson et al., 2022).

BRCs show potential for treating various oxygen-demanding pollutants, as shown in Table 2.7. For instance, Mahmoud et al., (2019) reported a removal rate of BOD_5 of 51% after 13 months of field monitoring of a BRC implemented in in a parking area with sand-based media while, Takaijudin et al. (2021) observed that BRCs planted with vegetation achieved BOD_5 removal rates of 88% and 87%, compared to 79% in a cell without plants. This highlights the major role of plant absorption. However, it is important to note that since plant uptake and biodegradation are slow processes, COD removal rates are highly dependent on the adsorption rate of the filter media (He et al., 2022; Mahmoud et al., 2019). According to the outcomes of the study in the study of He et al., (2022), vermiculite and coal slag were shown to have higher and constant COD removal rates compared to zeolite, volcanic rock, and perlite. This might be attributed to the static adsorption capabilities of particles such as vermiculite and coal slag. The effects of appropriate additives (WTR, vermiculite, and zeolite) were also seen in the study of Liu et al., (2022) throughout 9 months of field monitoring, achieving average of 78% COD removal. However, as the influent COD concentration increased from 125 mg/L to 500 mg/L, removal rates decreased below 20% (He et al., 2022), suggesting that the fillers' maximum adsorption capacity had been reached. Additionally, rainfall intensity appeared to have only a minor effect on COD removal, with variations of only about 9% observed (Jiang et al., 2017), whereas mature BRCs outperformed newly constructed systems—for example, Jeon et al., (2021) reported a 91% COD removal rate in a BRC after 5 years of operation.

Due to the pervasiveness of microorganisms in the environment, urban stormwater comprises a vast diversity of them. Fecal indicator bacteria (FIB), with E. coli and enterococci making up the majority of these bacteria, are commonly used to evaluate the possibility of microbial contamination of urban stormwater (Galfi et al., 2016). A study conducted by Paule-Mercado et al., (2016) found that urban stormwater had the highest concentrations of fecal contaminants among rural, mixed land use, and urban catchments. The presence of fecal bacteria in urban stormwater poses a concern to human health and is a substantial obstacle to stormwater reuse. Pathogen microorganisms enter runoff from a variety of sources, including sewage leaks, animal waste, and human waste. It is generally known that the

number of fecal indicators and total bacterial cells in urban stormwater is affected by land use and the seasons (Davis et al., 2009; der Hoven et al., 2017).

Microplastics

Microplastics (MPs) negatively affect the environment and human health owing to their chemical properties, prolonged existence, toxicological effects, and bio-accumulation characteristics (Hale et al., 2020; Kershaw & Rochman, 2015). MPs are defined as plastic particles of 100 nm to 5 mm in diameter and include intentionally produced MP beads (primary MPs) or fragments from degraded plastic products (secondary MPs) (Hale et al., 2020). It has been determined that urban stormwater, with MP concentrations ranging from 0.4 to 191 p/L (particles per liter), is the principal source for MP entry points into waterbodies (Gilbreath et al., 2019; Smyth et al., 2021). The principal sources of MPs in urban stormwater include tire particles in high numbers (Werbowski et al., 2021), artificial turf, air deposition, industrial paved surfaces, and litter (Hale et al., 2020). Moreover, face masks are also a significant source of MPs following their widespread use after the outbreak of COVID19 (Fadare & Okoffo, 2020; Wang et al., 2021). There is heterogeneity in MP concentrations because the sources of MP are not uniform across land uses.

After highlighting the significance of considering MPs in urban stormwater, the BRC mechanisms for reducing MPs will be outlined. Physical filtration and soil–media interactions both contribute to the reduction of MPs by BRCs (Gilbreath et al., 2019; Lange et al., 2021) with physical filtration has been identified as the principal process for reducing MPs (Smyth et al., 2021). The effectiveness of BRCs in reducing MPs has not been thoroughly investigated; nevertheless, initial studies have given positive results, as illustrated in Table 2.7. According to the investigation of Smyth et al., (2021) carried out during a two-year monitoring phase, the studied BRC achieved a concentration-based decrease in MPs of 84% and a load reduction of more than 92%. The study of Lange et al., (2021) found that MP particles in the range of 100 to 300 µm could be effectively removed by a BRC, the average particle concentration was reduced from 12 to 1.4 p/L. Keeping in mind that BRCs are better able to retain bigger particles of MPs, although based on solely three monitored storm events, Gilbreath et al., (2019) found an efficiency of 100% for MPs with size fractions of >500 µm, 81% for particles between 355 and 500 µm, and 55% for particles between 125 and 355µm. In the framework of the present review, only one work was found that evaluated the MP removal efficiency of BRCs in the

range of 20 to 100 µm (Lange et al., 2022); MP particles between 20 and 100 µm in size were not significantly reduced by the sand media. In contrast, rubber and bitumen particles in the 100 to 300 µm size fraction were efficiently removed by the BRC.

Table 2. 7 The heavy metals, microplastics (MP) and oxygen demand contaminants reduction performance, including cupper (Cu), lead (Pb), zinc (Zn), chemical oxygen demand (COD) and biological oxygen demand (BOD_5) of the BRC literature studies. For each study, the site characteristics, including the land use category, together with the system characteristics, including media depth and composition, fraction between the BRC and contribution drainage areas (A_{BRC}/CDA), and the internal water storage (IWS).

Reference	**Site**	**Land Use category**	**Media Depth [cm]**	**Media compositions**	**A_{BRC}/CDA [%]**	**IWS [cm]**	**Cu [%]**	**Pb [%]**	**Zn [%]**	**MP [%]**	**COD [%]**	**BOD_5 [%]**
Gilbreath et al., (2019)	Califor-nia (USA)	Roadway	46	70% sandy loam, 10% clay, 20% compost	0.15	**	68	-	-	91	-	-
Jiang Ch. et al. (2017)	Xianyang (Cina)	Urban area	50	79.9% silt, 11.31%, sand, 8.8% clay	8	**	-	-	-	-	39.8	
Mahmoud et al., (2019)	Texas (USA)	Parking area	76	Sand-based	3	**	-	-	-	-	-	51
Smyth et al., (2021)[1]	Vaughan (Canada)	Parking area	40	99-93% sand, 1–7% silt and clay	11	**	-	-	-	84	-	-
Lange et al., (2021)	Sundsvall (Swe-den)	Roadway	50	Sand-based	1	**	-	-	-	70		
Li.Qian et al. (2022)	Tianjin (Cina)	Roadway	65	30% soil, 24% river sand, 6% peat soil, 20% WTR, 10% vermiculite, 10% zeolite	10	**	-	-	-	-	78.9	-
Jeon et al., (2021)[2]	Cheonan (South Korea)	Roadway and Park-ing area	80	Sandy	10	**	65	73	-	-	91	-
He, et al., (2022)	China	Lab.Exp	50	sand-based sand-based, 10%Volcaninc rock sand-based, 10% Zeolite sand-based, 10% coal slag sand-based, 5% vermiculite sand-based, 5% perlite	10	**	95 97.5 95 98 93 99	96 97 100 100 100 100	100 100 100 100 95 90	-	37 40 39 47 56 37	-

Takaijudin et al., (2021)[3]	Malaysia	Lab.Exp	29	Engineered meida:60% sand, 30% soil 10% compost	N/A	**	-	-	-	-	66 66	88 87
Russo et al., (2019)	Italy	Lab.Exp	30	N/A	N/A	**	-	99	-	-	-	-
Chai et al., (2022)[4]	China	Lab.Exp	78	75% topsoil, 25% sand 37.5% topsoil, 12.5% sand, 50% coal ash 22% topsoil, 12% sand, 33% lava rock, 33% coal ash	10	**	-	-	-	-	72 76 78	-

*Note: "-" not evaluated, "**" not included. CDA: Contribution drainage area, IWS: Internal water storage, BRC: Bioretention cell. [1] The results are in median. [2] This study is an evaluation of the maturation of the BRC's effectiveness (2014 to 2018): the results recorded are the average of the 5 years. [3]The comparison of the different vegetations: Ixora Padulosa sp. (first row) and Hisbiscus Rosa-Sinensis sp. (second row).[4] The results are based on mass reduction*

2.4.3 Numerical Modelling of BRC

Numerous field and laboratory studies have demonstrated that BRCs improve the hydrologic performance and load reduction of urban stormwater; consequently, BRCs have gained widespread acceptance among practitioners, researchers, and communities. Despite BRCs' effective performance, their modelling has not received enough attention (Lisenbee et al., 2022). The present review study will explore only a few of the numerous compelling reasons that highlight the importance of BRC modelling in the investigation, design, implementation, and evolution of BRCs.

- Before implementing BRCs, it is essential to model them to predict their hydrologic and quality performance under various situations. The use of models makes it possible to simulate BRC performance by varying local conditions such as climate variables (e.g., temperatures and precipitation), vegetation, and other location specifics. Researchers employ models on the site scale to overcome the limitations in doing fieldwork and to explore more problems than they could assess by monitoring. When BRC performance is evaluated in a controlled environment, such as a laboratory experiment, those results can be transferred to the field scale using modelling approaches.
- To date, most of studies of BRC effectiveness have been undertaken on the site scale (including laboratory experiments), while the impacts of BRCs on the catchment scale have received relatively less attention. Indeed, the effects of implementing several BRCs in a catchment, as well as the optimum placements for these BRCs, can be determined with the use of BRC modelling, as filed monitoring on this scale needs more time and resources (Lisenbee et al., 2021).
- Modelling allows researchers to comprehend the complex internal dynamic mechanisms associated with the movement of water and the fate, transport, and retention of pollutants within a BRC (Li & Lam, 2015).

Considering these factors, both quantity and quality modelling of BRCs is essential for reliable findings, despite the emphasis on hydrologic and hydraulic aspects in these modelling studies over quality behaviour. In Tables 2.8 and 2.9, the most relevant quantity studies are reported, focusing on the analysis at the site scale and at the catchment scale, respectively, while the quality studies are reported in Table 2.10.

Tables 2.8–2.10 report the site characteristics, including the location and spatial scale; the modelling features, including the program type and calibration phase; the simulation conditions; and the simulated variables for each study. Analysis of the modelling tools reveals that the US EPA's Storm Water Management Model (SWMM) was the most commonly used model, used in 35% of the studies reviewed. This was followed by HYDRUS-1D or HYDRUS 2D/3D, which accounted for 11%, and RECARGA, which comprised 4% of the studies analysed. Additional models employed include the Source Load Assessment and Management Model for Windows (WinSLAMM), the Model for Urban Stormwater Improvement Conceptualization (MUSIC), the Green Infrastructure Flexible Model (GIFMod), DRAINMOD developed by NC State University, MIKE URBAN by DHI, and various other specific algorithms.

In terms of the quantity, modelling tools generally involve the following hydrologic variables: inflow, outflow, and drainage. For specific applications, the simulations also consider soil moisture, lateral flow, ponding depth, and water table. In terms of the quality, models reproduce the mass and effluent concentration of the following pollutants: TSS, TP, and TN. A more detailed modelling analysis allows to predict the nitrogen species (NO_3-N and NH_3-N), dissolved fractions (such as Dissolved Reactive Phosphorus, DRP, and dissolved organic carbon, DOC), Total Organic Carbon (TOC), and trace metals (e.g, Cu, Zn, and Cd).

In hydrological modelling, using a high-resolution discretization, such as 1-minute intervals, is crucial for accurately representing the dynamic changes in hydrologic variables. Conversely, Simulations that rely primarily on cumulative values, such as daily, event, monthly, or annual volumes, may neglect transient variations that considerably affect system performance and response (Hernes et al., 2020; Smolek et al., 2015). The application of lower-resolution time steps results in the loss of critical temporal dynamics within the BRC system during storm events, leading to an analysis that does not align with the time of concentration recorded in urban catchments. Consequently, high-resolution discretization is essential for examining the event-based performance of BRCs, especially in the context of evaluating urban flood mitigation at the catchment scale (Baffaut et al., 2015; Dutta et al., 2021). Simultaneously, continuous long-term simulations at various time steps can provide insight into the hydrologic variables, such as the flow duration curve (Dutta et al., 2021), improve the understanding of BRC biogeochemical reactions and physical processes (Alikhani et al., 2020), and are essential in defining operation and maintenance conditions (Massoudieh et al., 2017).

Quantity modelling studies at the site scale acknowledged that the SWMM can be used to simulate BRCs (Gülbaz & Kazezyılmaz-Alhan, 2017; Lisenbee et al., 2020; Lisenbee et al., 2022), although, its calibration optimizes one single variable, and the IWS representation should be improved (Lisenbee et al., 2022). Specific advanced algorithms and/or other programs, such as HYDRUS, HM-RWB, and RECHARGE, can provide more accurate estimates of the involved hydrologic processes (Fowdar et al., 2022; Lisenbee et al., 2022), especially when the calibration involves more variables (Stewart et al., 2017) or includes the drainage flow (Lisenbee et al., 2022) . These modelling tools help to design effective BRC configurations by determining ideal media characteristics, IWS, and ponding depths, including cost evaluations (Jiang et al., 2017), and considering site-specific groundwater dynamics (Kandra et al., 2015).

Quantity modelling studies at the catchment scale, eventually calibrated at the site scale for a single BRC installation (Dutta et al., 2021), can support the selection of the optimal footprint design of BRCs based on a single objective (such as volume and peak flow reduction) or multiple objectives including a cost analysis (Baffaut et al., 2015). It is crucial to highlight that different modelling studies on the catchment scale are focused on determining how combined LIDs may contribute to improving the management of stormwater rather than on concentrating solely on BRC implementation.

Quality modelling encompasses a huge number of parameters with various degrees of uncertainty. For instance, several pollutants, both soluble and particulate, may interact with or be modified by microbial degradation mechanisms in BRCs; therefore, models should reproduce nonlinear biogeochemical reactions and associated physical processes affecting them. However, numerical tools on this are still limited. Consequently, quality modelling has its own difficulties, and existing models predict stormwater quality with less reliability than stormwater quantity (Heasom et al., 2006; Y. Li & Lam, 2015), even if several studies (e.g., (Lisenbee et al., 2020; Tiveron et al., 2018)) have highlighted the importance of accurate hydrologic modelling in making reliable predictions of BRC quality performance. In the modelling study of Tiveron et al., (2018), the calibration and validation of TSS reduction by BRCs has been performed, in addition to the hydrograph inflow and outflow. In this study, a developed SWMM add-in tool was implemented to predict the BRC performance in TSS reduction and bench-marked against the TSS removal predicted by WinSLAMM. In the

investigation conducted in J. Li et al., (2020), HYDRUS-1D was used to model BRC performance using calibration and validation data for contaminants including COD, NO_3-N, NH_3-N, TN, TP, Cu, Zn, and Cd with fairly good performance. For instance, the average Nash–Sutcliffe model efficiency (NSE) for COD calibration was 0.57, while the NSEs for NO_3-N, NH_3-N, and Zn were 0.60, 0.66, and 0.65, respectively. However, in Alikhani et al., (2020), it was noted that 95% confidence interval for the reproduced load reduction metrics was wider than the findings for quantity modelling. This is due to the greater uncertainty in the parameters associated to the water quality modelling as well as the lower number of observed data points in comparison to the number of model parameters used.

Modelling results for both quantity and quality variables support the optimization of BRCs by pointing out that design characteristics significantly affect the system behaviour and efficiency. For instance, Alikhani et al., (2020) found that the effectiveness of BRCs may be affected by the IWS height, the media depth, and the size of the CDA, while Stewart et al., (2017) performed a sensitivity study to determine the effects of changing the saturated hydraulic conductivity on BRC performance. Alikhani et al., (2020) revealed that the effect of IWS on N load reduction was between 10 and 20%, and considering the minimal cost of implementing IWS, indicated that it was a desirable practice. Due to the higher hydraulic retention time (HRT) and duration of anoxic conditions in engineered soil media and aggregate layers, IWS was found to have a more apparent influence on load reduction component load during moderate and small occurrences, but not during large events. Increasing the media layer's thickness had comparable consequences to increasing the IWS's height. Additionally, it was also shown that doubling the CDA considerably decreased the volume reduction efficacy of the BRCs.

Table 2. 8 Modelling studies of the hydrologic processes in BRCs on the site scale. For each study, the site characteristics, including the location and spatial scale, are reported together with the modelling features, including calibration phase, simulation conditions, and modelled variables.

Reference	Location	Spatial scale	Modelling tool	Calibration	Simulation	Hydrologic Metrics	Highlights
Lisenbee et al.(2022)	Cleveland (OH, USA)	Site scale (3600 m^2)	DRAINMOD-Urban and SWMM	Y	Individual events (1-min time step)	Outflow, overflow volume and drainage	DRAINMOD-Urban calibration improves both volumes and hydrographs; the percolation is predicted with a physically based equation considering the unsaturated flow. The SWMM calibration optimizes one single variable. The IWS representation should be improved.
Bonneau et al, (2021)	Melborne (Australia)	Site scale (1800 m^2)	R Algorithm	Y	Individual events (6-min time step)	Outflow, overflow, infiltration, drainage, water level	The model is based on storage in series, accounting for the water balances in storage and water fluxes exchanges between storage. The model is not able to reproduce empty initial conditions
Wang et al., (2019)	Singapore	Site scale (280 m^2)	RECHARGE	Y	Individual events (1-min time step) Continuous (0.5-year long)	Surface and subsurface outlets, soil moisture, ponding depth	Simulation results support the definition of configurations that improve performance efficiency.
Liu et al., (2022)	McAllen (TX, USA)	Site scale (1618 m^2)	WinSLAMM	Y	Individual events	Runoff	The calibrated model suitably reproduces the outflow runoff volume. A cost analysis is available
Gülbaz & Kazezyılmaz-Alhan (2017)	Istanbul (Turkey)	Laboratory scale (40 m^2)	HM-RWB	Y	Individual events	Runoff, infiltration, drainage	The model accuracy is better with respect to SWMM simulations, the accuracy is also evaluated for drainage flow.
Stewart et al., (2017)	Cleveland (OH, USA)	Laboratory scale (48 m^2)	HYDRUS 2D/3D	Y	Continuous (500 days long)	Drainage, ponding depth, water	The model can describe the ground water dynamics that occurred at the site. The

						table depth, soil water content	model sensitivity to key parameters, including the saturated hydraulic conductivity for soil layers within and around the BRC, is examined.

Note: Y/N in the calibration column refers to whether the calibration phase was performed/not performed.

Table 2. 9 Modelling studies of the hydrologic processes in BRCs on the subcatchment scale, eventually including model calibration at the site scale for a single BRC installation. For each study, the site characteristics, including the location and spatial scale, are reported together with the modelling features, including the calibration phase, simulation conditions, and modelled variables

Reference	**Location**	**Spatial scale**	**Modelling tool**	**Calibration**	**Simulation**	**Hydrologic Metrics**	**Highlights**
Hernes et al., (2020)	Oslo (Norway)	Site scale (100 m^2) Subcatchment scale (50 ha)	MIKE Urban (MU)	Y N	Individual events (1-min time step) Continuous (1-year long)	Outflow FDC [1]	A sensitivity analysis of RG parameters was carried out. The simulations for FDC do not account for evapotranspiration. The model predicts the efficiency of different degrees of implementation of NBS (seven scenarios)
Wang et al (2019)	Guangzhou (China)	Sub-catchment scale (5000 m^2)	SWMM	N	Individual events	Outflow	Model results, including a cost analysis support, the definition of the optimum extent (aerial coverage) of BRCs in the catchment based on a single objective (i.e., outflow volume or peak flow reduction) or multiple objectives
Mei et al., (2018)	Beijing (China)	Catchment scale (651 km^2)	SWMM	N [2]	Individual events	Runoff, flood volume	Model results have been paired with an LCA cost analysis to evaluate an integrated LID strategy to mitigate urban flooding.

Note: Y/N in the calibration column refers to whether the calibration phase was performed/not performed. [1]FDC: flow duration curve. [2] The model calibration involved the runoff at the outlet section of the catchment, no calibration has been carried for the BRCs.

Table 2. 10 Modelling studies of BRCs including quality processes at the subcatchment scale, eventually including model calibration at the site scale for a single BRC installation. For each study, the site characteristics, including the location and spatial scale, are reported together with the modelling features, including the calibration phase, simulation conditions, and modelled variables.

Reference	Location	Spatial scale	Modelling tool	Calibration	Simulation	Hydrologic Metrics	Quality variables	Highlights
Fowdar et al., (2022)	Punggol (Singapore)	Site scale (480 m^2)	MUSIC	Y	Individual events (5-min time step)	Outflow rate and volume	TSS, TN, TP	The quantity module was not able to predict different inflow in dry/wet conditions. The treatment modules were able to simulate outflows and effluent pollutant concentrations.
Alikhani et al.,(2020) and Massoudieh et al.,(2017)	Cincinnati (USA)	Site scale	GIFMod	Y	Continuous (3 years long)	Inflow, outflow, drainage	TP, DRP [1], TN, NO_3, NH3, TOC, DOC, TSS, VSS	GIFmod allows for the incorporation of nonlinear biogeochemical reactions and the associated physical processes affecting them
J.Li et al., (2020)	Xi'an (China)	Site scale	HYDRUS-1D	Y	Individual events (15-min time step)	Inflow, outflow, drainage, soil moisture	COD, NO3-N, NH3-N, TN, TP, Cu, Zn, Cd	The model can simulate 1D vertical water and solute transport ignoring lateral transport. Model results support the optimization of BRC facilities
Tiveron et al., (2018)	Woodbridge, (ON, Canada)	Site scale (297 m^2)	SWMM	Y	Continuous (4 months long)	Inflow, outflow	TSS	The SWMM add-in tool can suitably predict the TSS reduction
Y. Yang et al., (2018)	Hong Kong (China)	Site scale (5000 m^2)	SWMM	N	Continuous (9 years long)	Inflow, outflow	First flush	Model results define an optimization problem (single and multi-objective)
Smolek et al., (2015)	Cul-de-sac (Sint Maarten, Caribbean)	Sub-catchment scale (2.4 km^2)	SWMM	N	individual events Continuous (20 days long)	Outflow	TSS, TN, TP	Different combinations of NBS are modelled. Continuous simulation is essential to define operation conditions.

Note: Y/N in the calibration column refers the performed/not performed calibration phase; [1] DRP is Dissolved Reactive Phosphorus.

2.6 Research Needs

Even if BRC performance has recently improved, further research is necessary, especially in system optimization, including design recommendation, long-term performance assessment, emerging pollutant treatment efficiency, and model validation.

In terms of the system optimization, future research should focus on determining the optimal media composition for BRCs. The properties of the media influence both the quantity and the quality of BRC effectiveness in urban stormwater management. Therefore, significant selecting a BRC media with long-term permeability, suitable hydraulic characteristics, and the ability to support plant growth is essential. Furthermore, it is suggested that appropriate amendments, particularly those from waste products that support eco-friendly waste management, can be used to enhance the BRC media performance in pollutant treatment. However, further studies are required to select the optimal type, distribution, and longevity of these amendments.

BRCs with sand-based media have a significant water infiltration rate, leading to a short retention duration. This provides limited possibilities for dissolved pollutants, including trace organic contaminants, to undergo transformation during a runoff event. Adding an appropriate additive will improve the elimination of organic pollutants because their characteristics, such as large surface area and porosity, can address the issue of short retention time. In addition, the configuration of the underdrain can be modified through the installation of IWS to help to solve this issue; however, further research is required on the IWS design, including its depth, and the addition of an appropriate quantity of carbon source to the BRC bottom (in the IWS zone). On the other hand, further research is needed to determine how existing BRC systems might be altered to increase treatment efficiency while still providing sufficient hydrologic performance.

Particular attention should be given to the design of the outlet section. For example, a reduced flow outlet valve, which prolongs the time that water stays in the media, provides outstanding hydrologic and quality performance. This encourages water to leave the filter media from the sidewalls and the bottom of the cell, creating a more suitable environment for treating contaminants such as N species. Future study needs to evaluate the effect of valve design, placement, and control (manual or automated) on overall BRC performance, since the feasibility, cost-effectiveness, and reliability of automated systems remain unproven.

There are comparatively few long-term research studies in the BRC field. Consequently, the real performance of BRC components during an extended period of field operation is unclear. There is a lack of long-term modelling of BRCs under various climatic and design situations (Y. Li & Lam, 2015). More research with bigger datasets (calibration and validation) must be undertaken to strengthen statistical results, particularly for quality modelling and overflow events.

The efficacy of BRCs in treating MP concentrations has not been thoroughly investigated. To produce a more definitive performance assessment and to enable comparisons of different BRC performances, studies should be performed in various geographical regions with varying media composition and design. Furthermore, as nano-plastics are a growing concern, research on BRC's effectiveness for filtering particles smaller than 100 µm is required.

Despite the availability of several BRC modelling tools, calibrated and validated models are essential for evaluating hydrologic and load reduction performance. Future models need to include dynamic processes, such as plant and root growth, temporal variations in soil characteristics, and changes in drainage design, to accurately represent the developing performance of BRCs over time.

2.7 Conclusions and Recommendation

BRCs are an effective solution for controlling urban stormwater, according to this systematic review. BRCs are one of the most successful LID practices for limiting the hydrologic effects of fast urbanization and enhancing the rainfall-runoff quality in urban settings. Several knowledge gaps impede the advancement of BRCs in the context of managing and treating vast quantities of urban stormwater with variable characteristics. The key design recommendations for BRC implementation that have been addressed in the selected studies are summarized and discussed below.

- The IWS design has several advantages; however, IWS installation requires careful consideration. First, the top of the IWS should not be closer than 30 cm to the media's surface and should not be lower than 30 cm above the cell bottom (Brown & Hunt III, 2011). In addition, for sandy sites, it is recommended that the IWS outlet be 30 cm from the surface of the medium, whereas for clay sites, this value might vary between 47 cm and 60 cm. The reason for the suggested distance could be the plants' ability to survive (Hirschman

et al., 2017). The plants in a BRC can be damaged by a long duration of saturated soil conditions. A vadose zone (free draining depth) of at least 30 cm is necessary at the top of the cell to enable appropriate root growth. Additionally, if the IWS takes up too much of the soil medium layer, there is a chance that organic matter or nutrients might leak out through the underdrain (Brown & Hunt III, 2011; Hirschman et al., 2017).

- The composition of the medium plays a crucial role in both hydrological and load reduction effectiveness. The appropriate ratio of these components will vary depending on local conditions, but a typical mix may consist of 40–60% silty loam, 30–50% sand, and 10–30% organic matter. In some cases, other amendments can be added to the mix to improve water holding capacity, increase retained moisture, and promote plant growth. In addition, adding suitable amendments can enhance the load reduction performance of BRCs. For instance, adding a carbon source can be an effective method for enhancing the performance of BRCs, but the source and amount of carbon added should be considered carefully.
- The media depth is a critical design variable. According to studies, 20–50% of the runoff entering BRCs was lost owing to exfiltration and ET (Brown & Hunt III, 2011) and their field investigation demonstrated that deeper media enhance exfiltration and decrease outflow. Furthermore, Spraakman et al. (2020) noted that dead volumes can occur when the entire volume of BRC is not used efficiently for storage (parts of the system remain underused). Increasing the media depth may decrease these dead volumes and improve the interaction between runoff and the filter media. Nonetheless, deeper media may increase excavation expenses and affect groundwater levels, potentially resulting in BRC failure. Consequently, the appropriate media depth must be carefully designed by considering criteria such as the minimal distance between the BRC bottom and the groundwater table, overall cost efficiency, and the precise mix of the media.
- The issue of clogging, which is the limiting factor in BRC long-term performance, must be carefully considered. it can be classified as either happening at the surface or within the media. When stormwater has a high concentration of fine and silt particles, surface infiltration can be hindered, which can have an adverse effect on the hydrologic performance of BRCs and cause them to be undersized. In addition, the physical, chemical, and biological processes inside the media may be constrained, resulting in a decrease in

the hydrologic and quality performance of the BRCs (Brown & Hunt III, 2011; Kandra et al., 2015). The application of appropriate amendments can help limit clogging of the media. Additionally, to prevent clogging and deterioration of BRC performance, the (EPA, 2000) recommends replacing BRC media every 5 to 10 years, although this guideline did not take into consideration the effects of plant roots.

- Vegetation for BRCs is usually chosen for its resilience in the face of adversity, its esthetic appeal, and its local availability. In most cases, plants are not evaluated based on strict performance criteria for their ability to remove specific contaminants and deal with hydrological processes. To select the vegetation for a BRC, it is essential to consider the following criteria: the plant should be native, have a high phytoremediation ability, have significant above-ground biomass, have thick and widespread roots, require minimal care or fertilizer, be able to resist dry conditions, and offer a habitat for a variety of microorganisms. Although this promising practice may represent the greatest effort to restore the hydrology of urban areas and improve the load reduction of stormwater, with additional advances in the development of BRCs, its performance in terms of quantity and quality will become more reliable, thereby contributing to the establishment of long-term solutions to stormwater urban drainage problems.
- Before the implementation of BRCs, numerical modelling needs to be employed to predict their hydrologic and load reduction effectiveness under diverse local conditions, including changes in climate, vegetation, and other site-specific variables. Modelling not only addresses the constraints of field monitoring and controlled laboratory research but also offers significant insights into the complex internal dynamics that regulate water flow and the fate, transport, and retention of pollutants. These prediction instruments are crucial for optimizing BRC design, facilitating efficient stormwater management, and eventually improving overall system performance.

Chapter3

Analytic hierarchy process in Selecting Bioretention Cells in Urban settings: Analysing Hydrologic and Hydraulic Metrics for Sustainable Stormwater Management

This chapter is based on the paper published of Nazarpour et al., 2024. It provides a framework to evaluate optimal bioretention cell configurations in urban residential settings to mitigate flood risks.

3.1 Abstract

This study aims at evaluating the role of bioretention cells (BRCs) in supporting sustainable stormwater management and reducing flood risk focusing on urban residential settlements. For this purpose, an analytic hierarchical process (AHP) is employed to select the optimal BRC configuration (in terms of spatial settings and footprints). The optimal BRC spatial footprint is assessed for specific rainfall conditions and BRC spatial settings by considering 5 relevant criteria: the hydrologic (Volume Reduction – VR; Peak Flow Reduction – PR) and hydraulic metrics (Node Flooding Reduction – NFR; Network Stress Reduction – NSR) and the total cost. The modelling framework to evaluate the hydrologic-hydraulic metrics of the urban settlement is implemented by the TRIG Eau DST platform (http://www.trigeau.servergis.it/), a web-GIS based application that incorporates the SWMM v.5.1 (Stormwater Management Model). The simulation scenarios are defined based on five key variables: 4 precipitation regimes, 3 return times, 4 degrees of imperviousness, 2 BRC settings, and 4 BRC footprints, resulting in a total of 384 modelling scenarios. Simulation results, examined based on the hydrologic and hydraulic performance metrics, reveal that BRCs are effective in controlling runoff, with negligible overflow observed solely in limited cases. Furthermore, the BRC impact at the urban residential settlement is confirmed by the average values of the PR and VR ranging from 0.15 to 0.35 and 0.16 to 0.32, respectively. Focusing on the affecting factors, the impact of rainfall intensity on the effectiveness of BRC is moderate, whereas the degree of imperviousness has a significant effect. Findings of the AHP analysis demonstrate that for high precipitation regimes, BRC with a 15% footprint is optimal, while BRC with a smaller footprint (equal to 10%) is more appropriate for low precipitation regimes. These results underscore the significance of strategic BRC placement and customization to improve the sustainable stormwater management practices in urban areas. Future research may incorporate other

benefits of BRC (e.g., load reduction metrics) as well as investigate a broader range of BRC designs (e.g., underdrains). The proposed methodology based on AHP analysis may support the implementation of sustainable urban drainage solutions (besides BRCs) within the existing urban areas.

3.2 Introduction

3.2.1 Motivation

The expansion of impermeable surfaces driven by urban sprawl has significantly changed the natural hydrological cycle, leading to lower infiltration, and evapotranspiration rate (Li et al., 2023; Walsh et al., 2005). This change is expected to be exacerbated by the projected increase in intense precipitation and flooding worldwide in the 21st century, as indicated by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (Zhou et al., 2022), especially in highly urbanized areas. Additionally, conventional drainage systems, which were once effective, are currently struggling with the combined impacts of urbanization and climate change, resulting in elevated flow rates and greater discharge volumes (McGrane, 2016). Catastrophic flooding events have become more prevalent in urban areas worldwide, which put people's lives at risk and generate enormous economic damages (Ma et al., 2022). To tackle these challenges and promote sustainable urban ecosystems, several concepts, such as sustainable drainage systems (SUDS), low impact development (LID), water sensitive urban design (WSUD), green infrastructure (GI), and stormwater control measures (SCMs), have been introduced to restore the urban water cycle to a state as close to its natural pre-development conditions as possible (Fletcher et al., 2015). Among various LID practices, bioretention cell (BRC) has been widely used due to its ability to effectively control the hydrology of urban stormwater (Davis, Asce, et al., 2012; Lisenbee et al., 2021b; Nazarpour et al., 2023).

Extensive field and laboratory research has demonstrated the effective performance of BRCs in urban stormwater control at the site scale or system scale/laboratory (inflow and outflow of the BRCs) (Spraakman et al., 2020; Walsh et al., 2015). However, there is a noticeable gap in understanding the effectiveness of BRCs at the scale of urban area (Li et al., 2017; Walsh et al., 2022). To fill this gap, modelling approaches may significantly improve the comprehension of BRC performance in urban catchment, as conducting monitoring studies on

this scale requires considerable time and resources (Lisenbee et al., 2021b; Nazarpour et al., 2023a).

Additionally, a major challenge in BRC planning and development is the absence of agreed-upon guidelines and processes (Calvert et al., 2018). Although some research has suggested important guidelines for designing BRCs (generally for GI), such as multi-functionality, connectivity, integration, communicative and social-inclusive processes, and long-term strategies, there is still a lack of explicit guidelines. To address this, multi-criteria decision-making (MCDM) approaches can provide an effective analytical tool to solve decision-making issues that involve several objectives, criteria, and stakeholder preferences (Yang and Zhang, 2021).

3.2.2 Literature Review

To assess the effectiveness of BRCs in improving the sustainable urban stormwater management, prior modelling research has concentrated on the hydrological performance of BRCs, either as standalone practice or in combination with other LIDs at the catchment scale (e.g., Bah et al., 2023; Mehri et al., 2024a; Tansar et al., 2023). Several studies have emphasized the significance of BRCs in reducing the runoff generation and consequently in mitigating flood risk in various geographical contexts.. For example, Tansar et al., (2023) performed the sensitivity analysis techniques on the design parameters of BRC at the catchment scale considering different rainfall conditions. However, the assessment of the influence of BRCs on urban stormwater management and flood risk mitigation remains uncomprehensive. Noteworthy findings by Mehri et al (2024a) showed that the implementation of BRCs in a 65-ha area with a 2.7-ha BRC surface area can effectively decrease both total runoff volume and peak flow rate at the outlet section of the investigated subcatchment located in Teheran (Iran). Specifically, for design storm with a return period ranging from 2 to 100 years, the reductions in runoff volume and peak range from 60.7 to 75% and 16 to 65%, respectively. A study by Kuok et al., (2024) in Sarawak, (Malaysia), encompassing approximately a 6.5-ha area with 90% impervious surfaces explored employing SWMM different alternatives of LID practices including BRC and vegetated swales in supporting the quantity and quality management of stormwater. The results indicated that the combination of BRC and swales in the optimal scenarios significantly reduced peak runoff by up to 25%. Additionally, Bah et al., (2023) demonstrated the better performance of LID

combinations with respect to the individual ones across various return periods of rainfall events in an urban catchment area of about 26-km^2 located in Conakry City (Guinea), even if individual LID implementations, including BRC, can lower runoff and flooding.

If extensive research is carried out on how BRCs enhance urban stormwater management by means of numerical studies that predict decreases in runoff volume and peak flow (hydrologic metrics), numerical evaluations that include the stormwater network behaviour to assess network efficiency and flood prevention (hydraulic metrics) are still limited in the literature. Only few literature studies deal with monitoring data concerning widespread BRC installation (combined with other LIDs) at the scale of urban area, despite the necessity of experimental data for the comprehensive knowledge of the processes and the validation of the hydrologic and hydraulic models (Shuster and Rhea, 2013; Walsh et al., 2015).

The use of MCDM, also known as multiple objective decision support (MODS) and multi-criteria decision analysis (MCDA), provides a structured approach for addressing decision-making issues that involve several objectives, various criteria, and variable preferences (Yang and Zhang, 2021). When many criteria are combined and a wide variety of stakeholder preferences are considered, MCDM works as an efficient analytical tool to support decision-making processes (Kremer et al., 2016). Several methodologies have been developed for MCDM analysis (Velasquez al., 2013), including Analytic Hierarchy Process (AHP) (Bai et al., 2019), Fuzzy AHP (Alvarez et al. 2021; Mansur et al., 2016), Analytic Network Process (ANP) (Coban et al. 2018), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Babaei et al., 2018), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Jayasooriya et. al., 2018; Qiao and Pei, 2022), and Choquet Integral (Chi et al. 2021). Recent research has increasingly focused on the application of MCDM models to optimize LID scenarios including BRC, highlighting their effectiveness in reducing urban flood risk through strategic combinations of LID practices (e.g. Bousquet et al., 2023; Hajkowicz and Collins, 2007). MCDM models are crucial for facilitating decision-making by identifying appropriate LID practices that conform to technical, economic, and environmental goals. Numerous studies s (e.g. Ashofteh and Pourali Dougaheh, 2024; Nazari et al., 2023). highlight the efficiency of MCDM frameworks in supporting the widespread implementation of sustainable urban runoff management practices. The MCDM models frequently are frequently combined with hydrologic models or integrate results of stand-alone hydrologic

models (such as SWMM). In a recent study, Mehri, et al., (2024b) adopted Fuzzy TOPSIS to give priority to LIDs according to four indicators including runoff volume reduction, peak flow reduction, economic sustainability, and social sustainability. Results confirm that the rain barrel and BRC combined scenario is the best option based on all four criteria.

Similarly, Nazari et al., (2023) conducted a comparison of two MCDM methods—TOPSIS and Complex Proportional. Assessment (COPRAS)—to evaluate LID scenarios according to technical and economic criteria, highlighting significant discrepancies in their findings mainly due to the different cost analysis methods. TOPSIS selected scenario includes rain barrels, permeable pavements and vegetated swales as the optimal choice. Conversely, COPRAS preferred the more economical scenario including rain barrels, BRC and vegetated swales while realizing decreases in hydrologic performance. Ashofta and Pourali Dougaheh (2024)showed that the MCDM technique identifies permeable pavement as the most efficient alternative for reducing runoff and minimizing cost over both historical (1988-2005) and prospective scenarios (2030-2047 and 2048-2065) under climate change scenarios. Yang et al. (2015) employed TOPSIS to determine the most appropriate locations for the construction of permeable pavement in the Mokgamcheon Basin in Korea, considering environmental, economic, and social factors. Furthermore, Bai et al. (2019) used AHP to assess LID systems in Jiangsu, China, emphasizing the superior performance of green roofs in volume and peak reduction as well as economic factor. The study conducted by Eckart et al., (2018) established an optimization-simulation model by integrating the SWMM with the Borg Multi Objective Evolutionary Algorithm (MOEA) to evaluate LIDs for stormwater management for a selected 77-ha urban sub-catchment in Windsor, (Ontario) according to three objectives of minimizing peak flow, reducing total runoff, and minimizing cost. The model effectively produced results on LID implementation, including cost benefit curves, optimal LID combinations, sizing, and placement. Additionally, Mahdiyar et al. (2020) implemented the Fuzzy Delphi Method (FDM) and the Fuzzy Best-Worst Method (FBWM) to identify obstacles to the implementation of green roofs in Malaysia identifying the high initial cost as the key barrier together with the lack of social awareness. This result highlights the importance of financial incentives and participation activity to increase awareness.

Considering the various MCDM methodologies, it is essential to assess which approach is most effective for decision-making in the LID context (e.g., Bai et al., 2019.). Several factors

distinguish the AHP among these methodologies. AHP provides a structured framework that enables decision-makers to integrate both quantitative and qualitative data while systematically evaluating different criteria. The capacity to establish a clear hierarchy of priorities renders it especially effective in complex decision-making contexts characterized by diverse stakeholder preferences. The use of AHP enables decision-makers to conduct thorough evaluations by considering the complex interrelationships among technical, economic, and environmental factors that influence the effective implementation of LID strategies.

3.2.3 Research Gaps

Based on the critical analysis of the state of the art, it emerges that there is a substantial gap in the comprehension of the effects of the widespread BRC installation at the scale of urban area. This study addresses this gap by numerically investigating the interaction between the spatial distribution of BRCs characterised by different footprints, various levels of imperviousness of the residential settlement and various rainfall regimes. Numerical results for various BRC installation scenarios are discussed based on the combination of hydrologic and hydraulic metrics.

To achieve this gap, it is relevant to consider variables including the spatial distribution of BRCs within the catchment, their interaction with different levels of imperviousness, different rainfall patterns, and the application of both hydrologic and hydraulic metrics.

Furthermore, it is essential to develop a framework for optimizing the widespread BRC installations according to expected benefits and objectives. Most studies prioritize technical and hydrologic performances, frequently disregarding economic and social factors. Considering the increasing focus on cost-effective urban planning, it is imperative to incorporate economic factors into BRC performance assessments to guarantee viable and sustainable solutions. In this research, the integration of MCDM approach can address this gap by integrating stakeholder preferences and economic considerations into BRC planning and evaluation.

3.2.4 Objectives and Contributions

To enhance the comprehension and practical application of BRCs in urban runoff management strategies, this research intends facilitating informed decision-making and

optimized deployment strategies in urban runoff management practices. The overall objective of the present research is to develop a modelling framework to evaluate the effectiveness of BRCs in enhancing sustainable urban stormwater management and mitigating flood risk, specifically within urban residential settlements. To achieve this overall objective, the study aims to explore three specific questions:

(a) What is the extent of the effectiveness of BRCs when translating beyond the commonly evaluated site scale to the urban residential settlements?

(b) What is the performance of BRCs in different scenarios, considering variations in rainfall characteristics, the imperviousness degree of the residential area, and the configuration of BRCs?

(c) What is the most effective BRC footprint, employing a MCDM framework that considers both hydrologic and hydraulic metrics, as well as economic metrics for urban flood mitigation?

3.3 Material and Method

3.3.1 The Web-GIS Application

This study applies a model-based approach to assess the effectiveness of BRCs in improving urban stormwater management at the urban settings. To achieve this, a decision support tool (DST) integrated into the TRIG Eau platform's web-GIS based application is used. This platform, developed as a part of the INTERREG IT-FR Maritime Programme project, incorporates the SWMM v.5.1 (Stormwater Management Model) for the purpose of hydrologic-hydraulic modelling. It is accessible online (http://www.trigeau.servergis.it/, accessed in February 2025). This study applied an event-based modelling to compare situations before (namely the reference scenario) and after the installation of the BRC (Palla and Gnecco, 2022). The following section provides a detailed description of the TRIG Eau platform and its functionalities.

The TRIG Eau platform (Trans-Boundary, Resilience, Innovation and Governance for Hydrogeological Risk Reduction), developed as part of the homonymous project, is a web- GIS application built on the Plone content management system and uses the Zope Python application server. This platform incorporates SWMM to model the hydrologic and hydraulic behaviour of urban drainage systems (Palla and Gnecco, 2021), enabling a comparative

analysis between the current state (actual scenario which in this study is the situation before the implementation of the BRCs) and a modified state (post-intervention scenario which in this study is the situation after the implementation of the BRCs). The platform aims to increase awareness of stormwater management problems and promote using LID systems such as BRCs, green roofs, permeable pavements, and rainwater harvesting systems. The platform's interface is organized into three main sections (see Figure 3.1):

- Actual configuration (left side): the platform illustrates a map of a nonspecific urban catchment (refer to Figure 3.2) showing the planimetric configuration of the drainage network, containing conduit dimensions, slope, and junctions. It is important to note that 13 junctions, which comprises the outfall, and 12 conduits are identified as essential parts of the network. The degree of imperviousness of residential subcatchments (30%, 45%, 75%, and 90%), the drainage network type (coastal, medium-slope, or high-slope), and the design storm intensity (expressed as a return period in years, refers to 3.3.1.2) can all be selected by users. A list (refer to Table 3.4) shows the network stress index and node flooding index, which defines the hydraulic performance under the specified conditions (before BRC implementation).
- Post-Intervention configuration (right side): Allows users to select intervention parameters (in this study, the footprint of BRCs with diverse spatial distributions) through a drop-down menu, which updates both the map and the revised network stress index and node flooding index values for the modified drainage network.
- Performance metrics (bottom): The results are summarized in two categories, one for hydraulic performance (network stress reduction and node flooding reduction) and the other for hydrologic performance (volume reduction and peak flow reduction). For simplicity of comprehension, these four performance measures are shown graphically in a radar graph.

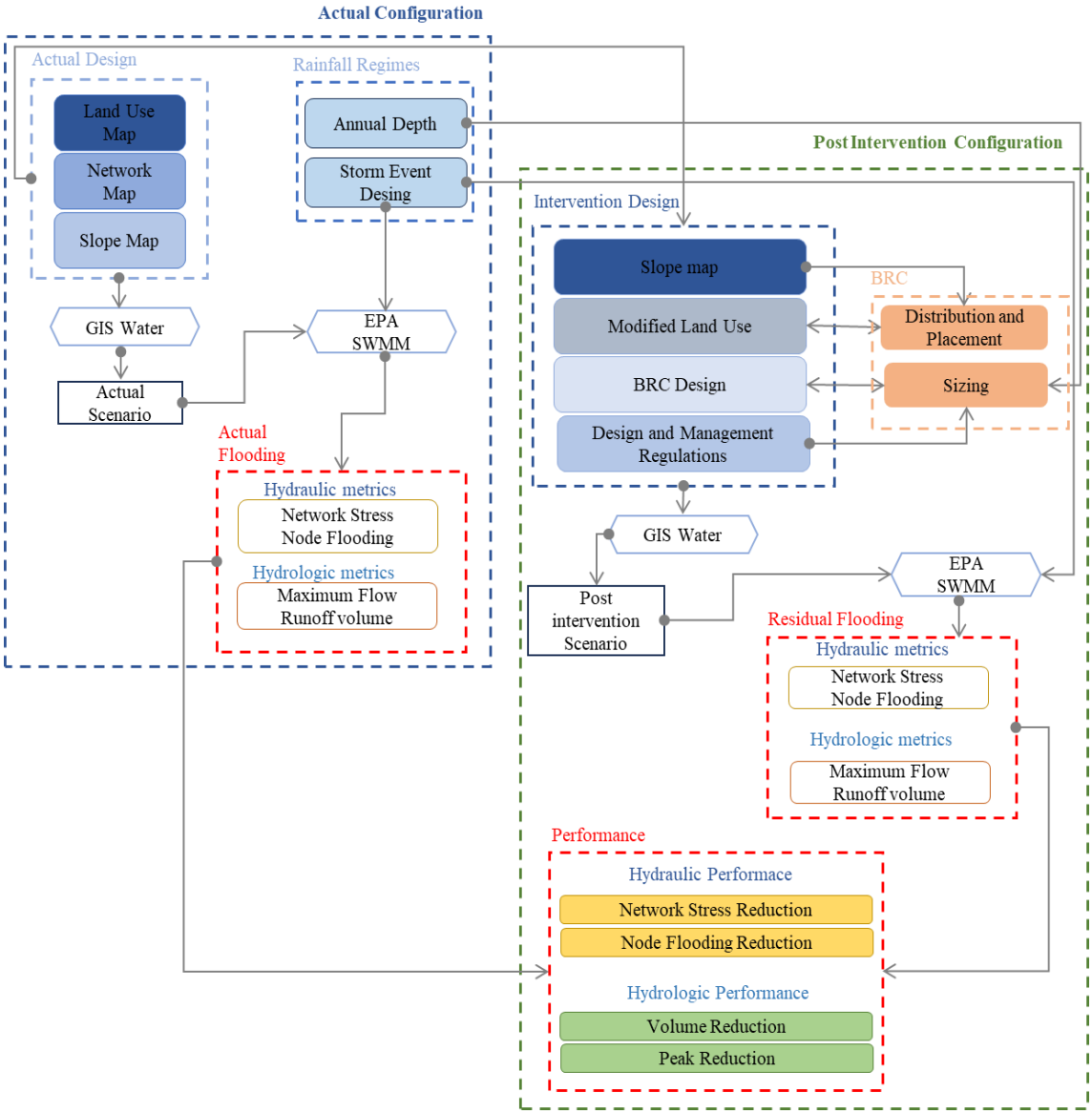

Figure 3. 1 Flow chart of the case study webpage of the TRIG Eau platform adapted from Palla & Gnecco, (2021).

It is also important to note that the three separate drainage network configurations of the platform represent a particular plane-altimetric profile. Despite the uniformity in drainage areas (defined by the number of nodes and conduits), these profiles exhibit variations in conduit slope and length. Furthermore, the two sub-catchments under study are distinguished by a single land use type with homogenous features, allowing for a reliable simulation of the catchment's hydrologic response and precise source control scenario definitions.

3.3.1.1 Urban residential settlement description

The urban residential framework is defined as a non-specific urban area of 2-ha that is representative of typical residential settlement patterns. Figure 3.2 illustrates the outline of the urban area, including an overview of subcatchments and the plan of the drainage network (blue line). The area is divided into two separate subcatchment typologies: roadways and

Figure 3. 2 The outline of a non-specific urban residential settlement of 2-ha including overview of subcatchments (roadways and residential areas) and plan of the drainage network (blue line). The figure highlights the Main roads with 10% BRC implementation in high imperviousness

residential areas. The roadways (distinguished into main and secondary roads) and residential areas have an extension of 0. 54-ha (27% of the total) and 1.46-ha (73% of the total), respectively.

To provide accurate modelling of the hydrologic response of the investigated urban area and an accurate description of source control scenarios, the subcatchments are defined by single land use categories and uniform characteristics (Krebs et al., 2014). The roadways are assumed to be completely impermeable (100% imperviousness), while the residential areas were simulated with several levels of imperviousness (30%, 45%, 75%, and 90%), thus allowing for the investigation of various urbanization scenarios.

The stormwater drainage network underlying the residential settlement has 12 junctions, one outfall (the outlet downstream boundary), and 12 conduits (see Figure 3.2). The physical dimensions of these drainage systems are specifically designed to manage a 10-year, 30-min design storm without experiencing any flooding, considering the 30% level of imperviousness. In this study the coastal drainage system was selected.

3.3.1.2 Precipitation characterization

The TRIG Eau platform encompasses four different precipitation regimes — Humid Temperate (HuT), Mediterranean Continental (MeC), Hot Temperate (HoT) and Sublitoral (Sub)— to represent the various climatic conditions in the cross-border region covered by the INTERREG IT-FR Maritime Programme project. Each regime corresponds to specific geographical areas: HuT represents the Liguria Region in Italy, MeC belongs to the Provence-Alpes-Côte d'Azur (PACA) Region in France, HoT refers to the Sardinia Region in Italy, and Sub is related to the coastline section of the Tuscany Region in Italy. The parameters for Depth-Duration-Frequency (DDF) curves were obtained by regional frequency analysis of extreme precipitation events (Palla and Gnecco, 2021). The DDF relationships were utilized to design synthetic storm events using the Chicago method for return periods of 2, 5, and 10 years. The Chicago method was used to replicate synthetic rainfall events that emphasize the highest intensity during shorter periods, specifically matching a rainfall duration of 30-minute and a time-to-peak ratio of 0.5 (Keifer and Chu, 1957). Table 3.1 shows the overview of features derived from the analysis of Chicago hyetographs for the four different precipitation regimes for the chosen return periods.

Table 3. 1 Total depth and the maximum intensity over 5 minutes of the Chicago hyetographs evaluated for the four precipitation regimes (Humid temperate, Hot temperate, Sublittoral and Mediterranean continental) with respect to the three selected return periods (T = 2, 5, and 10 years).

Precipitation regime	**Return Period**	**Total depth [mm]**	**I_{max}-5' [mm/h]**
HuT – Humid Temperate	2 - year	30	169
	5 - year	40	227
	10 - year	47	269
HoT – Hot Temperate	2 - year	15	110
	5 - year	21	153
	10 - year	26	186
Sub - Sublitoral	2 - year	21	161
	5 - year	30	231
	10 - year	36	274
MeC – Mediterranean Continental	2 - year	21	115
	5 - year	23	127
	10 - year	28	152

Through a comparison of maximum intensity over a 5-minute interval, it becomes feasible to establish two distinct rainfall design cases: Heavy precipitation regimes (HPR), which align with the HuT and Sub precipitation regimes, and Light precipitation regimes (LPR), which correspond to the HoT and MeC precipitation cases (Palla and Gnecco, 2022).

3.3.1.3 Hydrological model

The hydrological modelling is undertaken using EPASWMM 5.1, that implements specific LID control modules, including BRC (Rossman, 2010). The infiltration method employed is the curve number (CN), while the dynamic wave method is used for flow routing. The hydrologic and hydraulic parameters, including the CN values and manning's roughness coefficients, are determined according to literature values or established guidelines. The CN values for roadways and residential areas are set at 90 and 72, respectively. For pervious areas, Manning's coefficient is assigned as 0.1 $\frac{s}{m^{1/3}}$, while for impervious areas, it is set at 0.01 $\frac{s}{m^{1/3}}$ (Rossman, 2010). Simulation is carried out at the event-scale; therefore, evapotranspiration has been neglected, and consequently climatic variables such as temperature, evaporation, wind speed, and snow melt are not considered.

The BRC implemented in SWMM as LID control module is represented by a combination of the horizontal layers, namely, surface, soil, storage, and optionally drain, whose properties are defined on a per-unit-area basis. The design properties of each relevant layer include thickness, void volume, hydraulic conductivity, and drain characteristics, among other factors. It is possible to install one or more BRC modules within an existing subcatchment that will replace an equivalent amount of non-LID area within the subcatchment.

In the present study, a fully-exfiltration streetscape BRC is modelled as a single BRC LID control module within the selected road subcatchment. The fully-exfiltration streetscape BRC is designed to manage the runoff from roads and to rely entirely on exfiltration into the native soil and does not include an underdrain system because the infiltration rate of surrounding soil is set up higher than 15-mm/hr as recommended by (Tennessee Department of Environment and Conservation, 2015). The conveyance criteria for managing runoff are designed to be on-line, which means all runoff from the contributing drainage area (CDA)

enters the BRC and the flow exceeds the design capacity, overflowing the system via an overflow structure.

The specific BRC parameters are determined based on an in-depth analysis of relevant literature body (Davis et al., 2012; Prince and County, 1999; Rossman, 2010; Woods-Ballard et al., 2015). Specifically, the ponding zone is designed with a berm height of 300-mm. The soil layer consists of sandy loam with a porosity of 0.45, a field capacity of 0.179, a wilting point of 0.081, and a saturated hydraulic conductivity of 50-mm/hr. In addition, the storage layer has a depth of 400-mm and a porosity of 0.6. The detailed list of BRC design parameters can be found in Table 3.2 below.

Table 3. 2 Bioretention cell (BRC) parameters implemented in SWMM LID module.

Layer	Sub-layers	Unit	Value
Surface	Berm heigh	mm	300
	Vegetation volume		0.15
	Surface roughness	$s/m^{1/3}$	0.1
	Surface slope	%	1
Soil	Thickness	mm	700
	Porosity	volume/volume	0.45
	Field capacity	volume/volume	0.179
	Wilting point	volume/volume	0.081
	Hydraulic Conductivity	mm/hr	50.29
	Conductivity slope		40
	Suction head	mm	109.98
Storage	Thickness	mm	400
	Void ratio	volume/volume	0.6
	Seepage rate	mm/hr	15
	Clogging factor		0
Drain	Flow coefficient		0
	Flow exponent		0
	Offset Height	mm	0

In addition, the study evaluates 4 distinct BRC surfaces that are evaluated as different percentages of the BRC surfaces with respect to the relative CDA. The selection of the 4 BRC footprints equal to 5%, 10%, 15%, and 20%— is determined based on several guidelines and previous studies (Nazarpour et al., 2023a). Furthermore, the spatial distribution of BRC is analysed using two settings: BRC to manage runoff from main roads and from main and

secondary roads (hereinafter, namely All Roads). These settings are designed to assess the impact of the BRC not only based on the hydrologic and hydraulic metrics but considering installation, maintenance and lifecycle costs. The goal is to determine which BRC spatial configuration is the most suited regarding precipitation characteristics, imperviousness degree of the urban area, as well as in terms of both footprints and spatial distribution (settings).

This study analyses a diverse array of modelling scenarios by considering 5 key variables. The investigated variables encompass precipitation regimes and return periods of the storm events, degree of imperviousness, different BRC settings, and footprints. Table 3.3 summarizes all the simulated scenarios.

Table 3. 3 Performed modelling scenarios referring to different degrees of imperviousness, precipitation regimes, return periods of the rainfall event, BRC placement in terms of spatial settings and footprints.

Modelling parameter	**Parameter options**
Precipitation Regime	MeC- Mediterranean Continental
	HoT- Hot Temperate
	HuT- Humid Temperate
	Sub- Sublitoral
Imperviousness Degree [%]	30
	45
	75
	90
Return Period	2-Year
	5-Year
	10-Year
BRC Setting	Main Roads
	All Roads
BRC Footprint [%]	5
	10
	15
	20

The placement of BRC is evaluated based on the two spatial settings (Main Roads and All Roads), and four BRC footprints (5%, 10%, 15%, and 20%), thus representing different spatial distributions and coverage ratios. Note that, for the Main Roads BRC settings, the CDA convey to the BRCs represents 15% of the total drainage area, while for the All Roads BRC

setting, the CDA represents 27% of the drainage area. The CDA remains constant in BRC settings, regardless of the urban area's degree of imperviousness.

3.3.1.4 Performance metrics

Table 3.4 reports the two sets of performance metrics examined in the present study (consistently with those accessible on the TRIG Eau platform): the hydrologic and hydraulic metrics (Palla and Gnecco, 2021). The hydrologic metrics are Volume Reduction (VR) and Peak Flow Reduction (PR), while the hydraulic metrics are Node Flooding Reduction (NFR) and Network Stress Reduction (NSR).

Table 3. 4 Hydrologic and Hydraulic performance metrics.

Performance Metrics	**Formula**	**Description**
Hydrologic metrics	VR = $\frac{V_0 - V_{BRC}}{V_0}$	V_0 and V_{BRC} are the volume at outfall of the catchment before (control unit) and after the BRC implementation.
	PR = $\frac{Q_0 - Q_{BRC}}{Q_0}$	Q_0 and Q_{BRC} are max flowrate at outfall of the catchment before and after the BRC implementation.
Hydraulic metrics	NSR = $\frac{NSI_0 - NSI_{BRC}}{NSI_0}$	NSI_0 and NSI_{BRC} are network stress indexes before and after the BRC implementation. NSI = $\frac{n_{conduits\|0.8}}{n_{conduits}}$ where $n_{conduits\|0.8}$ is the number of conduits that show maximum fulfilment greater than 0.8, $n_{conduits}$ is the total number of conduits.
	NFR = $\frac{NFI_0 - NFI_{BRC}}{NFI_0}$	NFI_0 and NFI_{BRC} are node flooding indexes before and after the BRC implementation. NFI = $\frac{n_{junction\|flooded}}{n_{Junction}}$ where $n_{junction\|flooded}$ is the number of junctions that are flooded, and $n_{Junction}$ is the total number of junctions.

3.3.2 Numerical data analysis

Hydrologic and hydraulic performance metrics are evaluated with respect to the different modelling scenarios and presented using box plots, providing statistical results on a sample basis. The lower and upper boundaries of each box indicate, respectively, the 25th (Q_1) and 75th (Q_3) percentiles, while the continuous line within the box marks the median values (Q_2); whiskers above and below each box indicate the 95th and 5th percentiles.

3.3.3 Multi-criteria decision-making analysis

The present study employs the AHP (Saaty, 1987) as MCDM methodology for decision-making. This approach uses the relative importance of two criteria by using pairwise

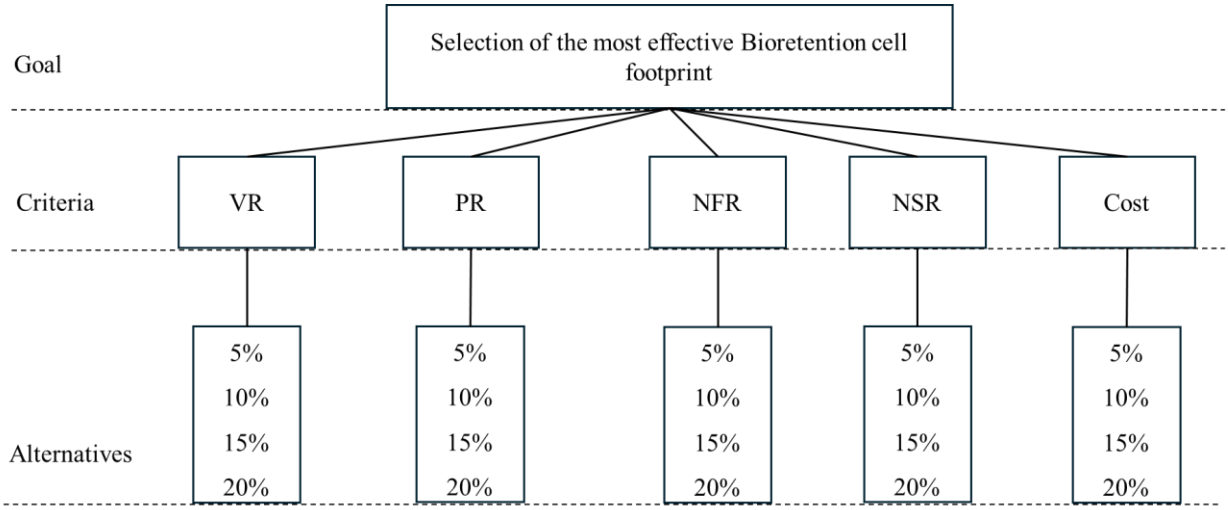

Figure 3. 3 Decision Hierarchical structure of goal, criteria and alternatives in analytic hierarchy process (AHP).

comparisons. In multi-stakeholders' situations, this method excels because of its versatility and simplicity. The primary benefit of AHP is its ability to generate weights and total scores using matrix algebra, even in cases where the inputs are incomplete or inconsistent. However, a notable drawback of AHP is that adding additional criteria to the process could alter or reverse the final ranking (Velasquez et al., 2013). To address this problem in practice, it is common to reduce the number of criteria that are considered (Yang and Zhang, 2021). This study's AHP methodology is a systematic approach structured in five key phases, as described in the following sections.

Phase 1: Decision hierarchy. An organized hierarchy breaks down the problem, placing the overarching goal at the top, relevant criteria and sub-criteria in the middle, and the various alternatives at the bottom. In this application the overarching goal is the selection of the most effective BRC footprint, and the relevant criteria are 5, including the 4-performance metrics (Volume and Peak Reduction; Node Flood and Network stress Reduction) and 1 economic factor (total cost); no sub-criteria are considered. The total cost is computed as sum of capital cost, operation and maintenance (O&M) costs that have been estimated by STEP's LID Lifecycle Costing Tool made available by the Sustainable Technologies Evaluation Program (STEP's LID Lifecycle Costing Tool, 2024). The selected alternatives are the 4 BRC footprints (5%, 10%, 15% and 20%). The scheme of the Decision hierarchy phase for this application is

illustrated in Figure 3.3. The scheme is repeated twice: once for the All Roads and once for the Main Roads BRC settings.

Phase 2: Pairwise comparison matrices. With respect to each relevant criterion, this phase determines the significance of each alternative at a level in relation to the subsequent higher level. These comparisons are quantified using the evaluation scale (Saaty, 1987). The importance values associated with each alternative on the pairwise scale is presented in Table 3.5 reported below. The outcomes of the pairwise analysis are structured as square matrices, as described below.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{3.1}$$

The equation (3.1) refers to a reciprocal square matrix of dimensions (n x n), where n represents the number of alternatives under comparison (equal to 4 in the present application) and a_{ij} represents the importance value of the element i with respect to the element j.

$$a_{ij} = 1 \text{ for i} = \text{j} \tag{3.2}$$

$$a_{ij} = \frac{1}{a_{ij}} \text{ for i} \neq \text{j} \tag{3.3}$$

Table 3. 5 Evaluation scale of importance value applied in analytic hierarchy process (AHP) (Saaty, 1987)

Importance Value	**Definition of Importance Value**
1	Equally Important Preferred
2	Equally to Moderately Important Preferred
3	Moderately Important Preferred
4	Moderately to Strongly Important Preferred
5	Strongly Important Preferred
6	Strongly to Very Strongly Important Preferred
7	Very Strongly Important Preferred
8	Very Strongly to Extremely Important Preferred
9	Extremely Important Preferred

The reciprocal matrix structure ensures consistency by setting each component on the diagonal to 1, indicating that it holds equal importance to itself (equation 3.2). The relative relevance of alternatives is acknowledged by the reciprocal nature of AHP, which ensures consistent comparisons (equation 3.3). Then, a further comparison matrix (m x m) is similarly defined to determine the importance value of each relevant criteria in relation to the other ones, where m is the number of relevant criteria (equal to 5 in the present application).

Phase 3: Weights calculation and normalization. With respect to each relevant criterion, each importance value in the comparison matrices is divided by the sum of all values in the corresponding column to find the weights of each criterion, as follows:

$$A_N = \begin{bmatrix} \frac{a_{11}}{\sum_{i=1}^{n} a_{i1}} & \cdots & \frac{a_{1n}}{\sum_{i=1}^{n} a_{in}} \\ \vdots & \ddots & \vdots \\ \frac{a_{n1}}{\sum_{i=1}^{n} a_{i1}} & \cdots & \frac{a_{nn}}{\sum_{i=1}^{n} a_{in}} \end{bmatrix} = \begin{bmatrix} a''_{11} & \cdots & a''_{1n} \\ \vdots & \ddots & \vdots \\ a''_{n1} & \cdots & a''_{nn} \end{bmatrix} \quad (3.4)$$

This procedure allows to normalize the comparison matrix such that the sum of each column ($\sum_{i=1}^{n} a''_{i1}$) is equal to 3.1. The normalized matrix is similarly computed for the criteria comparison matrix.

Phase 4: Preference column vector and Ranking. With respect to each relevant criterion, the preference vector of the alternatives is calculated by averaging the value in each row of A_N as follows:

$$C = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{bmatrix} = \begin{bmatrix} \frac{1}{n}\sum_{j=1}^{n} a''_{1j} \\ \frac{1}{n}\sum_{j=1}^{n} a''_{2j} \\ \vdots \\ \frac{1}{n}\sum_{j=1}^{n} a''_{nj} \end{bmatrix} \quad (3.5)$$

Similarly to the alternatives, a preference vector of the criteria is calculated by averaging the values in each row of the normalized criteria comparison matrix.

After these steps, the outcomes are m preference vector columns for each criterion to rank each alternative and one preference vector column for criteria, C_C, to rank each criterion.

A matrix of the preference of the alternatives is then composed with the m preference vector columns as follows:

$$C_A = \begin{bmatrix} C_{11} & \cdots & C_{1m} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nm} \end{bmatrix} \tag{3.6}$$

The final step is the multiplication of the matrix of the preference of alternatives C_A with the preference vector of criteria, C_C in order to obtain the ranking vector U of the n alternatives.

$$U = C_A \times C_C = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} \tag{3.7}$$

Phase 5: Consistency check. This phase is incorporated into the AHP approach to guarantee that the pairwise comparisons are coherent. In particular, a consistency ratio, CR, is estimated to verify the overall procedure. The acceptable ratio of consistency is usually guaranteed by CR values lower than 0.1.

To calculate the consistency ratio, the consistency index, CI, is divided by the random index, RI. The appropriate value of RI is selected from the literature and reported in Table 3.6 in the appendix

$$CR = \frac{CI}{RI} \tag{3.8}$$

Table 3. 6 Random index (RI) of analytic hierarchy process (AHP)

Size of matrix (n)	Random index (RI)
1	0
2	0
3	0.58
4[1]	0.9
5[2]	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.58

Consistency check was applied in two groups of matrices: Criteria and sub-criteria [1]: The size of the alternatives (BRC footprints (5%, 10%, 15%, and 20%)) in each criterion. [2]: the size of the criteria: (Volume reduction (VR), Peak flow reduction (PR), Network stress reduction (NSR), node flooding reduction (NFR), and economic factors)

where the CI is estimated as reported in equation (3.9) in relation to the number of selected criteria, m

$$CI = \frac{\lambda - m}{m - 1} \tag{3.9}$$

where λ is the eigenvalue of the pairwise comparison matrix that is evaluated as the average value of the ratios of the significant values X_i of the ith criteria and the corresponding preference value C_i

$$\lambda = \sum_{i=1}^{m} \frac{X_i}{C_i} \tag{3.10}$$

Note that to obtain the vector $[X]$ representing the significance level of criteria, the comparison matrix of criteria is multiplied by the corresponding preference (3.11).

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mm} \end{bmatrix} \times \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{bmatrix} \tag{3.11}$$

3.4 Results and discussion

The modelling framework includes 5 key variables consisting of 4 precipitation regimes, 3 return periods, 4 degrees of imperviousness, 2 BRC settings, and 4 BRC footprints) for a total of 384 modelling scenarios. The hydrologic and hydraulic BRC performance are then evaluated at the outlet section of the urban residential settlement for all the modelling scenarios.

Firstly, the performance is discussed by understanding the BRC hydrologic-hydraulic functioning at both the single installation and at the outlet section of the drainage network underlying the urban residential settlement. Secondly, the impact of the main affecting factors on BRC performance at the urban settlement scale is deeply examined. Thirdly, the optimal BRC configurations are evaluated by means of the AHP methodology.

3.4.1 Hydrologic and hydraulic modelling of BRC performance

In order to accurately determine the functioning of the BRC layers, it is essential to have a solid understanding of the involved hydrologic and hydraulic processes. This also pertains to the role that these layers make to stormwater management. The BRC is conceptualized as a sequence of horizontal layers, each of which assumes a distinct function. Direct rainfall and runoff (total inflow) from the contributing area reach the surface layer, while two distinct contributions represent the outflow: infiltration within the soil layer and surface runoff as overflow. The soil layer is composed of engineered soil designed to support vegetation; it receives infiltration from the surface layer, and the outflow is represented by percolation and evapotranspiration losses. The storage layer consists of coarse crushed stone or gravel. The inflow is the percolation from the soil layer, and the outflow exfiltration into the natural soil. If there is an underdrain system, the outflow can also be drained towards the downstream drainage pipeline.

Figure 3.4 illustrates a detailed analysis of the simulated hydrologic response of the BRC at site (graph at the top - left) together with the flow rates and water depth within the various BRC layers modelled with the BRC LID control module in SWMM, the example reported in Figure 3.4 refers to the BRC footprint equal to 10% and the 10-year return period event in the Sub precipitation regime. Furthermore, the top right graph of Figure 3.4 shows the hydrologic response at the outlet section of the urban residential settlement for the reference

scenario characterised by the 90% degree of imperviousness and the corresponding BRC Main Road setting.

By comparing the hydrographs simulated for the reference (continuous line) and the BRC (grey area) scenarios at the site installation (the top-left graph of Figure 3.4) and the ones simulated at the outlet of the urban residential settlement(the top-right graph of Figure 3.4), it clearly emerges how the impact in the hydrologic restoration of BRC is reduced at the outlet section of the drainage system due to the limited areas of BRC with respect to the high degree of imperviousness of the investigated area. At the site installation, the inflow is completely managed by the BRC except for the overflow that occurs for almost 15 minutes when, the maximum infiltration rate is achieved in the surface layer, and the water depth exceeds the berm heights (equal to 300 mm). At the urban residential settlement scale, both peak and volume reduction due to the BRC installations are respectively limited to 0.09 and 0.18, while at site scale, these values increase to 0.86 for VR and 0.81 for PR. this limited impact is due to the characteristic of the reference scenario (90% degree of imperviousness) as well as to the BRC setting (installed solely in the main roads).

Detailed insights into the hydrologic processes occurring in the various BRC layers are discussed for the BRC system implemented in the present study (see Figure 3.4 and Table 3.2). In the surface layer, the overflow occurs when the water depth exceeds the berm height. In the soil layer, the infiltration occurs when the saturation condition is reached at the top of the soil layer; the maximum infiltration rate is dynamically dependent by the characteristics of the soil media including the porosity, wilting point, hydraulic conductivity, suction head, and cumulative infiltrated volume. In the soil layers, the percolation occurs when the field capacity is achieved; the maximum percolation rate is equal to the soil hydraulic conductivity. In the drainage layer, the exfiltration occurs when there is water in the storage layer or when soil percolation occurs: in the first case, it is constant and equal to the seepage rate, while in the second case, it is equal to percolation rate up to the seepage rate.

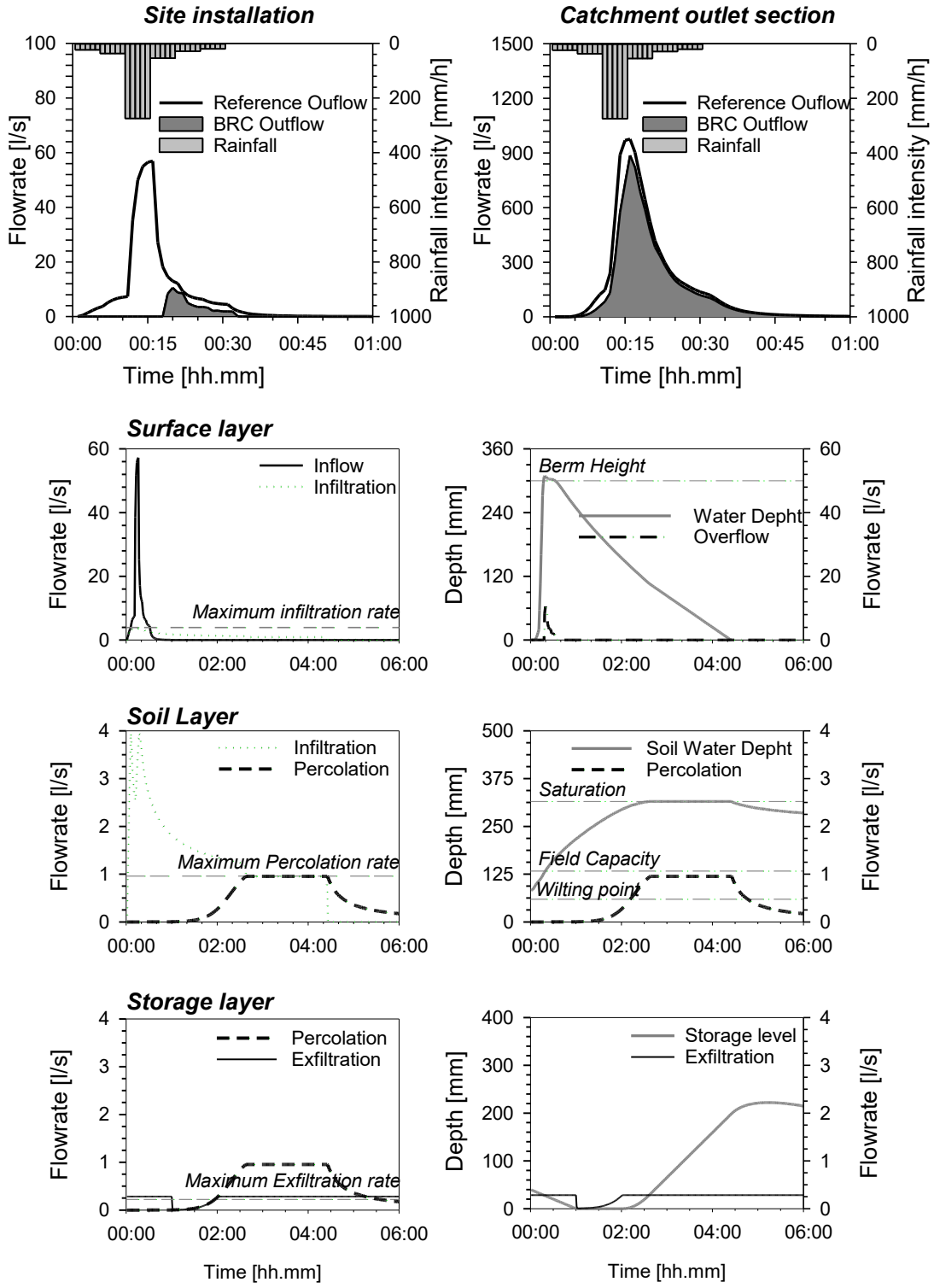

Figure 3. 4 The hyetograph, the corresponding hydrographs simulated for the reference and the BRC scenarios at the single installation (graph at the top -left) and at the outlet section (graph at the top-right) of the urban settlement; comparison between the inflow and outflow at each BRC layers (graphs at the left side); the ponding, soil water, storage depths together with the corresponding threshold water depth (dash-dot line) at each BRC layers (graphs at the right side). The reference scenario indicates the scenario without any BRC implementation.

3.4.2 Factor affecting the BRC performance

The factors affecting the BRC performance at the urban residential settlement is discussed based on both hydraulic and hydrologic metrics. Particular attention is posed to the hydrologic metrics to deeply understand the factor affecting the BRC hydrologic response rather than the drainage network behaviour.

3.4.2.1 The impact of BRC settings

The impact of BRC settings on BRC effectiveness at the urban residential settlement is expected to be significant due to the different CDA with respect to the drainage area.

According to the rainfall characteristics of the simulated hyetographs, the impact of the BRC settings is evaluated with respect to the two precipitation regime cases: light (LPR) and heavy (HPR) precipitation regime. Figure 3.5 shows the non-parametric distribution of VR, PR, NSR and NFR metrics versus the BRC settings (All Roads and Main Roads) with respect to and the heavy (grey box) and light (white box) precipitation cases. Each box describes the results of 96 modelling scenarios including 2 precipitation regimes, 3 return periods, 4 BRC footprints and 4 degrees of imperviousness.

The hydrologic metrics (graphs on the left in Figure 3.5) present higher medians for All Roads compared to Main Roads, as expected. This is because All Roads have larger effective impervious area reduction (larger CDA) than Main Roads, thus producing lower volume and peak flow rates. (Palla and Gnecco, 2015). Furthermore, the hydrologic metrics reveal higher variability, for All Roads compared to Main Roads. This is likely due to the enlarged BRC storage capacity for All Roads, which allows to differently responses to various forcing factors such as the return period or the BRC footprints. Specifically, the PR median in LPR increases from 0.2 to 0.35, while in HPR these values change from 0.15 to 0.29 across BRC settings. The PR range in All Roads is smaller in LPR, ranging from 0.2 to 0.58, while it ranges from 0 to 0.55 in HPR. Conversely, in Main Roads BCR setting, a limited variation in PR emerges for both precipitation regimes: values range from 0 to 0.3 in HPR and from 0.12 to 0.31 in LPR. Focusing on VR, the median value for Main Roads setting increases from 0.16 to 0.3 and 0.18 to 0.32 for HPR and LPR respectively. By comparing the results of each BRC setting with respect to the precipitation cases, it clearly emerges that the hydrologic metrics are higher for LPR while their variability is larger in HPR, indicating a greater sensitivity of these metrics to the rainfall intensity. Furthermore, the interquartile range is larger for PR with respect to VR, suggesting

that BRC is more sensitive to the peak flowrate rather than the total volume. Similar results are reported in the literature (e.g. Mehri, et al., 2024b): the implementation of BRCs determines a notable decrease in peak flow (equal to 0.38) during rainfall events with a 10-year return period.

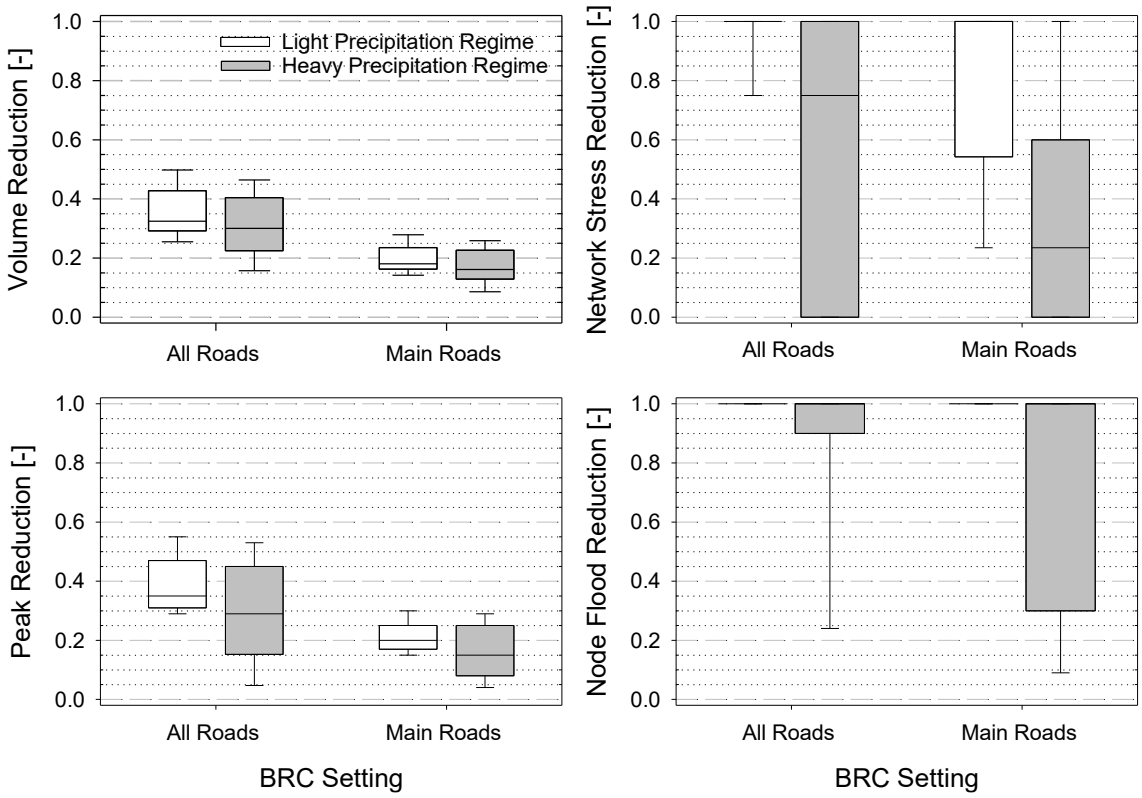

Figure 3. 5 Non-parametric distribution of Volume Reduction (VR), Peak Reduction (PR), Network Stress Reduction (NSR) and Node Flooding Reduction (NFR) metrics versus the BRC settings (All Roads and Main Roads) with respect to the heavy (grey box) and light (white box) precipitation cases.

The hydraulic metrics (graphs on the right in Figure 3.5) present a dichotomic behaviour, and the metrics values are mainly close to one. Focusing on NFR, it remains consistently 1.0 for the BRC settings in LPR, while in HPR it reveals a higher variability (interquartile range) mainly in Main Roads setting. Focusing on NSR, it shows a constant median value (equal to 1) in BRC settings for LPR, even if in the Main Roads the interquartile range is considerable. On the contrary, in HPR, NSR median values decrease to 0.75 and 0.24 in the All and Main Roads, respectively. Differently from the hydrologic metrics, the hydraulic metrics generally show a large interquartile range for the Main Roads with respect to All roads, due to the higher impact of the main conduits (under the Main Roads) on the network stress and on the flooded nodes than the secondary pipes.

Results on both hydrologic and hydraulic metrics imply that the implementation of BRC on All Roads is more effective, indicating that the economic and technical constraints of the BRC project can be supported by the expected performance. However, if economic resources are limited, prioritizing BRC installation on Main Roads may be a more viable alternative because it focuses on the main hydraulic components of the pipeline network.

3.4.2.2 The impact of imperviousness, rainfall characteristics

The impact of the imperviousness degree and rainfall characteristics on the BRC effectiveness at the urban settlement scale is assessed by examining solely for the hydrologic metrics. Figure 3.6 illustrates the scatter plot of the mean values of the VR (top) and PR (bottom) metrics plotted versus the percentage of subcatchment imperviousness with respect to the All roads (square) and Main Roads (dot) BRC settings evaluated for the heavy (grey) and light (white) precipitation cases. Note that the mean and error bars (standard deviations for both directions) are referred to the results of 24 modelling scenarios including 4 BRC footprint, 2 precipitation regimes,3 return periods, and 4 imperviousness degrees.

Figure 3.6 shows that imperviousness has a considerable effect on the BRC effectiveness, even if the CDA in each BRC setting is independent of the imperviousness degree. With increasing imperviousness from 30% to 90%, the VR and PR metrics decrease in both settings and in both rainfall categories, underscoring the impact of impervious surfaces on the hydrological efficiency of the BRCs

Focusing on VR, results confirm higher values in LPR with respect to HPR and higher values for All Roads with respect to Main Roads for all the degrees of imperviousness. Regarding the imperviousness degree (90-30%), the VR mean values for All Roads and Main Roads show a range of 0.27 to 0.47 and 0.15 to 0.26, respectively, in LPR. However, under HPR, these ranges are slightly lower, changing from 0.22 to 0.41 and from 0.12 to 0.23, respectively.

The trends in PR are similar to the ones observed for VR: moving across the various imperviousness degrees, PR decreases on average from 0.54 to 0.29 for All Roads and from 0.30 to 0.16 for Main Roads under LPR and, under HPR, the PR varies between 0.44 and 0.16 for All Roads and 0.24 to 0.08 for Main Roads showing a larger range of variation for All Roads in both metrics.

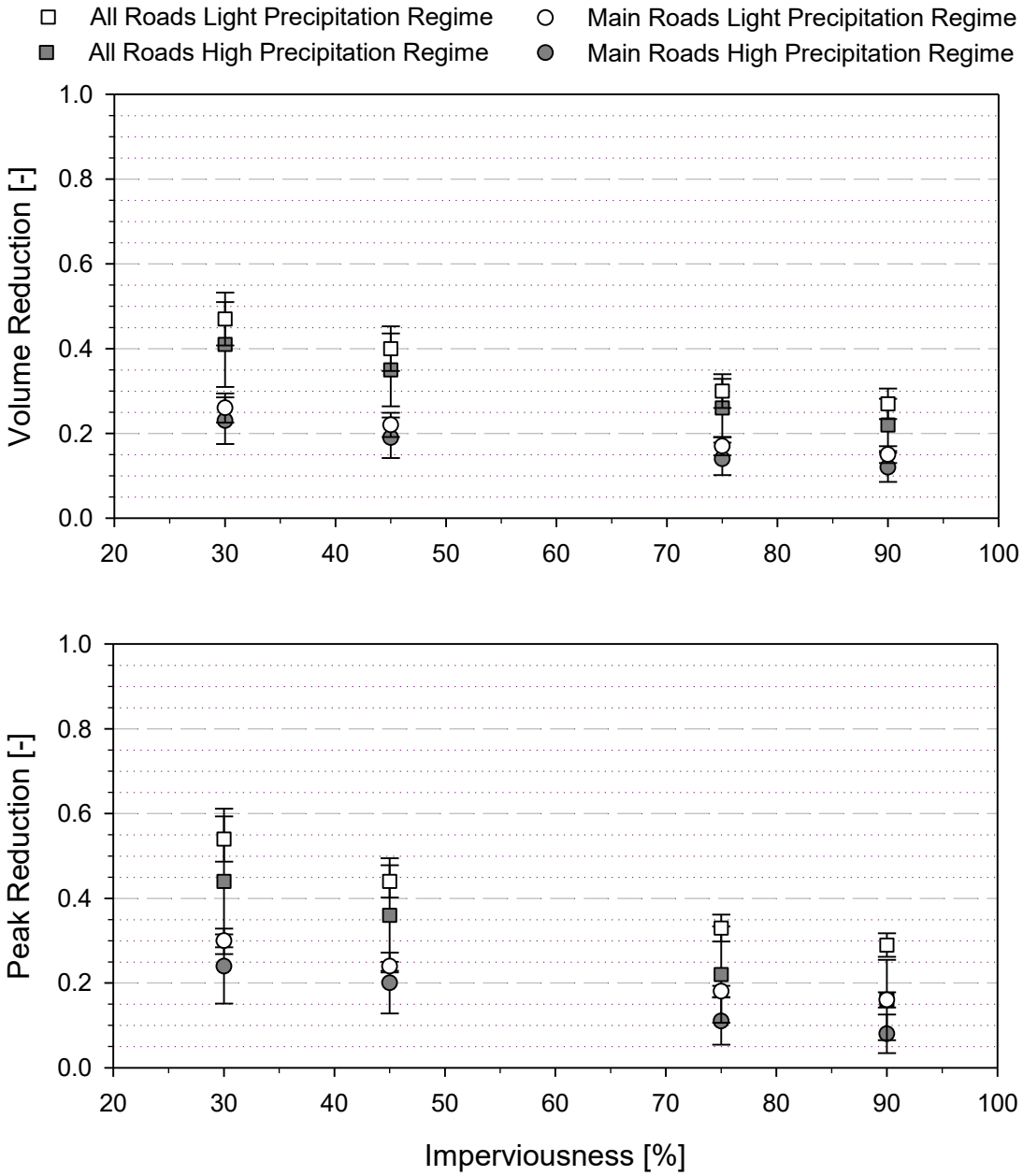

Figure 3. 6 Scatter plot of mean values of the Volume Reduction (top) and Peak flow Reduction (bottom) metrics plotted versus the percentage of subcatchment imperviousness with respect to the All Roads (square) and Main Roads(dot) BRC settings and with respect to the heavy (grey) and light (white) precipitation cases. Note that the error bars represent the standard deviations.

Results plotted in Figure 3.6 confirm that the imperviousness degree of the urban area is a limiting factor of the hydrologic metrics evaluated at the outlet section of the drainage network irrespective of the BRC spatial configurations. Liu et al. (2014) noted that generally an increase of impervious surfaces from 50% to 90% resulting in elevated runoff, determined a corresponding decreasing in VR ranging from 90% to 50.

Figure 3.7 shows the scatter plot of the mean values of the VR (top) and PR (bottom) metrics plotted versus maximum rainfall intensity with respect to the All Roads (square) and Main Roads (dot) BRC settings evaluated for the heavy (grey) and light (white) precipitation cases. Note that the mean and error bars (standard deviations for both directions) of the VR and PR metrics refer to the results of 16 modelling scenarios, including 4 BRC footprints and 4 imperviousness degrees. The data are plotted against the 12 simulated maximum rainfall intensities, which encompass 3 return periods and 4 precipitation regimes.

The analysis of the data in Figure 3.7 shows that, in BCR settings, the maximum intensity has a limited impact on the mean VR, while the PR is more sensitive to these factors. In accordance with previous studies (Davis and Asce, 2008; Winston et al., 2016; Zhang et al., 2021), higher VR and PR values are observed under LPR; generally, as rainfall intensity increases, VR and PR decrease. With increasing rainfall intensity, both metrics typically show a decrease in effectiveness, while BRCs exhibit greater efficiency during storms of lower intensity. The result is linked to enhanced runoff infiltration in BRCs during less intense conditions, as noted by Sun et al. (2019).

The decrease in VR and PR performance at elevated intensities is mainly attributed to the constraints of BRC storage capacity. High-intensity rainfall events frequently result in BRCs reaching capacity, causing overflow, especially in smaller footprint designs (such as 5%). The system's capacity to retain runoff and reduce peak flow is consequently reduced. The overflow issue restricts the effectiveness of BRCs and increases variability in PR performance, particularly during extreme rainfall events. These findings align with the observations of Brown and Hunt (2011), who reported that 16% of the overflow occurred during large storm events, further restricting the effectiveness.

These results underscore the effectiveness of BRCs during moderate to low-intensity precipitation, as this condition minimizes the risk of overflow and allows the system to function within its designed capacity. In contrast, heavy rainfall limits the effectiveness of BRCs, highlighting the combination with additional stormwater management strategies to address extreme conditions.

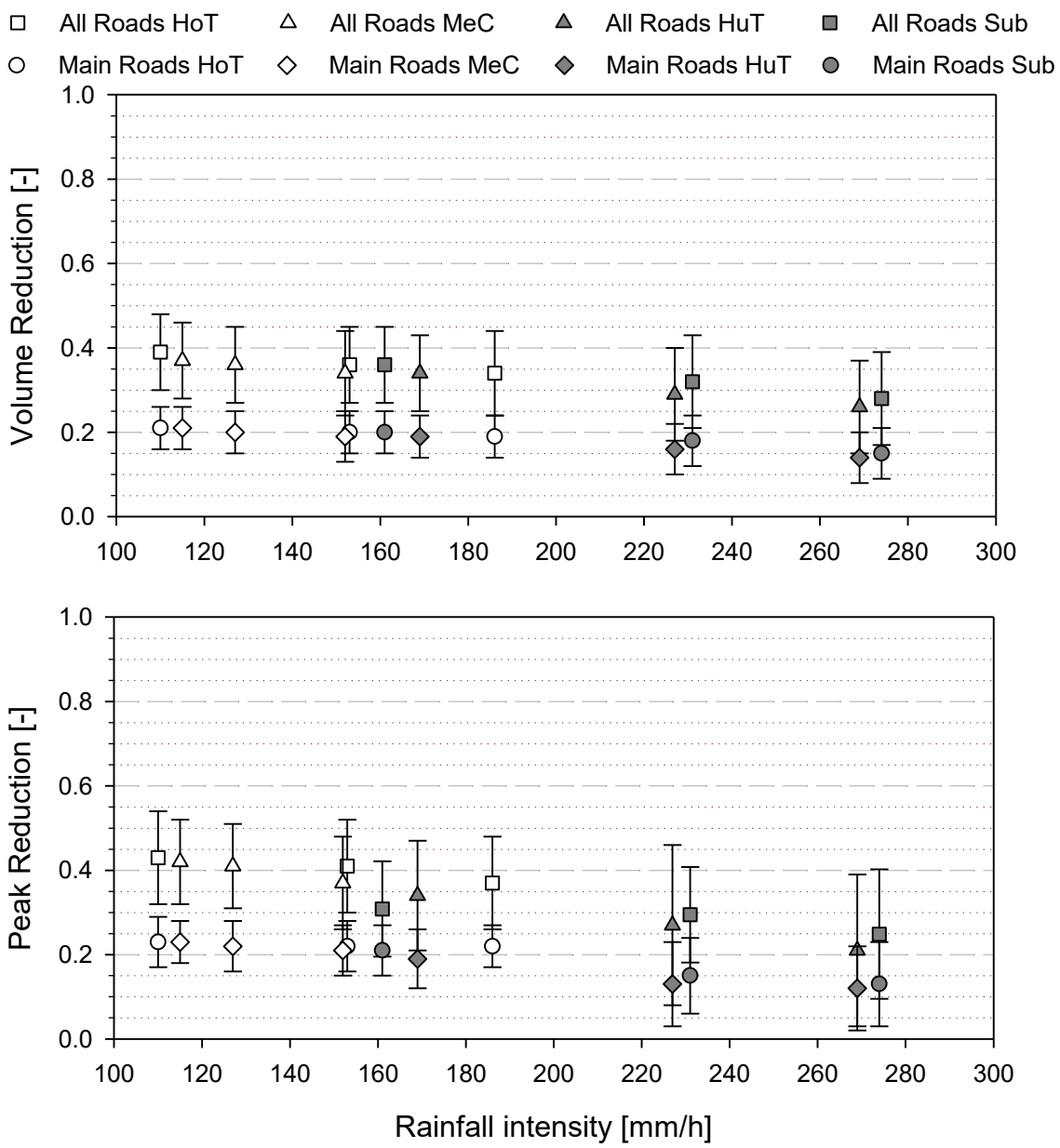

Figure 3. 7 Scatter plot of mean values of the Volume Reduction (top) and Peak flow Reduction (bottom) metrics plotted versus the 5-min maximum rainfall intensity with respect to the All Roads (square) and Main Roads(dot) BRC settings and with respect to the heavy (grey) and light (white) precipitation cases. Note that the error bars represent the standard deviations.

3.4.2.3 The impact of BRC footprint

The impact of the BRC footprint on the BRC effectiveness at the urban residential settlement is analysed, focusing solely on hydrologic metrics. This assessment considers two precipitation cases (LPR and HPR) and two BRC settings (All Roads and Main Roads). Figure 3.8 illustrates the non-parametric distribution of VR and PR metrics vs. the BRC footprints (5%, 10%, 15% and 20%) evaluated for the heavy (grey box) and light (white box) precipitation cases according to All Roads (left side) and Main Roads (right side) BRC settings. Note that each box

describes the results of 24 modelling scenarios, including 2 precipitation regimes, 3 return periods, and 4 degrees of imperviousness.

In both hydrologic metrics, the median values of All Roads across all BRC footprints are greater than those of Main Roads, as expected and already discussed. By comparing the results of each BRC footprint with respect to the precipitation categories, it is confirmed that the median values of VR and PR are higher for LPR with respect to HPR, again as expected.

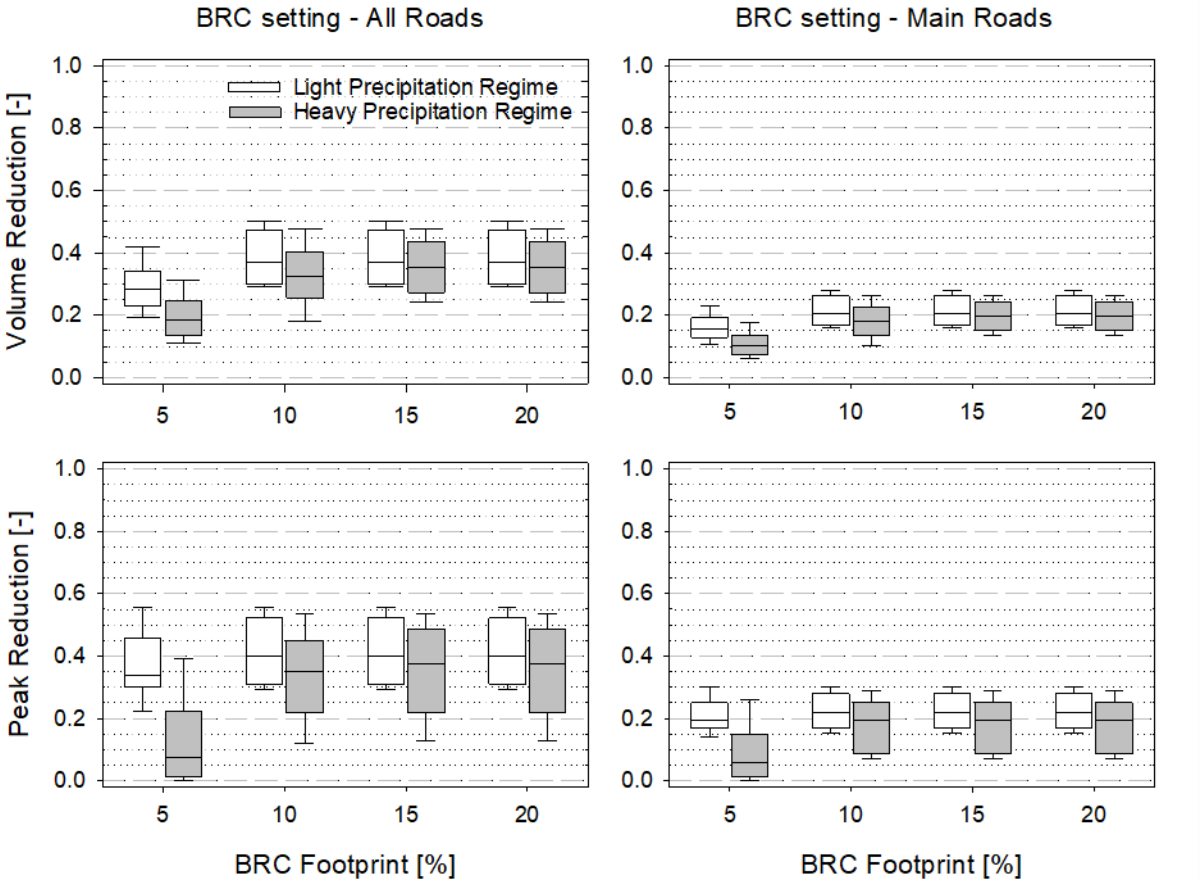

Figure 3. 8 Non-parametric distribution of Volume Reduction (VR) and Peak Reduction (PR) metrics Versus BRC footprints (5%, 10%, 15% and 20%) with respect to the heavy (grey box) and light (white box) precipitation cases according with the All Roads (left side) and Main Roads (right side) BRC settings.

The median values of both hydrologic performances of the three larger BRC footprints (10%, 15%, and 20%) are similar for the two precipitation categories and for the two BRC settings. However, when considering the 5% of BRC footprint, the median values decrease for both settings and both precipitation categories, even if large differences are detected for HPR. Likewise, research study by Davis and Asce (2008) underscored that larger BRC footprints improved both VR and PR metrics, indicating that proper sizing is crucial for maximum performance. This highlights the importance of defining threshold values for the BRC footprint to achieve detectable stormwater control.

Based on the above-mentioned results, thresholds could differ for sites characterised by LPR where the 5% BRC footprint may be a cost-effective and viable option for BRC implementation, assuming that it complies with other site-specific design criteria. Li et al. (2009) also supported this notion, indicating that BRCs can achieve satisfactory performance at smaller footprints in areas with less intense precipitation, thereby balancing performance.

3.4.3 Analytic hierarchy process (AHP) results

In the present study, the AHP methodology is implemented to determine the most effective alternatives in terms of BRC footprints for each BRC spatial setting (All Roads and Main Roads), each degree of imperviousness of the drainage area (30%, 45%, 75%, and 90%), each precipitation regime (HoT, MeC, Hut and Sub), and each return period (2, 5 and 10 years).

The selected relevant criteria adopted to achieve the goal are the 4 performance metrics (VR, PR. NSR, and NFR) and the total cost. The numerical analysis of the performance metrics has been utilized in the definition of the importance value of each alternative according to the relative differences in the performance assessment. For instance, if the NSR for the 5% BRC footprint does not vary for the 10% BRC footprint, the importance value is fixed equal to one for that criterion. To determine the comparison matrix of the criteria, the opinions of relevant stakeholders including, the local authorities and the water management company, have been collected and discussed. According to the relevant stakeholder, using evaluation scale (Saaty, 1987), the PR and NFR are given the highest priority for their immediate impact on mitigating pluvial flood risk, with the VR and NSR following behind. Economic criteria, while important, are recognized as moderate importance since initial costs are frequently weighed against long-term results. Note that the optimal BRC footprint should be fitted for the implementation site; therefore, the most significant importance should be given to the physical characteristics of the site (Davis and Asce, 2008; Nazarpour et al., 2023). However, in this application, the physical characteristics are not considered as criteria, since during the BRC design phase, the stratigraphy of BRC and the alternative BRC footprints are determined according to the available space of roadways, following the manuals and guidelines (Prince and County, 1999; Woods-Ballard et al., 2015). This study concentrates on performance-based and economic criteria, enabling broader applicability of the findings across diverse urban settlements. Table 3.7 reports the comparison matrix of the criteria while implementing the weighting and normalization procedure in phase 3 of AHP methodology the

following preference vector of criteria (C_C) values are determined:0.37 for PR and NFR, 0.09 for VR and NSR and 0.07 for economic cost.

Table 3. 7 Comparison matrix of the selected relevant criterium in the analytic hierarchy process (AHP)

	VR	PR	NSR	NFR	Cost
VR	1	0.2	1	0.2	2
PR	5	1	5	1	4
NSR	1	0.2	1	0.2	2
NFR	5	1	5	1	4
Cost	0.5	0.25	0.5	0.25	1

The AHP analysis provides insights into identifying the optimal BRC footprints for the two BRC settings with respect to each degree of imperviousness, each precipitation regime, and each return period. The selected BRC footprints are consistent for all the degrees of imperviousness of the drainage area, and light (HoT and MeC) and heavy (Hut and Sub) precipitation regimes. In Table 3.8, the results of the AHP, valid for each degree of imperviousness are summarized for the LPR and HPR.

Table 3. 8 Result of analytic hierarchy process for the selection of the most effective BRC footprint according to a specific precipitation regime and BRC settings.

Precipitation Regimes	BRC setting	Return period		
		10-year	5-year	2-year
Heavy	Main Road	15% footprint	15% footprint	10% footprint
	All Road	15% footprint	15% footprint	10% footprint
Light	Main Road	10% footprint	5% footprint	5% footprint
	All Road	10% footprint	5% footprint	5% footprint

In HPR, the 15% footprint is generally the appropriate choice, except for the 2-year return period, where 10% BRC could be more suitable. However, in the LPR, 5% is shown to be the preferred, except for the 10-year return time, where the 10% BRC footprint is needed to comply with the relevant criteria. These findings imply that the 20% BRC footprint for HPR and the 15% and 20% BRC footprints for LPR are potentially oversized for the specific sub catchment, despite its greater capacity for runoff management. The extra storage capacity of oversized BRCs can only be used during infrequent, extreme storm events, while the costs of construction and maintenance continue to rise proportionally to the BRC size. This led to

minimal improvements in runoff management, but the capital and operational/maintenance costs still increased. This indicates that the higher cost might not be justified by the benefits it provided to hydraulic and hydrologic metrics (Guo, 2023). It is important to note that the selection of the BRC setting is not included in the AHP analysis conducted in this study.

3.4 Conclusion

The overall objective of the present research is to develop a modelling framework to evaluate the effectiveness of BRCs in enhancing sustainable urban stormwater management and reducing flood risk, specifically within urban residential settlements. In order to achieve this aim, the present study employs the AHP as methodology for decision-making. The idea is to implement a multi-criteria decision-making approach to select the optimal configuration (in terms of spatial settings and footprints) of BRCs along the road networks within a residential urban settlement. The selection of the optimal set is based on quantitative criteria that include performance metrics associated with the hydrologic and hydraulic behaviour of various BRC scenarios implemented in the residential settlements as well as the corresponding economic cost of each BRC spatial configuration. It has to be noticed that other potential co-benefits, such as the improvement of water quality, the limitation of biodiversity loss, etc., (actually not accounted) may further enhance the BRC effectiveness.

The modelling framework to evaluate the hydrologic-hydraulic behaviour of the urban settlement is carried out by means of the TRIG Eau web-GIS platform (http://www.trigeau.servergis.it/) and comprises five key variables: 4 precipitation regimes, 3 return times, 4 degrees of imperviousness, 2 BRC settings, and 4 BRC footprints, resulting in a total of 384 modelling scenarios. The 8 examined BRC configurations differ for spatial settings and footprints, while the BRC design features are maintained fixed. Focusing at first on the hydrologic and hydraulic performance analysis, the main simulation results can be summarized as follows:

- BRC are effective in stormwater control, as confirmed by the following average values of the PR and VR, ranging from 0.15 to 0.35 and0.16 to0.32, respectively.
- BRC settings characterized by greater effective impervious area reduction reveal greater performance.
- rainfall intensities slightly impact the performance.

- the smallest investigated BRC footprints (5%) reveals a more sharply decreasing in performance with respect to the larger footprints.

By combining the hydrologic-hydraulic performance metrics with the economic costs (including the capital cost as well as operation and maintenance costs) to build the criteria matrix, the AHP analysis concludes that:

- The 15% BRC footprint could be the optimal selection for HPR, while the 10% BRC footprint could be the optimal one for LPR with respect to all the investigated return periods.
- Oversized BRC footprints may not be economically viable for frequent or moderate storm events, and the related extra costs frequently exceed the advantages in relation to hydraulic and hydrologic performance.

The research is conducted using a 2-ha non-specific urban area with fixed characteristics, except for the imperviousness degree. This model can be regarded as a representative scale for urban residential settlements, despite the fact that it does not accurately represent a real-world application The model incorporates an independent stormwater drainage network, allowing the assessment of stormwater management strategies designed to mitigate pluvial flooding risk. It is important to notice that in larger urban catchments with complex stormwater drainage networks, the specific contribution of LIDs, such as BRCs, may be obscured by the superimposition of various hydrologic and hydraulic effects. This study employs an urban residential settlement model, which describes the relationships between various BRC spatial configurations and their related hydrologic-hydraulic performance, assessed at the drainage system outlet. Based on the above considerations, the approach could be replicated for the larger scale of the urban settlement extending the analysis till the receiving water bodies. Furthermore, these research findings may be generalized and transferred to other contexts, including eventually climate change scenarios.

This analysis highlights the significance of considering the spatial extent of BRC implementation when aiming to achieve broader stormwater management goals, such as enhancing urban resilience to climate change. It indicates that a more extensive or strategic placement of BRC may be required to maximize their benefits on a larger scale. Moreover, the

TRIG Eau web-GIS application that incorporates the SWMM engine, although in a representative residential settlement, contributes to provide an additional tool that can make such preliminary evaluation affordable for the urban planners thus supporting the implementation of BRC in urban resilience strategies.

The lack of established guidelines for promoting the implementation of sustainable urban drainage systems in town planning and land management is one of the major barriers, as documented in the literature (Palla et al., 2024). However, the proposed methodology based on quantitative metrics represents a tool that may support the implementation of solutions (including BRCs) within the existing urban areas. It facilitates the informed decision-making process at different levels and stakeholders, thus supporting the deployment of BRC in local stormwater management and adaptation strategies

This research offers insights into the widespread implementation of BRCs by emphasizing their role in sustainable urban stormwater management. Future study may include load reduction measures into both the modelling platforms and the AHP framework, while also incorporating a wider range of design characteristics to strengthen the technical implications of the findings. Furthermore, evaluating the effectiveness of BRC under projected climate scenarios, can yield important insights for the adaptation of urban stormwater systems to the impacts of climate change.

Chapter4

Hydrologic, hydraulic, and water quality characterization from laboratory test and SWMM modelling: A full-scale evaluation of Filterra® bioretention cell for urban stormwater management

This chapter is based on the paper under review. It provides a framework to establish a set of applicable model parameters for the FIlterra® across *similar urban settings by developing a procedure for SWMM calibration and validation in terms of hydrologic and total suspended solid effectiveness.*

4.1 Abstract

Bioretention cells (BRCs) are widely implemented to restore undeveloped hydrologic cycle however, conventional BRCs need considerable land space, making them impractical in densely populated areas. To overcome this issue, compact BRCs like Filterra® have been designed to provide comparable hydrologic and pollutant removal effectiveness with a considerably smaller footprint. Despite their benefits, there are still research gaps regarding their performance; specifically, the hydraulic properties of the engineered media of Filterra and their behaviour over time need to be deeply investigated. Furthermore, validated models based on field quality and quantity dataset are still limited. This study assesses the hydraulic characteristics of Filterra's engineered media through laboratory testing and integrates these results with field monitoring to implement a calibrated SWMM model. The results of laboratory experiments showed a high hydraulic conductivity (1750 mm/h). The validated SWMM model effectively replicated the outflow dynamics with satisfactory accuracy (KGE > 0.35, R^2 > 0.47); however, it showed a tendency to underestimate outflow volume because of the simplified representation of the infiltration process through Filterra system. The outflow TSS is suitably predicted showing a strong correlation with observed outflow concentrations, although the constant removal rate in SWMM cannot reproduce the complexity of the removal processes. The results indicate that a calibrated and validated SWMM model of the Filterra could potentially be utilized to evaluate the hydrologic and pollutant removal efficiencies of compact BRCs in urban catchment. Further research should integrate high-resolution water quality monitoring to improve pollutant transport modelling and strengthen long-term stormwater management strategies.

4.2 Introduction

4.2.1 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). BRCs perform a variety of functions, such as recharging groundwater, fostering biodiversity, controlling microclimates, and improving urban runoff quality, in addition to hydrological benefits (Asleson et al., 2009; Kasprzyk et al., 2022; Vijayaraghavan et al., 2021).

In urbanized settings, 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, LIDs, specifically BRCs, offer decentralized and more effective solutions to deal with these issues. These systems aim to decrease stormwater volume, mitigate peak flows, and improve load reduction while also supporting urban development (Hamel & Fletcher, 2014; W. Liu et al., 2016; Tameh et al., 2024; Vijayaraghavan et al., 2021; Winston et al., 2016). BRCs employ natural processes, including filtration, adsorption, and biological treatment, to decrease the load of contaminants such as total suspended solids (TSS), nutrients, and heavy metals from stormwater. As a source control solution, BRCs effectively capture stormwater in areas with high imperviousness and elevated pollutant concentrations, such as parking lots and roadways, reducing direct discharge into the storm drainage network and enhancing water quality (Davis et al., 2012; Lammers et al., 2022).

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, which are designed to treat runoff from areas that are significantly larger than their own footprint, present a promising alternative with respect to conventional BRCs. Indeed, as urbanization continues and space becomes increasingly limited, compact BRCs may become essential for enhancing sustainable stormwater management. For the compact systems additional research is necessary to validate their hydrologic and water quality capabilities as well as to improve modelling accuracy.

4.2.2 Literature review

The effectiveness of BRCs in urban stormwater management has been extensively studied. These systems, which are often constructed with a large surface area—typically 5% to 20% of the overall contributing drainage area (CDA)—, have shown high effectiveness in decreasing stormwater volume, mitigating peak flows, and enhancing runoff quality. Well-designed BRCs can reduce volume by more than 70% and peak flow by more than 90% (Nazarpour et al., 2023; Skorobogatov et al., 2020; Vijayaraghavan et al., 2021). For instance, Shrestha et al. (2018) and Spraakman et al. (2020) reported volume reductions of 75% and 98% for BRC having a surface area ($Area_{BRC}$) ranging between 8% and 12% of the CDA, respectively. 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%. Other examples include Willard et al., (2017), who showed that in a parking lot a BRC system with an Area BRC/CDA of 2% could reduce volume by 84% and mitigate peak flow by 82%. Numerous studies have demonstrated the high pollutant removal capacity of BRCs, particularly for total suspended solids (TSS). Jiang et al. (2017) monitored a non-exfiltrating BRC with sandy loam media for 14 months and observed a 52% decrease in TSS in the urban area at an 8% $Area_{BRC}$/CDA ratio. Research conducted by Li et al. (2022) showed the effectiveness of the BRC with media amended using vermiculite, zeolite, and water treatment residuals, achieving a TSS reduction of 63%. While Shrestha et al., (2018) and Spraakman et al. (2020) reported a 94% and 63% TSS removal rate, respectively ($Area_{BRC}$/CDA ranges between 8% and 12%). Jeonet al. (2021) obtained an 85% TSS reduction with sandy media for a BRC with a $Area_{BRC}$/CDA ratio of 10%.Despite their demonstrated effectiveness, conventional BRCs require a considerable surface area which poses issues in highly populated urban areas. To address these constraints, compact BRCs system have emerged, including the patent system Filterra (Terry Lee Siviter, 2008), hereinafter named Filterra. Filterra is designed to manage runoff from a CDA up to 100 times greater than its surface area, presenting a viable solution for densely urbanized settings with constrained space, but it can be effectively employed to manage area up to 500 times greater (e.g., Braswell et al., 2018).

Although research on compact systems remains limited compared to conventional BRCs, early studies have demonstrated notable pollutant removal and hydrological benefits. Gilbreath et al., (2019) reported a remarkable 94% TSS removal using a semi-exfiltration

compact BRC design with sandy loam media and an $Area_{BRC}$/CDA ratio of just 0.2%, which was effective in treating highly impervious roadway runoff. In another study, Braswell et al. (2018) evaluated a combined system that integrated permeable pavement with Filterra as a secondary treatment in series. The standalone Filterra demonstrated limited efficacy in volume and peak flow reductions, achieving 1% and 14%, respectively, while successfully achieving a 96% reduction in TSS. The research showed that combining the two systems did not provide significant benefits in terms of load reduction enhancement when compared to using Filterra independently. As hydrologic enhancement was not the primary objective at the study site, it was determined that the combination was unlikely to be cost-effective for that specific location. Smolek et al. (2018) monitored a Filterra system over two years, observing a 50% peak flow reduction and 92% TSS removal despite 22% of runoff bypassing the system due to the small footprint of Filterra and media clogging.

Literature studies demonstrate the potential of compact BRCs while highlighting the necessity for more thorough evaluations, especially under different environmental conditions and utilizing field-calibrated modelling frameworks. Additional research is necessary to confirm their performance, analyse their hydraulic behaviour, and facilitate their integration into comprehensive urban stormwater management strategies.

4.2.3 Research gaps

Despite the potential of compact BRCs, such as Filterra, to enhance runoff quality in urban contexts with limited space, there are still several research gaps that limit their performance and widespread implementation in urban settlements.

First, the hydrologic performance of compact BRCs is limited across a wide range of climatic conditions and urban environments. more studies are needed to capture system behaviour under wide range of rainfall characteristics. Indeed, most extant studies examine a limited number of rainfall events thus limiting their generalizability and the capacity to build robust design principles.

Second, further verification is required to establish a connection between site-specific water quality and quantity outcomes and well-established laboratory-derived media properties, including the soil water retention curve and hydraulic conductivity. This is important to enhance the accuracy of modelling. Moreover, these properties are frequently

inferred or estimated rather than measured, which introduces uncertainty into model predictions and restricts the transferability of findings.

Third, modelling frameworks for compact BRCs remain underdeveloped, particularly with respect to calibration and validation. Numerous studies employ uncalibrated models therefore there is a need for physically based field-validated modelling approaches that are specifically designed for compact systems. This gap limits the capacity to model system performance, limiting both their integration into larger-scale stormwater planning and improved implementation.

4.2.4 Contribution and objectives

This study seeks to enhance the comprehension and modelling of compact BRC, specifically focusing on the Filterra system to address the identified gaps. A comprehensive approach is used, including laboratory characterization, field data, and numerical modelling to evaluate the hydraulic, hydrologic, and pollutants removal performance of this compact system. Unlike previous studies that rely on literature soil parameters, this research incorporates directly measured media properties (input parameters) to improve the modelling reliability and provide more accurate findings. 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 dynamics of the Filterra in urban settlements. This is accomplished through three distinct objectives:

1. To assess the soil water retention characteristics and saturated hydraulic conductivity of the Filterra growth media, providing essential information for reliable modelling and enhancing the hydraulic characterisation of engineered media employed in compact bioretention systems.
2. To provide a calibrated and validated SWMM-based modelling framework specifically designed for compact BRCs, utilizing limited but high-resolution field data addressing the need for reliable simulation tools for both quantity and water quality performance.
3. To provide a set of model parameters that can be applicable to other similar urban contexts to evaluate the impact of Filterra in controlling the quality-quantity issues related to stormwater.

The present study contributes to the advancement of compact BRC modelling and design by achieving these objectives, thereby facilitating the development and deployment of high-performance, space-efficient solutions for stormwater management in densely urbanized environments.

4.3 Materials and methods

4.3.1 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 from a roadway with about 300 m² of contributing impervious area, directing flow into the unit via a 70 m asphalt gutter. 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. The CDA is approximately 210 times larger than the surface area of the Filterra, which corresponds to an $Area_{BRC}$/CDA ratio equal to 0.5%. The Filterra cell comprises a 7 cm mulch layer, 53 cm of the 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 is conveyed through a perforated underdrain with a 10 cm diameter to the downstream drainage pipeline. In cases of high-intensity rainfall, when the capacity is exceeded, the excess runoff is directed to the overflow basin by an overflow system (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 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. Figure 4.1 provides an overview of the field site and the monitoring gauge station.

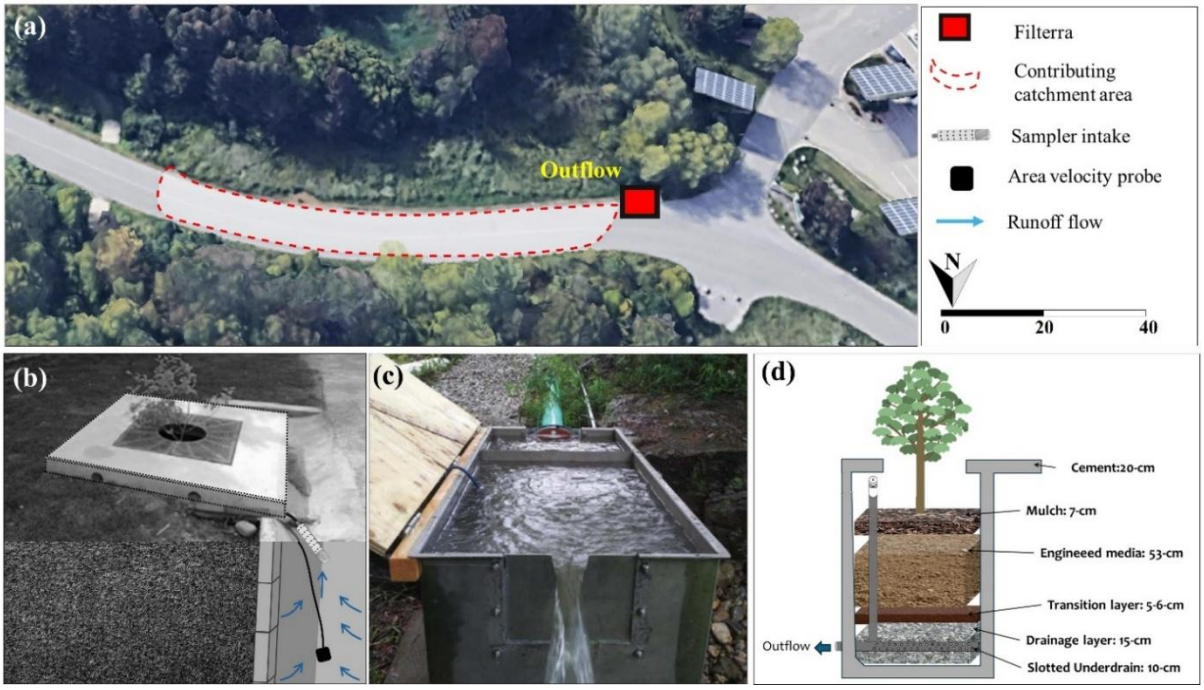

Figure 4. 1 Overview of the study site located at Kortright (Vaughan, ON): (a) Aereal image of the site with contributing drainage area and Filterra location; (b) Filterra monitoring system with inlet area velocity probe and sampler intake, (c) outlet V-notch weir box; (d) Schematic cross-section of 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).

4.3.1.1. Monitoring data

The TRCA STEP evaluated the hydrologic and load reduction performance of the Filterra over two years, from mid-June to early November 2017 and from May to November 2018. Data from this project was shared with Carleton University in 2023 for modelling purpose. Rainfall data was 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 programme 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-minute resolution rainfall data, 1 minute resolution flow data, and inlet and outlet event mean concentrations for TSS.

Rainfall-runoff events for calibration and validation (hydrologic and TSS) of the model are extracted from the continuous precipitation and inflow-outflow 2018 dataset. To separate events, a defined rainless interval, referred to a minimum the antecedent dry weather period (ADWP) that represents the minimum dry period needed before and after a rainfall event to

consider it as independent, was applied (Dunkerley, 2008; Medina-Cobo et al., 2016). This study selected a 6 hours ADWP to identify distinct rainfall-runoff events within the study area. This criterion resulted in the identification of 58 independent rainfall events. However, due to discrepancies in data reliability, only events demonstrating consistent and high-quality measurements of rainfall, inflow and/or outflow were chosen for model calibration and validation. The selection criteria highlighted quantity data continuity, providing uninterrupted and temporally consistent records for rainfall, inflow, and outflow as well as quantity data consistency in terms of runoff and outflow coefficients. Indeed, the hydrological relevance of events was assessed, with a particular emphasis on those that demonstrated the typical rainfall-runoff responses that are indicative of the climatic and catchment conditions of the study area. For example, this method excluded events characterized by anomalies resulting from operational issues. In total, 15 rainfall-runoff events that satisfied the reliability criteria were employed for hydrologic and TSS calibration-validation purposes. Table 4.1 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 minutes, as well as the role of each event in the SWMM calibration and validation.

Table 4. 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

The hydrological calibration of Filterra was based on three inflow and three outflow events. The inflow calibration events were: July 16, July 30, and October 2, and the outflow calibration events were: July 16, August 21, and September 30. For hydrological validation, three inflow events included August 7, August 21, and October 7 and three outflow events included August 8, August 17, and November 1. The TSS calibration of Filterra encompassed four events: August 6, August 8, August 21, and September 21 and for TSS validation, four events were chosen: August 25th, September 2nd, October 2nd, and October 4th.

4.3.2 Media characterization

Two undisturbed soil samples from a second Filterra system were collected in November 2023 to understand better 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 & Ghane, 2020). These parameters are critical for understanding the water retention dynamics and unsaturated flow through the EM in Filterra. The samples of Fillterra units were located at the Carleton University Campus in Ottawa, Ontario. The growing media of these units was assumed to represent the newly installed Fillterra 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 programme was carried out.

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

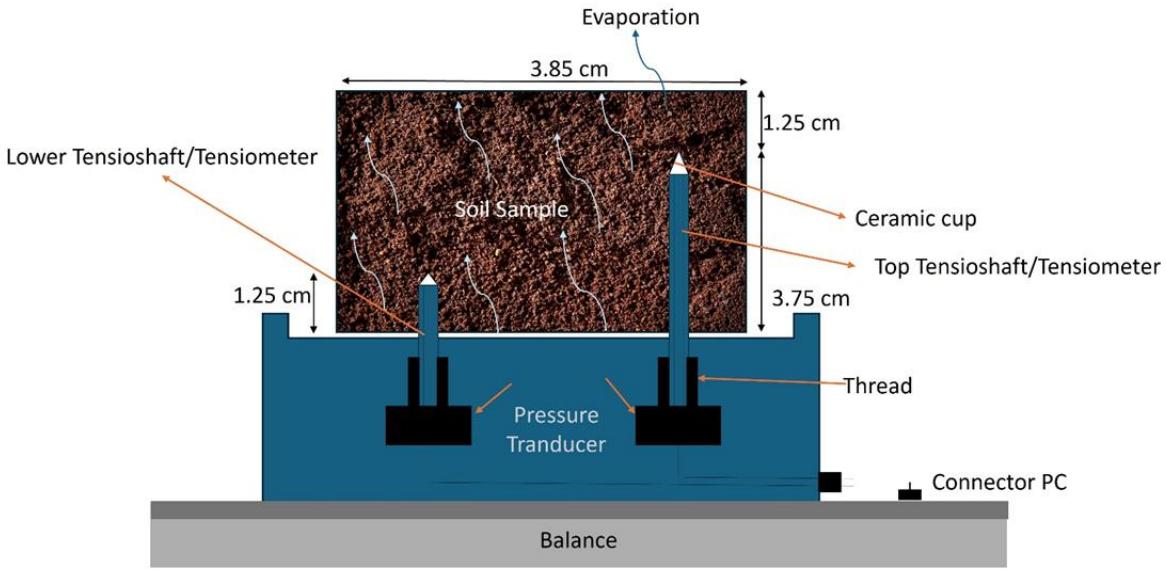

Figure 4. 2 Schematic cross section trough HYPROP tool.

the Filterra media characterisation. Two tensiometers are positioned in the soil column (Figure 4.2) 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 first phase is the degassing of deionized water. Deionized water is contained in a vacuum bottle linked to the HYPROP system via a tube. The tube from the vacuum bottle is connected to the vacuum mount of the HYPROP system, which is subsequently linked to a vacuum pump. The pump serves to generate a vacuum, so eliminating air bubbles or gas from the deionized water. The tube within the vacuum bottle must remain above the water surface

to guarantee that air is evacuated without extracting the water. The degassing process typically requires several hours to be completed.

After the degassing of the deionized water, the next essential step is the degassing of the HYPROP sensor unit and the two tensio shafts. The purpose of this procedure is to eliminate any residual air bubbles within these components, thus ensuring accurate measurements during the experiment. There are two methods for carrying out the degassing process: (i) with the HYPROP refill equipment, or (ii) use syringes manually. While the manual method is time-consuming and disposed to error, the HYPROP refill unit is recommended for its automation and precision. A high-performance vacuum compressor is employed in the refill unit to achieve a vacuum pressure of 0.85 to 0.90 bars (85-90 kPa), thereby ensuring a comprehensive degassing of the tensio shafts and the sensor unit. The vacuum pump, vacuum mount, and beaker mount are all assembled and connected via tubes during this phase. The vacuum pressure is monitored on a regular basis to ensure that it is maintained, with the system operating for an average of 12 to 24 hours. If the vacuum cannot be maintained, leaks in the system should be discovered and repaired. The reliability and accuracy of the SWCC derived from the HYPROP experiment is ultimately improved by ensuring that no air pockets interfere with the measurements, which is a critical aspect of successful degassing. This study used the HYPROP refill unit for this objective.

Following the degassing of the sensor unit with the HYPROP refill unit, the soil sample was saturated with degassed water. The HYPROP manual recommends the use of degassed water for this procedure; nevertheless, the selection of water for saturation depends on the specific aims of the experiment. For instance, in agricultural applications, underground drainage water can be utilized to more accurately replicate natural conditions. In this study, the degassed water was used.

The saturation procedure included removing the caps from both parts of the soil samples core, covering the base with nonwoven cloth, and positioning the core in a tray filled with degassed water. Precautions were taken to avoid pouring water straight over the soil surface to prevent the entry of air. The length of saturation fluctuates based on soil type, generally spanning from 10 minutes for coarse sand to 6 hours for silt. The soil samples in the present study required 4hours for complete saturation (shiny surface of soil sample indicates saturation).

After saturating the soil sample, the subsequent step involves the careful placement of tensio shafts into the sensor unit. This includes gradually opening the valve linked to the beaker mount to avoid damage to the pressure sensors and detaching the tension shafts from their adapters. The ceramic tips of the tension shafts must remain hydrated throughout this procedure, and silicone caps or degassed water can be utilized to preserve moisture. The tension shafts are subsequently placed into the sensor unit, ensuring accurate alignment with the specified connection connectors. The shafts are carefully screwed (HYPROP manual suggests that it takes about 9 turns) in while observing the pressure in the HYPROP-View application to prevent exceeding the maximum permissible pressure of 200 kPa. After installation, silicone covers are detached, and the unit is secured with a silicone gasket to avoid dust contamination. The functionality of the shafts can be assessed by adding some small drops of water to the ceramic tips and monitoring pressure variations. If the pressure in both tension shafts returns to zero quickly, then the tension shafts are operating correctly. This is to verify the zero potential of the tension shafts.

Before starting the experiment, a calibration verification was conducted to check the accuracy of the sensor unit. If recalibration need to be done, the "set zero value" feature in the HYPROP-View software was used. Following confirmation of calibration, the sensor unit was linked to the USB adaptor, and the system was prepared for the next phase. The sensor unit was thereafter attached to the soil sample ring, and the saturated soil core is properly placed to maintain saturation. Holes were excavated in the soil core with a little auger, thereafter, filled with water to avoid air intrusion. After ensuring a tight seal, the soil core and sensor unit turned upside down to eliminate any extra materials. After completion of the setup, the measurements begin. The sensor unit was positioned on a balance and calibrated. Data collection begins via the HYPROP-View application, recording variations in weight and pressure over time. The frequency of data collection is adjustable, and the program records measurements for a duration of 2 to 10 days, depending on soil type. In this study it took approximately 10 days.

In the present study, the measurement procedure was manually stopped following the observation of the following 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 was analysed using the bimodal Van Genutchen – 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 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 at an accuracy of 0.01 cm, capturing dynamic changes in flow. Full experimental details are available in the KSAT manual (METER Group, 2018).

4.3.3 Modelling

4.3.3.1 Model setup

The Storm Water Management Model (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 equations systems (Lisenbee et al., 2021; Palla & 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 load reduction 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 Curve Number (CN) method for infiltration and the dynamic flow routing method with 1 min time intervals were 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. 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 washoff functions, considering the specified land uses. To model pollutant build-up and washoff, 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 washoff (Rossman, 2010). This study which focused on TSS delivery behaviour, employed exponential equations for the build-up and washoff 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

$$B = C_1 \cdot (1 - e^{-C_2 \cdot t}) \tag{4.1}$$

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 washoff model links pollutant removal to runoff intensity, ensuring a representative pollutant transport prediction.

$$W = C_3 \cdot Runoff^{C_4} \cdot B' \tag{4.2}$$

where W is the washoff load in units of mass per hour, where C_3 is the washoff coefficient $[h^{C_4-1}/mm^{C_4}]$, C_4 is the washoff exponent (-), which defines the nonlinearity

between $Runoff$ rate per unit of area $[mm/h]$ and pollutant transport, and B'(units of mass) is the available pollutant mass for washoff.

4.3.3.2 Hydrologic calibration and validation

The calibration process of the SWMM models for the hydrologic processes involves the selection of a set of parameters for inflow and outflow dynamics of the Filterra system (Table 4.2). 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 are chosen to accurately capture the hydrological dynamics of the fully impervious contribution drainage area, focusing on the processes 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-exponent, Flow-coefficient), and the initial water level in the storage media (Ini-saturation). 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 4.2, each parameter is assigned upper and lower bounds. The ranges of Surf-roughness, Surf-slope, Flow-coefficient, Flow-exponent, and Ini-saturation were selected according to SWMM manuals (Rossman, 2010). For $Depth_{storage}$ and offset underdrain, the calibration ranges were selected based on the TRCA STEP (2020) and adjusted to account for uncertainties in site-specific conditions and installation variability. The ranges of N_{imp} and Slope were chosen according to (Huber & Barnwell, 1988; Temprano et al., 2007), while those for DS_{imp} and $Zero_{imp}$ were derived from site-specific conditions.

The other parameters of catchments were fixed based on the TRCA STEP (2020) and QGIS analysis. 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 (TRCA STEP, 2020; Rossman, 2010).

Table 4. 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

The calibration was performed at the event scale using the Differential Evolution (DE) method (Storn & Price, 1997), implemented with the DEoptim library in R (Mullen et al., 2011). DE is a population-based technique to rapidly navigate complex, multi-dimensional solution spaces by applying evolutionary principles using mutation, crossover, and selection (Le Floch et al., 2022). 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 goodness-of-fitness mentioned.

The inflow and outflow optimization emphasized fitting the overall observed hydrographs to accurately capture peak flows and response timing, rather than just matching cumulative volumes. This approach was used to avoid hydrograph form distortions caused by volume-based calibration (Lisenbee et al., 2020). The Kling-Gupta Efficiency (KGE) (Gupta et

al., 2009) was used as the objective function for the optimization 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 KGE value of more than 0.35 was considered acceptable, representing a notable improvement over the mean flow benchmark (KGE ≈ -0.41) (Knoben et al., 2019). R^2 values above 0.45 and RMSE values below 0.25 l/s were selected to further ensure that the model demonstrates both a strong relationship with observed data and minimal residual error. 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. The weights were calculated based on the rainfall event characteristics (rainfall depth, event duration, ADWP, and maximum rainfall intensity)

3. 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 4.1. The validation was then performed at the event scale, assessing the goodness-of-fit metrics, KGE, R^2, and RMSE based on the calibrated weighted average parameters. Similarly to calibration, the validation was performed for three events for both inflow and outflow processes as indicated in Table 4.1.

4.3.3.3 TSS Calibration and validation

Table 4.3**Error! Reference source not found.** reports the SWMM parameters of the exponential build-up and washoff equations documented in the literature. Note that while the unit of measurement of C_2, C_3 and C_4 are univocally defined, C_1can 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 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 factors are essential, including rainfall patterns, volume, intensity, duration, and ADWP (Tu & Smith, 2018)..

Once the hydrologic and hydraulic parameters were validated, the calibration procedure for the quality aspects is implemented. 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 4.3). A range of washoff parameters (0.1 to 1.5 for C_3 and from 0.5 to 3 for C_4), were assumed in the calibration phase.

Table 4. 3 SWMM Parameters of the exponential build-up and washoff equations reported in the literature.

Location	**Land use**	**C_1 [kg/ha or kg/m]**	**C_2 [1/days]**	**C_3 [h^{C4-1}/mm ^{C4}]**	**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 Lum-pur, Malay-sia	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 ur-ban area	0.03-16.49 [kg/ha]	0.21-5.54	3.27-12.53	4.06-8.98	(Tu & 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 & Petrucci, 2017)

Calgary, Canada	Residential urban area	56 [kg/ha]	1	0.087	1.53	(Shrestha & 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	(Cambez et al., 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).

Table 4.1 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 0.81 was calculated and then used in the SWMM LID module as the pollutant removal rate for underdrain outflow. The Observed inlet and outlet TSS concentration of Filterra is shown in Table 4.4.

Table 4. 4 Observed inlet and out Total suspended solids (TSS) concentration of FIlterra for calibration and validation events, including reduction rate

Event role	**Rainfall event**	**TSS inlet concentration [mg/l]**	**TSS outlet concentration [mg/l]**	**Reduction rate [-]**
Calibration	6 Aug	60.8	22.3	0.63
	8 Aug	17.3	3.7	0.79
	21 Aug	62.5	8.2	0.87
	21 Sep	227	26.6	0.88
Validation	25 Aug	36.4	4.6	0.87
	2 Sep	63.9	10.9	0.83
	2 Oct	36.9	10.2	0.72
	4 Oct	65.1	12.1	0.81

Similarly to the hydrologic model optimisation procedure, the TSS calibration was organised into three phases: initial calibration, weighted average calibration and model pre-validation. For each event, the washoff parameters were evaluated using as an objective function the relative error (RE) of the simulated TSS concentration value with respect to the observed one. Following the calibration of individual events, a weighted criterion based on the rainfall event characteristics is used to calculate the average value of each washoff 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. Finally, the validation of TSS performance was assessed based on the set of four events, as illustrated in Table 4.1.

4.4 Result and discussion

4.4.1 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.

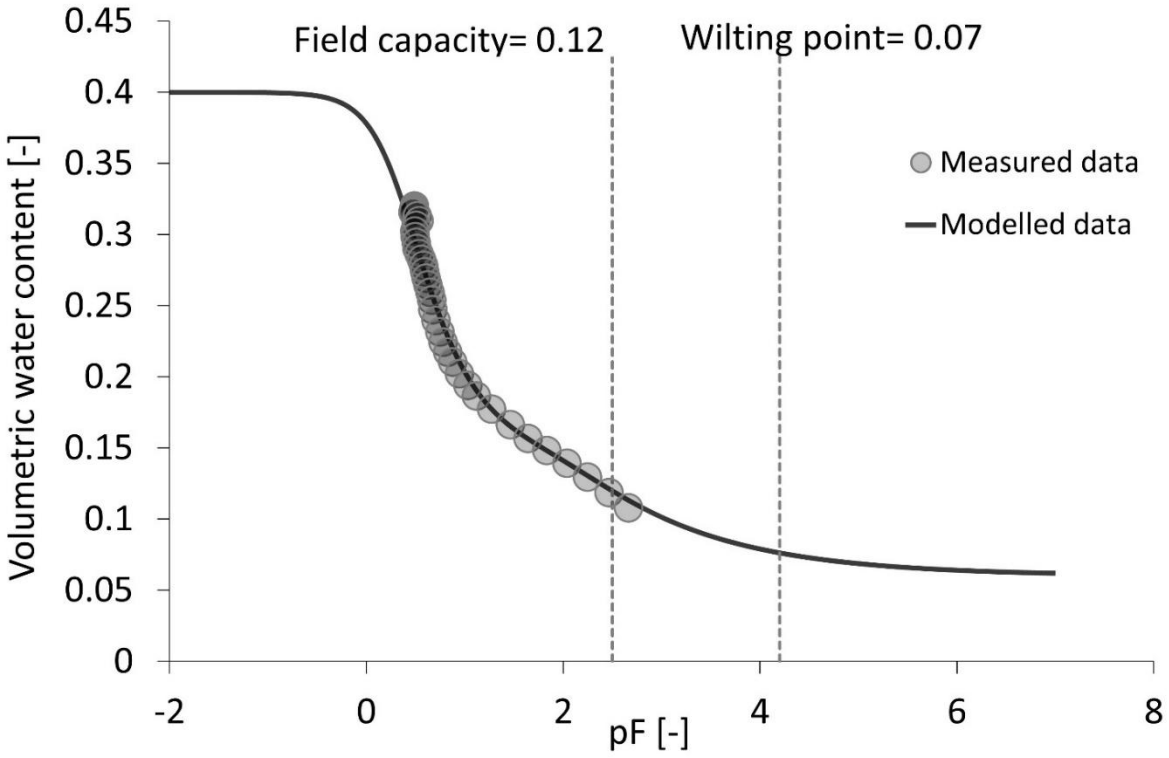

Figure 4. 3 Volumetric water content vs. pF (log scale of tension in hPa) and fitted soil water characteristic curve according to the bimodal Van Genutchen – Mualem model of the Filterra's EM.

Figure 4.3 shows the measured SWCC of the Filterra's EM alongside a fitted bimodal Van Genuchten-Mualem, which describes the relation 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 most 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 cm^3/cm^3 and a residual water content of 0.06 cm^3/ cm^3. As illustrated in Figure 4.3, the field capacity of the EM obtained from the model at pF 2.5 is 0.12 cm^3/ cm^3, while the wilting point at pF 4.2 is 0.07 cm^3/ cm^3, giving essential inputs for SWMM modelling.

Additionally, the porosity obtained from HYPROP is 0.4 (cm^3/ cm^3), which is the saturated water content of the fitting model. However, the porosity for the SWMM (LID module, BRC) was chosen 0.42. 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 cm^3/cm^3 represents approximately 90 to 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. 5 Hydraulic characteristics of Filterra EM and comparison with other sandy soil

Feature	**Unit**	**Filterra EM**	**Sandy soil** (Saxton & Rawls, 2006)	**Sandy soil** [1] (Rawls et al., 1983)	**Sandy soil** (Spraakman & 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	1,750	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

Table 4.5 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 & Rawls, 2006; Rawls et al., 1983; Sylvie and Drake, 2021). The Filterra's EM's porosity of 0.42 cm^3/cm^3, which is comparable with the reported values for sandy soils between 0.44 and 0.46 cm^3/cm^3. Its field capacity of 0.12 cm^3/cm^3 and the wilting point of 0.07 cm^3/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 Spraakman and Drake (2020) 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 1,750 mm/h, but aligns well with Filterra system design, which targets hydraulic conductivities in the range of 2,540 – 3,556 mm/hr (Lenth et al., 2010). This value markedly exceeds the K_{sat} found in sandy soils reported in the Table 4.5, which ranges from 100 to 150 mm/h. The elevated permeability points out the ability of Filterra 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 EM of Filterra, with were an estimated sand composition of roughly 90% and a clay part of 5%, the conductivity slope equals 47.45. Although some studies have revealed substantially less conductivity slope values than recommended by SWMM documentation in BRC simulations (e.g. Liu & Fassman-Beck, 2017; Lynn et al., 2018) ranging from 7 to 60, the outcome of this study is within the typical range of 30 to 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 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 EM requires less capillary pressure to trigger movement of water, resulting in faster infiltration and wetting front progression (Ball & 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).

4.4.2 Hydrologic calibration-validation

The hydrologic calibration of the Filterra system was conducted using the two specific sets of calibration parameters for the inflow and outflow dynamics illustrated in Table 4.2. The Cal-In events (16 July, 30 July, and 2 October) were used to calibrate the inflows to Filterra, whereas the Cal-Out events (16 July, 21 August, and 30 September) were employed to calibrate the Filterra outflows. The validation phase employed three inflow events, Val-In, (7

August, 21 August, and 7 October) and three outflow events, Val-Out, (8 August, 17 August, and 1 November), as shown in Table 4.1.

The weighted average calibrated values for the inflow parameters were established as follows: DS_{imp} = 30.6 mm, $Zero_{imp}$ = 58.5%, N_{imp} = 0.013, and Slope = 1.9%. For outflow calibration, the selected parameters were identified and improved to characterize the internal behaviour of the Filterra system: Offset-underdrain = 3.3 mm, $Depth_{storage}$ =152.8 mm, Surf-roughness = 0.36, Surf-slope = 0.86%, Flow-coefficient = 4.87, Flow-exponent = 0.38, and Ini-saturation = 29.3%. The detailed list of the assigned parameters for the Filterra system and the catchment characteristics of the site study can be found in Table 4.6.

Table 4. 6 Filterra and site study parameters implemented in SWMM LID module.

Category	Layer	Sub-layers	Unit	Value	Status
Filterra design parameters	Geometry	area	m^2	1.44	Measured[1]
		width	m	1.2	Measured [1]
		Filterra area: Catchment area ratio	%	0.5	Calculated
		Initially saturated	%	30	Calibrated
	Surface	Berm heigh	mm	100	Measured[1]
		Vegetation volume		0.25	Estimated
		Surface roughness	$s/m^{1/3}$	0.36	Calibrated
		Surface slope	%	0.86	Calibrated
	Soil	Thickness	mm	533	Measured[1]
		Porosity	cm^3/ cm^3	0.42	Measured[2]
		Field capacity	cm^3/ cm^3	0.12	Measured[2]
		Wilting point	cm^3/ cm^3	0.07	Measured[2]
		Hydraulic Conductivity	mm/hr	1750	Measured[3]
		Conductivity slope		47.45	Calculated[4]
		Suction head	mm	20.5	Calculated
	Storage	Thickness	mm	152.8	Calibrated
		Void ratio	cm^3/ cm^3	0.75	Estimated
		Seepage rate	mm/hr	0	

		Clogging factor		0	
	Drain	Flow coefficient		4.87	Calibrated
		Flow exponent		0.38	Calibrated
		Offset Height	mm	3.3	Calibrated
	Pollutant Removals	Total suspended solids	%	81	Measured[5]
Catchment design parameters	Geometry	Catchment area	m^2	303	Estimated
		Width	m	40	Estimated
		Slope	%	1.9	Calibrated
	Land cover	Imperviousness	%	100	Estimated
		Imperviousness Manning's n	$s/m^{1/3}$	0.013	Calibrated
		Pervious Manning's n	$s/m^{1/3}$	0	
		Depression storage of impervious area	mm	30.6	Calibrated
		Depression storage of pervious area	mm	0	
		Impervious area without depression storage	%	58.5	Calibrated

[1] The result obtained from field inspection by (TRCA STEP, 2020). [2] The results of HYPROP tool. [3] The result of KSAT tool. [4] The value was calculated using the formula as recommended by (Rossman, 2010). [5] The average quality monitoring of TSS reduction of Filterra in the filed in 2018.

The calibrated value of DS_{imp} is considerably greater than the typical range of 0 to 4 mm reported in the literature (Dayaratne & Perera, 2008; Dong et al., 2008; Skotnicki & Sowiński, 2015) and larger than recommend values in SWMM manual which reports typical DS_{imp} ranges between 0.6 mm and 2.5 mm (Rossman,2010). However, the actual values of depression storage for a specific catchment should be evaluated experimentally in practice by calibrating a rainfall-runoff model based on field observations (Dayaratne & Perera, 2008). The elevated DS_{imp} value observed in this study can be attributable to various site-specific factors related to the catchment, including cracks, joints and curb zones. The other inflow parameters are within ranges typically reported in similar studies. $Zero_{imp}$ value generally range from 1% to 45% (Temprano et al., 2006), whereas surface slopes in urban catchments vary from 0.5% to 3.5% (Rossman, 2010; Zakizadeh et al., 2022). The calibrated N_{imp} value is consistent with standard Manning's roughness values for impervious surfaces, which are

generally reported to range from 0.011 to 0.033 (Rossman, 2010). Outflow calibration parameters, offset-underdrain and $depth_{storage}$ are design-dependent parameters that reflect the specific geometric configuration of the Filterra. 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 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 4.7 for the calibration and validation events.

Table 4. 7 Goodness-of-fit metrics, KGE, R2 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
		07 Oct	0.47	0.28	0.10
Outflow	Calibration	16 Jul	0.57	0.76	0.23
		21 Aug	0.49	0.71	0.08
		30 Sep	0.71	0.47	0.26
	Validation	08 Aug	0.37	0.50	0.06
		17 Aug	0.39	0.58	0.12
		01 Nov	0.37	0.56	0.09

Results illustrated in Table 4.7 confirmed the suitability of the SWMM model in reproducing both 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. Model calibration typically produces higher efficiency metrics because it is adjusted to specific observed data, resulting in a closer match. The validation phase, which employs calibrated parameters, result in metrics that highlight a slight

decrease in efficiency. For validation and 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. 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 minutes, 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 Figure 4.4 for the six selected events of calibration and validation. Furthermore, the calibration and validation of inflow of Filterra are presented in Figure 4.5.

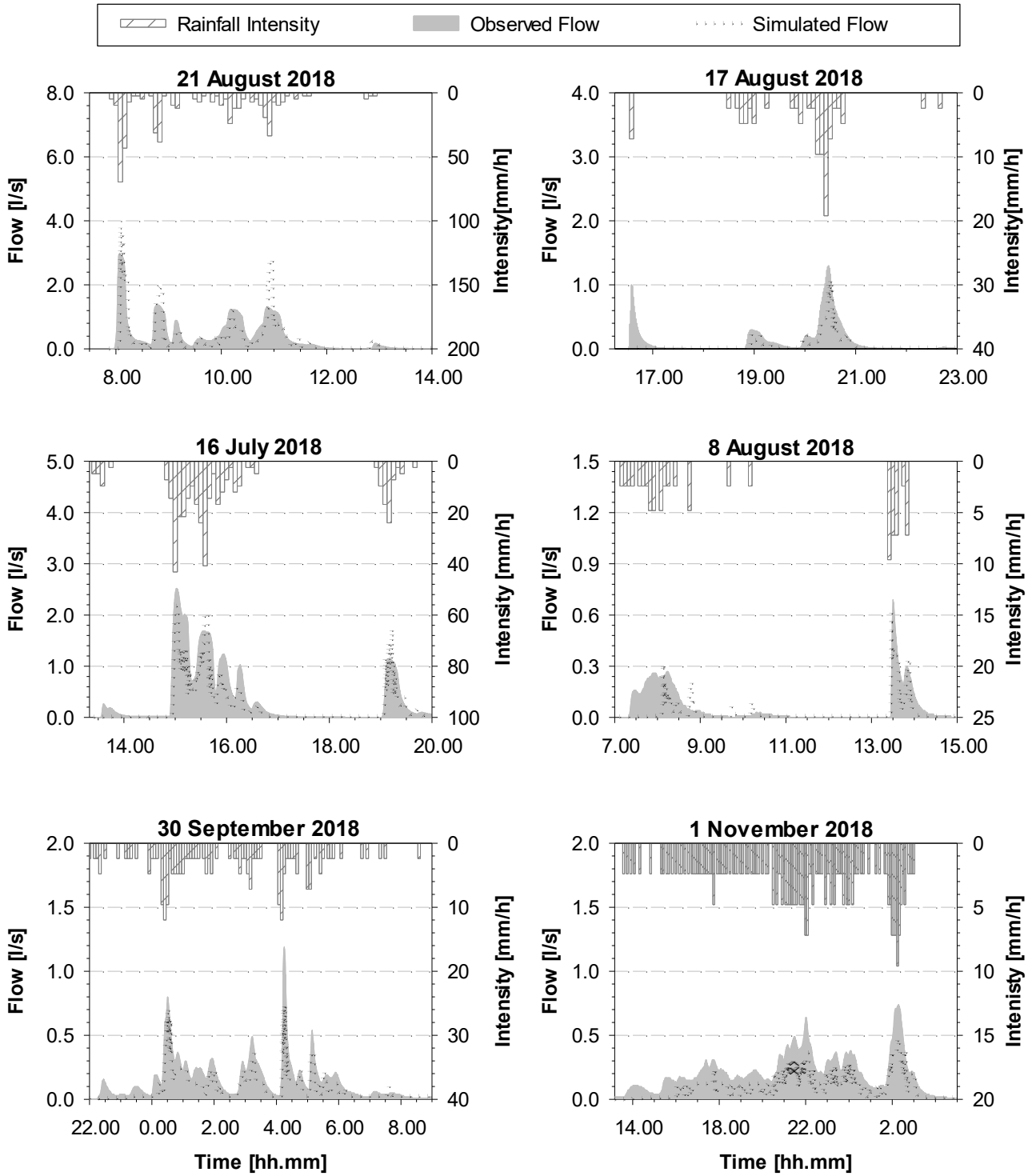

Figure 4. 4 *The hyetographs and the corresponding observed and simulated hydrographs of the Filterra outflow at the site. The left column refers to the calibration events while the right column refers to the validation events.*

Results plotted in Figure 4.4 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 light tendency to the volume underprediction can be detected due to the wrong simulation of the beginning of the outflow process (see the 17 Aug and the 8 Aug events in Figure 3) that could be

postponed due to the assigned initial saturation value (constant weighted calibrated value) and to the simplified scheme of the infiltration process.

As shown Figure 4.4, 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 underpredicted, while for the 21 Aug event is overpredicted leading to a 29% overprediction. This overprediction 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 & Kazezyılmaz-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 & 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 is accurate with average variances of less than 2 minutes in most instances. It signifies that the model is successful in accurately capturing the timing of peak flow runoff.

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 in the 30 Sep and 1 Nov events (see Figure 4.4), results from SWMM's simplified representation of soil moisture dynamics, particularly 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 & Kazezyılmaz-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

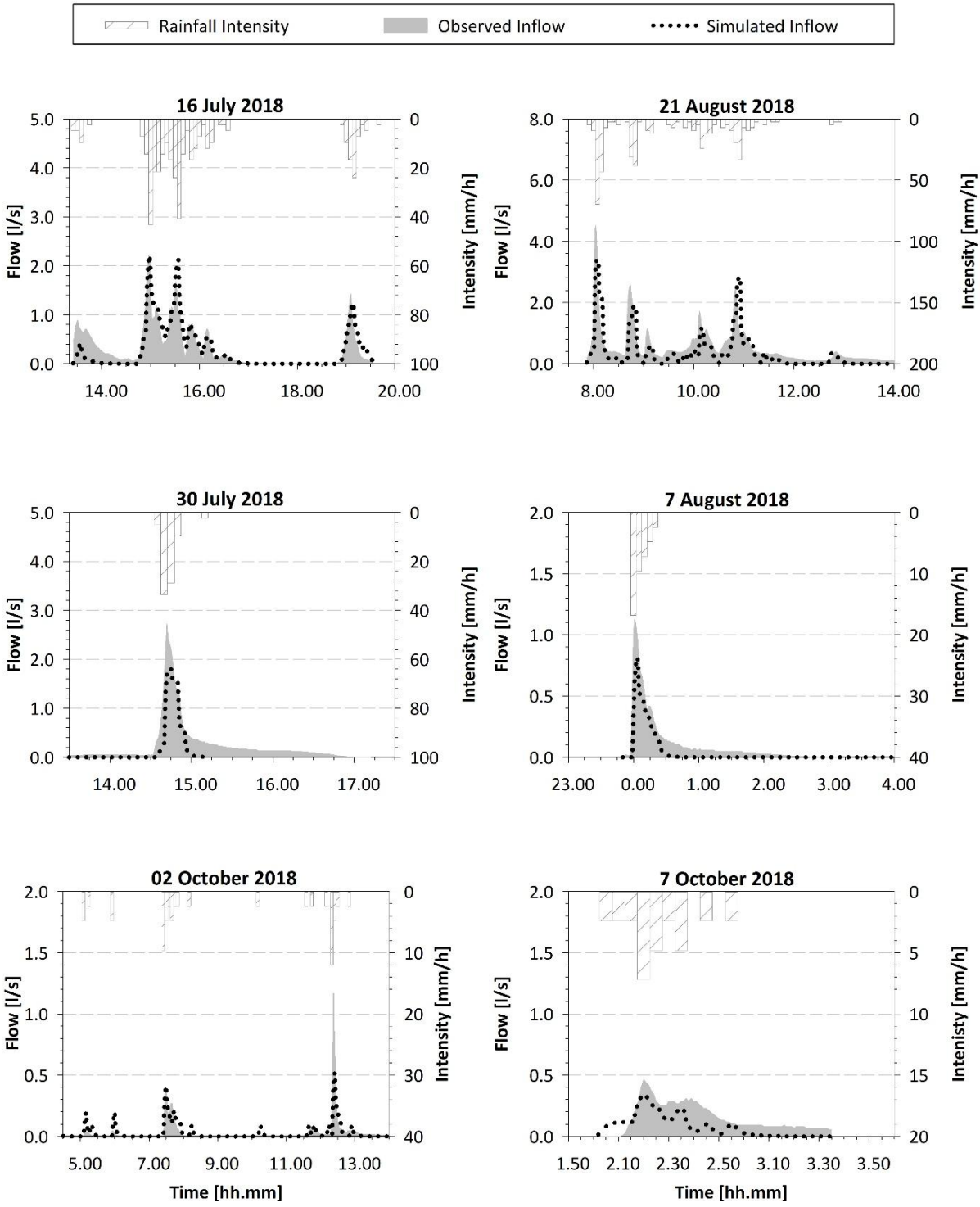

Figure 4. 5 *The hyetographs and the corresponding observed and simulated hydrographs of the Filterra inflow at the site. The left column refers to the calibration events while the right column refers to the validation events.*

rainfall events, when the max 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.

4.4.3 TSS calibration and validation result

After calibrating and validating the hydrologic model of the system, the calibrated washoff 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 4.8. By considering C_1 equal to 60 [kg/ha] and C_2 0.177 [1/day] and a removal rate equal to 0.81, the parameter C_3, fluctuated between 0.017 to 0.098 [h^{C4-1}/mm^{C4}], 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.

Table 4. 8 Initial calibrated washoff parameters (C_3 and C_4) and relative error (RE) of TSS modelling for each event

Rainfall event	**C_3 [h^{C4-1}/mm^{C4}]**	**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

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 4.3). For instance, Shrestha & 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 washout rates are markedly site-specific being affected by rainfall characteristics coupled with other factors such as the sub-catchment and the pollutant load characteristics. While previous studies, such as Shrestha & He, (2017) suggest that longer and more intense storm events result in increased pollutant washoff 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 maximin intensity of 40.8 mm/h, revealed the highest C_3 value of 0.098 [h^{C4-1}/mm^{C4}], 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 washoff 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 washoff rates may be even less predictable. In addition, the buildup 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 modify the initial pollutant mass present at the beginning of runoff, resulting in variations in washoff loads despite comparable rainfall conditions. The findings underscore the complexity of stormwater pollutant transport, indicating that washoff 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 washoff.

Following the calibration process, the weighted average calibrated values for the washoff parameters were established as follows: C_3= 0.056 [h^{C4-1}/mm^{C4}] and C_4= 0.77 [-]. Figure 4.6 shows a comparison of the simulated and observed TSS concentrations for the calibration and the validation events at both the inlet (Figure 4.6a) and outlet (Figure 4.6b) of the Filterra system, according to the weighted average calibrated values.

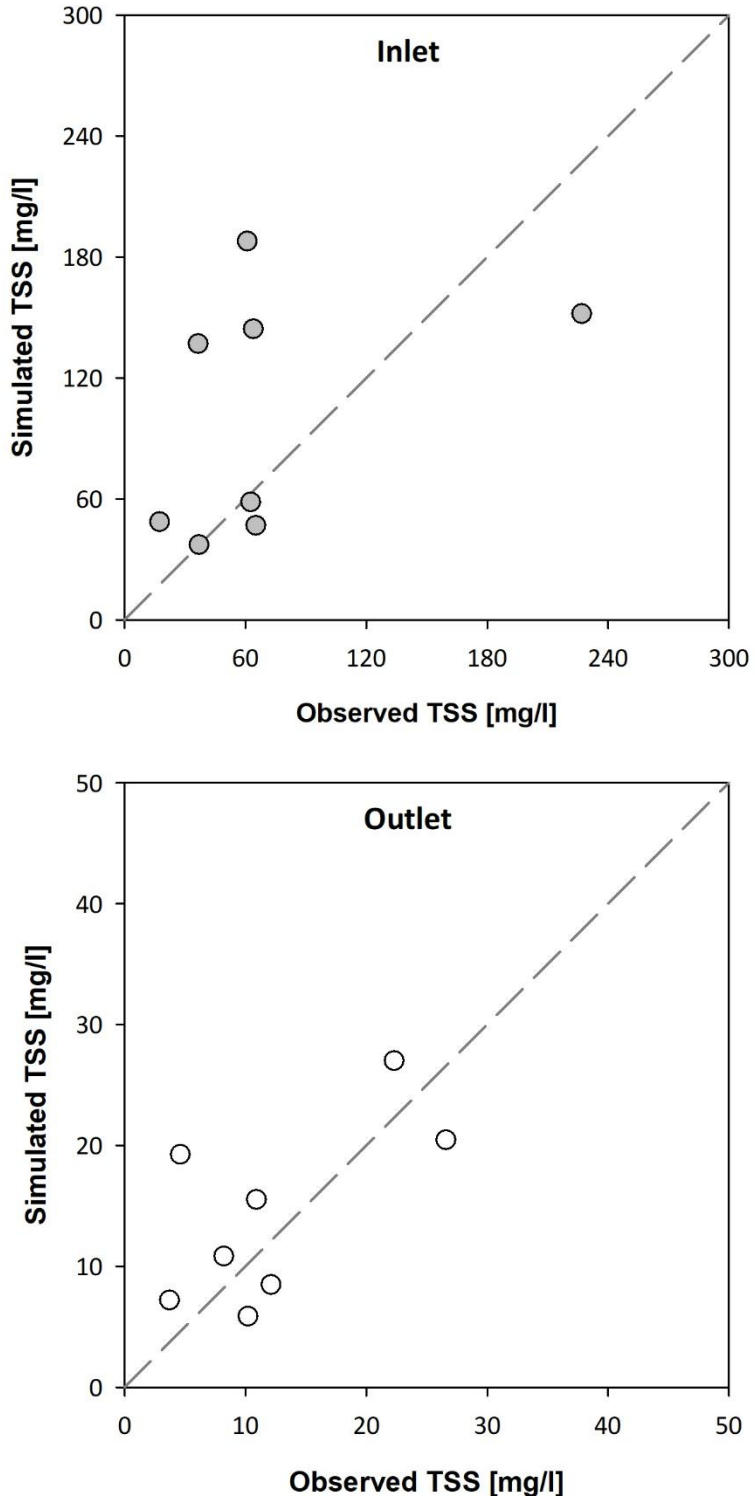

Figure 4. 6 Simulated vs observed TSS concentration at the (a) inlet and (b) outlet of FIlterra for calibration (Cal-TSS) and validation (Val-TSS) events. The simulated is based on the weighted average of C_3 and C_4

The calibration and validation data at the inlet, Figure 4.6a, 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 (Figure 4.6b) the simulated TSS concentrations well reproduce the measured ones. The enhanced alignment indicates that the SWMM model, although using a constant treatment rate of 0.81, provides an effective estimation of average treatment efficacy. Although this fixed efficiency is advantageous for establishing baseline performance expectations, it may not accurately represent the dynamic behaviour of TSS 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, the model's average performance is satisfactory; 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 consistent of concern.

4.5 Filterra® monitoring in Venice: Evaluation of pollutant load reduction

This section outlines the planning, design, and implementation of a monitoring program for the Filterra system at the Ecocentro Marcon (Marcon, VE). Unlike the system at the Vaughan site which was standalone; the one in Venice is part of a stormwater management system’s existing treatment system. The primary objective of this research activity is to evaluate the system's effectiveness in removing pollutant loads, specifically TSS, from stormwater to compare the performance it to the FIlterra located in Vaughan. Although data analysis has been limited due to installation and data collecting issues, the detailed description of the planning and design process might provide valuable information for future applications of compact BRC systems in urban settings. This research is part of a collaboration between the University of Genoa and SWI Group S.r.l. within this Ph.D. program.

4.5.1 Site and Filterra description

The Ecocentro is in Marcon, Venice (45°32'32.5"N, 12°19'34.7 E") and covers an area of approximately 2200 m² (Figure 4.7), mostly impervious to facilitate waste management activities. The site comprises a large impervious area where waste containers are arranged along the perimeter. Most of the area is dedicated to vehicular transit associated with waste delivery.

Figure 4. 7 Marcon Eco-centro, Venice site (Map data: Google 2022)

In 2017, during the facility's expansion, the existing stormwater treatment infrastructure was enhanced to include a Filterra unit. This improvement was implemented to comply with regulatory limits (as defined, for example, in Table 4 of Annex 5 of DLGS 152/06) and to eliminate the discharge of untreated runoff into surface waters. At the Ecocentro Marcon, the Filterra functions as an integrated component of a larger treatment system. During a storm event, runoff is first conveyed to a storage tank where preliminary sedimentation occurs (called pre-treatment storage tank). The collected water is then pumped to the Filterra unit (Figure 4.8a), where Filterra is the primary treatment component. A key design feature is the bypass feature within the Filterra system that conveys stormwater exceeding the Filterra capacity into a dedicated chamber (Figure 4.8e).

This chamber houses two Stormfilter™ units (which indicated by filter system), ensuring that all water is treated before discharge. Additionally, if the capacity of Filterra and the filter system is not enough, the stormwater is conveyed to overflow system and then it will be cleaned out manually (which occurs rarely). Notably, the system is connected to an

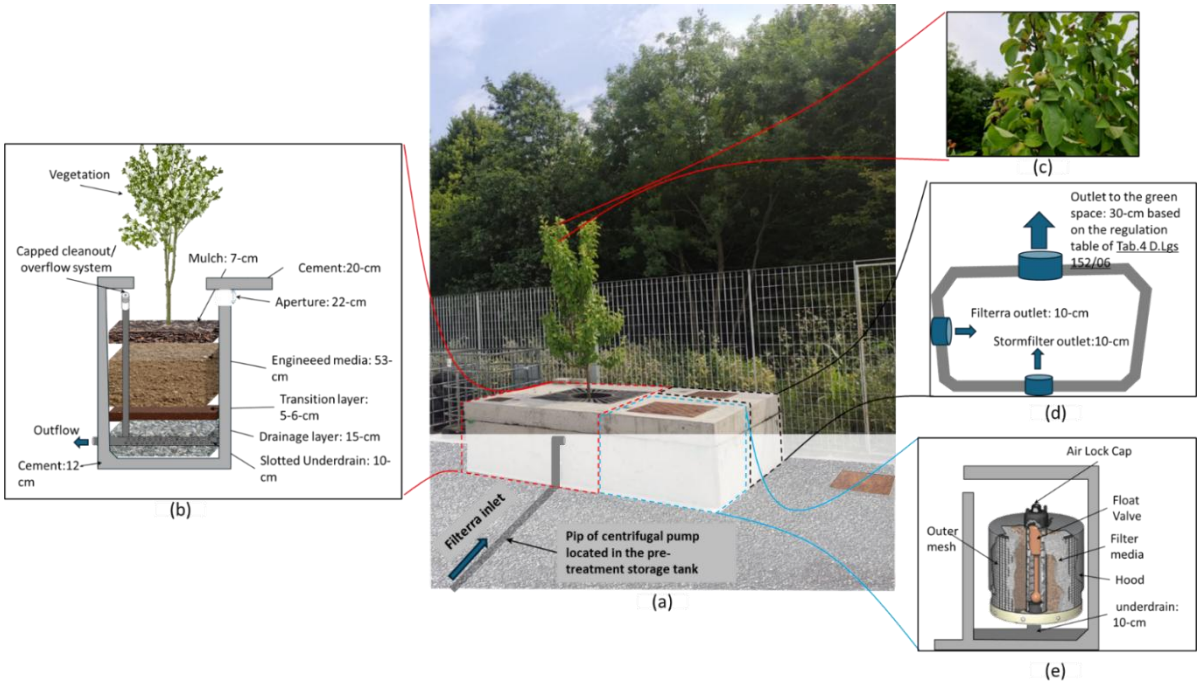

Figure 4. 8(a) Filterra system overview: an overview of the Filterra system's component and arrangement (b) side-view of Filterra layers with underdrain arrangement (c) vegetation status: illustrating the current state (April 11th, 2024) of an apple tree (d) plan-view of overflow section: there are three outlet pips (e) side-view of stormfilter system: referring the components of the stormfilter.

emergency management system integrated with a SCADA (supervisory control and data acquisition) unit and a multiparameter water quality probe (including turbidity, electrical conductivity, temperature, and pH). If the multiparameter probe (Figure 4.9a) indicates the parameters outside of nominal range, the pump does not transport water inside of the pre-treatment storage tank towards Filterra. This is a critical approach for managing occasional spills or elevated contaminant loads (e.g., those due to pavement cleaning activities).

4.5.2 Monitoring station design and instrumentation

A monitoring station has been designed to evaluate the pollutant removal performance of the Filterra by monitoring both hydraulic-hydrologic and water quality parameters at inlet and outlet. A designed inlet channel (illustrated in Figure 4.9 with PVC distribution channel) has been integrated into the system, features a slight slope, to ensure that the inflow is evenly distributed across the Filterra surface. Furthermore, a sampling unit has been integrated into the outlet piping to capture treated water from Filterra.

The collection of data is carried out using the Teledyne Isco 6712 automatic samplers, which are strategically positioned within the bypass chamber following the temporary

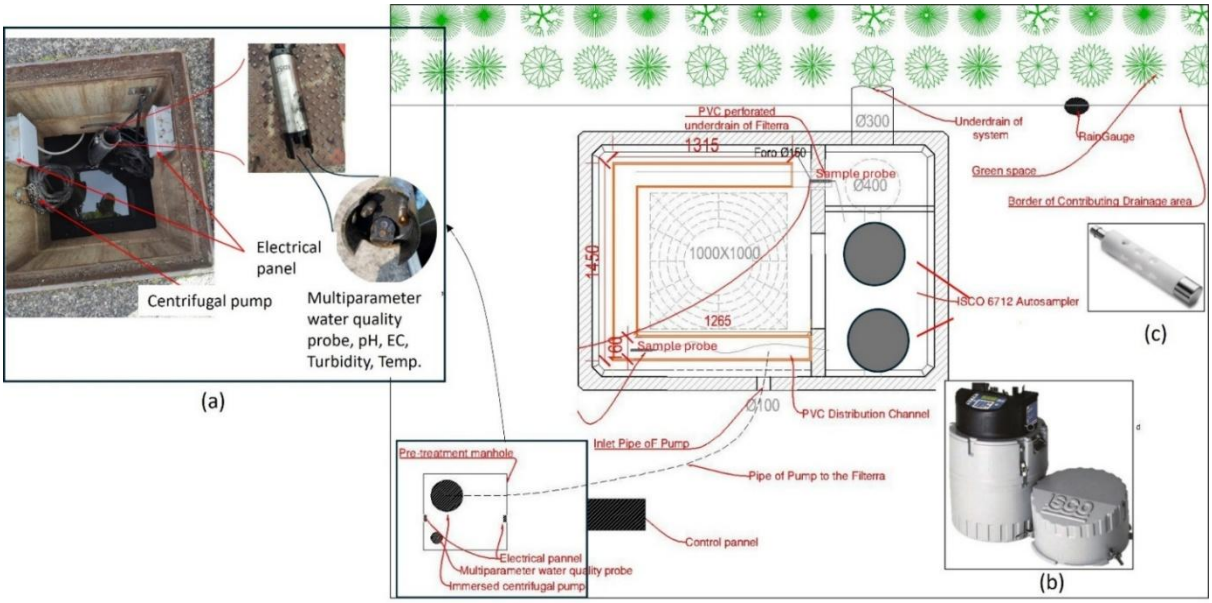

Figure 4. 9 Schematic of the monitoring setup to be installed at the Filterra at Ecocentro Marco: (a) detail of the inspection well at the pre-treatment storage tank with features of the multiparameter probe; (b) Teledyne Isco 6712 autosampler (c) and its sampling unit.

removal of the filter system, which reduces space constraints. Continuous monitoring is further enhanced by a multiparameter probe installed in the pre-treatment storage tank, which provides real-time measurements of water quality parameters entered from the drainage area. A rain gauge is also installed on site to record precipitation.

The integration of the SCADA system through remote access is currently undergoing testing to enhance the efficiency of data collection and control processes. To guarantee consistent and dependable operation, the instrumentation is powered either by integrating with the power network of the SCADA system or by employing an independent battery system.

4.5.3 Monitoring campaign and data analysis

The monitoring sampling is planned to capture data from significant storm events while correlating hydraulic measurements with chemical analyses. Considering that the inflow to the Filter is constantly conveyed by the pump, sampling will be performed based on time-based approach to guarantee the consistency of data collection. Ultimately, laboratory analyses will primarily focus on TSS as a key indicator of pollutant load, with additional chemical parameters.

4.6 Conclusion

The lack of a clear understanding of the hydraulic behaviour of compact BRCs, such as Filterra, and the need of field-validated model that can effectively predict the hydrologic and pollutant removal performance of Filterra continues to be a barrier to their wider deployment at the city scale. The purpose of this study was to overcome this gap by defining the hydraulic characteristics of Filterra's EM through laboratory testing as well as implementing a calibrated and validated SWMM model based on a comprehensive quality and quantity dataset to assess the Filterra system's hydrologic performance and TSS removal performance. The Key findings can be listed 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 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 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 of the SWMM.
- TSS modelling shows a suitable prediction of outflow concentration across multiple storm events; however, 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 can potentially be used to reproduce the hydrologic and TSS removal capabilities of compact BRCs. However, it remains difficult to completely describe the complex interactions that govern infiltration, drainage, and oversimplification of the mechanism of pollutant treatment in Filterra. Future research needs to include high temporal resolution monitoring program to accurately capture the dynamic behaviour of TSS transport and removal, instead of depending on composite sampling. This method would yield a clearer comprehension of pollutant dynamics across different hydrologic conditions thus providing suggestion for the improvement of the water-quality code in the LID module in SWMM. Furthermore, assessing Filterra's performance under varying rainfall patterns, land uses, and pollutant loading

scenarios is essential for evaluating its adaptability and long-term efficacy in urban stormwater management.

A monitoring setting at the Venice site (Ecocentro Marcon) was also designed and installed as part of this research chapter to collect hydrologic and load reduction data. Although an extensive analysis of this site is still ongoing due to installation and data collecting constraints, its inclusion in the research can improves the overall experimental framework. It establishes a basis for future comparisons across various Filterra installations in urban areas and enables the possible use of the calibrated and validated Vaughan model to the Venice system.

Chapter 5

Conclusions and recommendations for future work

This chapter presents the concluding remarks of the Ph.D. dissertation along with recommendations for future work.

This dissertation has systematically evaluated the hydrologic, hydraulic, and load reduction effectiveness —specially in terms of total suspended solids (TSS)— of bioretention cells (BRCs) as a sustainable urban stormwater management approach. This study aimed to address some of the knowledge gaps through a systematic literature review, numerical modelling, laboratory experiments, and field observations. These efforts focused on improving the design, implementation, and predictive modelling of BRCs to contribute addressing the challenges posed by urbanization, climate change, and the limitations of conventional drainage infrastructure. The present dissertation was organized into three research chapters to address the research gaps defined in section 1.2:

1. A systematic review to evaluate the variability in BRC effectiveness across different BRC design configuration and site-specific conditions in terms of hydrologic and pollutant removal.
2. A modelling-based framework to assess the improved configuration of BRCs in terms of location and footprint at the urban residential setting using SWMM and a multi-criteria decision-making (MCDM) approach considering hydrologic, hydraulic, and economic factors.
3. Establish an applicable SWMM model to the similar urban settings for a compact BRC (Filterra®) focusing on hydrologic-hydraulic performance and TSS removal efficiency through laboratory experiments, field observation, model calibration, and validation.

5.1 Conclusions

The systematic review (Chapter 2), which examined 114 field, laboratory, and modelling studies on BRCs, illustrated that BRCs are one of the most effective low-impact development (LID) approaches that can contribute managing urban stormwater. It showed the ability of BRCs to reduce runoff volumes, peak flow and improve constituent load reduction. Nevertheless, the review also highlighted

a noticeable degree of variability in the effectiveness of BRC across various studies. This variability was primarily influenced by site-specific and design configuration factors, including local climatic conditions, media composition, internal water storage (IWS) design, media depth, and contributing drainage area ratios (Area $_{BRC}$/CDA). Although elevated removal rates for TSS were consistently documented, the efficiencies of nutrient removal, especially for nitrogen and phosphorus compounds, exhibited considerable variability based on design configurations and operational circumstances. Key findings highlighted the significance of design considerations, for example, the optimal setup of an IWS (which is typically positioned no closer than 30 cm to the media surface and no lower than 30 cm above the cell bottom, with adjustments based on soil type) was determined to balance enhanced water retention with plant health. Additionally, deeper media layers promoted exfiltration, but they necessitated careful consideration of excavation costs and groundwater interactions (minimal distance between the BRC bottom and the groundwater table 30 to 60 cm). The composition of the media was identified as a critical factor, with optimal mixtures typically comprising 40–60% silty loam, 30–50% sand, and 10–30% organic matter. The addition of specific amendments, such as carbon sources, was observed to improve pollution load reduction, especially for nutrients. The problem of clogging, which is the aspect that limits the long-term functioning of BRC, needs to be properly considered. Media clogging can be reduced with the implementation of suitable amendments, periodic maintenance, and changing the media (every 5 to 10 yeas). Additionally, choosing vegetation proved to be an essential factor, contributing not only to esthetic appeal but also to the improvement of pollution removal and the preservation of infiltration capacity. The recommendation was to utilize native, resilient plant species with strong root systems to enhance the hydrologic and constituent load reduction of BRCs. Finally, the systematic review emphasized the necessity of integrating calibrated and validated numerical modelling tools, such as SWMM, into the BRC design and installation process. Modelling enables the predicting of hydrologic and load reduction performance under various scenarios, including variations in precipitation, impervious surfaces, and inflow pollution loads. These tools can help to improve BRC design and placement, enhance overall system efficiency, and contribute to the widespread adoption of BRCs.

Following the systematic review, the second research chapter (Chapter 3) developed a modelling-based framework designed to improve the spatial placement and footprint of BRCs within urban residential settings. This framework used SWMM with a MCDM approach, specifically the Analytic Hierarchy Process (AHP), to assess hydrologic, hydraulic, and economic factors across 384 distinct modelling scenarios. The scenarios included variations in precipitation regimes, return periods, imperviousness degree, BRC placement, and BRC footprints.

The simulation results indicated that BRCs achieved average VR and PR values between 0.16 to 0.32 and 0.15 to 0.35, respectively, indicating that BRCs effectively improved urban runoff control. Configurations with higher decreases in effective impervious areas (i.e., larger footprint) generally provided better results but with higher economic factor. It is important to note that the effectiveness of smaller BRC footprints (e.g., 5% of CDA) decreased significantly, particularly during higher-intensity rainfall events. Furthermore, oversized footprints did not provide a proportional performance benefit in comparison to their increased costs. AHP analysis demonstrated that a 15% footprint was preferred configuration for high precipitation regimes, while a 10% footprint was preferable under lower precipitation conditions, thereby balancing economic viability with hydrologic effectiveness. Furthermore, the proposed framework underlined that the footprint and distribution of BRCs are critical to improve their advantages, particularly in terms of lowering stress on urban drainage networks and lowering flood risk.

The third research chapter (Chapter 4) focused on addressing the specific challenges related to compact BRCs, particularly in densely urbanized settings where space constraints prevent the implementation of conventional BRCs with large surface areas (5 to 20% of CDA). Despite the potential of compact BRCs, these systems like the Filterra system have not been adequately investigated in the literature, and the limited understanding of their hydraulic behaviour, hydrologic performance, and pollutant removal capabilities has hindered their wider and improved implementation. Moreover, an applicable modelling framework that can simulate their behaviour are still limited. A combination of laboratory testing, field monitoring, and numerical modelling was conducted to address these knowledge gaps. Laboratory experiments were conducted to define the hydraulic properties of the engineered media (EM) of Filterra such as water retention properties and saturated hydraulic conductivity (K_{sat}). The

results showed a high K_{sat} of 1750 mm/h, total porosity of 0.42, and a field capacity of 0.12 at pF 2.5, highlighting the media's capacity to facilitate quick infiltration while retaining essential moisture for biological processes. The results from the laboratory experiments were incorporated into the SWMM model, which was subsequently calibrated and validated using event-based observation of inflow and outflow of Filterra. The model demonstrated acceptable accuracy, indicated by a Kling-Gupta Efficiency (KGE) exceeding 0.37 and a coefficient of determination (R^2) greater than 0.47, effectively representing essential hydrologic processes including runoff volume reduction, peak flow attenuation, and time-to-peak response. However, several limitations were noted, notably the tendency to underestimate outflow volumes because of assumptions about initial soil saturation rates and simplifications in SWMM's infiltration procedures. Additionally, the TSS reduction performance modelling within the SWMM framework exhibited an acceptable accuracy in simulating outflow concentration values under rainfall events with intensities up to 60 mm/h and inflow TSS concentrations between 17 and 227 mg/L in urban catchments. While the model shows good agreement with observed data in this context, its applicability beyond this range—particularly across varying catchment scales, BRC configurations, or pollutant loadings—requires further validation. However, the model's dependence on a constant removal rate does not adequately account for the dynamic variability in TSS removal processes across different hydrologic and loading conditions. This chapter of the dissertation has shown that a calibrated and validated SWMM model, based on laboratory characterization and field monitoring, can simulate the quantity and TSS reduction performance of compact BRCs. Additionally, it establishes a set of model parameters that are applicable to similar systems and urban environments. The study underscores the necessity for high-resolution, event-based load reduction data and additional pollutant removal modelling approaches to improve the predictive accuracy and operational reliability of compact BRCs in urban stormwater management strategies.

5.2 Recommendations for future work and research limitations

This dissertation has contributed to the comprehension, improved design, and modelling of BRCs in urban stormwater management; nevertheless, certain limitations were encountered, which provide opportunities for further research to expand upon the results of this dissertation.

Firstly, while the review study underscored critical design elements affecting BRC hydrologic and pollutant removal effectiveness, the literature's variability in methodologies, monitoring durations, rainfall characteristics, and site conditions presented obstacles to achieving a completely standardized comparison and understanding the consistency of BRCs' effectiveness. Furthermore, the systematic review was limited by incomplete datasets, inconsistency in data reporting, limited temporal coverage, and an inadequate assessment of the long-term longevity of the system. To address these limitations, future research can focus on the development of comprehensive, long-term field monitoring programs across different climates, urban settings, and diverse land uses. These studies need to attempt to assess the cumulative performance of BRC networks over long-term durations, considering variations in the seasons, media aging, clogging, and vegetation dynamics. Incorporating these comprehensive datasets into meta-analyses may allow the decrease of performance variability, and establish standardized benchmarks, thereby advancing BRC applications across various urban settings.

Secondly, the modelling-based framework that was developed to evaluate the improved BRC footprint and positioning at the urban residential setting was effective; however, it was implemented within a simplified, nonspecific urban catchment with a 2-ha area. This approach allowed for controlled scenario analysis and provided valuable insights into BRC footprint optimization, but it does not fully capture the complexities and heterogeneities of real-world urban drainage systems, such as varying land uses and interconnected drainage infrastructure. To address this limitation, future research should be broadened to include larger, more complex urban drainage networks, incorporating BRCs combined with other green and grey infrastructure components. Moreover, the current framework focused on hydrologic, hydraulic, and economic criteria; however, a more thorough assessment of BRC implementation strategies could be achieved by integrating co-benefits such as urban heat island mitigation, biodiversity enhancement, and load reduction improvement into the decision-making matrix.

Thirdly, while the SWMM model established for the Filterra effectively captured key hydrologic processes and load reduction rate, there are still certain limitations in fully modelling the intricate internal dynamics of infiltration and pollutant transport. Specifically, the use of constant pollutant removal rates oversimplifies the variability inherent in sediment

and pollutant behaviour under different hydrologic conditions. Additionally, the infiltration process of SWMM does not adequately account for variable antecedent soil moisture conditions, preferential flow paths, or dynamic influent characteristics. To address these limitations, future research should focus on improving SWMM's pollution removal modules, notably by including dynamic, event-based removal efficiencies that reflect changing influent characteristics and operational situations. The capabilities of SWMM can be enhanced by integrating machine learning algorithms. Furthermore, the monitoring program established at the Ecocentro Marcon site in Venice had initial operational obstacles that constrained the accessible data. Future research can emphasize continuous, high temporal resolution monitoring programs to capture pollution transport patterns across different rainfall intensities. The incorporation of real-time monitoring technologies, such as Internet of Things (IoT) sensors and remote data transmission systems, might improve data collecting efficiency and operational oversight. Moreover, future studies need to focus on a comparative assessment of the Filterra system's load reduction effectiveness in the Venice and Vaughan sites. Applying the calibrated SWMM model established for the Vaughan installation in the Venice setting might offer important insights into the model's applicability and the system's adaptability across similar urban areas. Finally, as climate change continues to change rainfall patterns, intensities, and frequencies, it is essential to assess the capacity of BRCs under anticipated climate scenarios. Studies that model scenarios to evaluate BRC performance regarding future climate projections can provide important insights into their long-term functionality and guide the development of robust urban stormwater infrastructure.

This dissertation has contributed to enhancing the knowledge and practical use of BRCs in managing urban stormwater. By employing an integrated approach that combines review, modelling, and experimentation, it provides perspectives for improving the design and implementation of BRCs and supports future development of urban drainage systems.

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