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Operational challenges and future directions

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A comprehensive review on the long-term performance of stormwater biofiltration systems (SBS): Operational challenges and future directions

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ABSTRACT

Stormwater biofiltration systems (SBS) are a popular technology for mitigating the negative effects of urbanization on the hydrological processes and water quality in urban areas. However, little is known about SBS's long-term performance in actual field conditions. The findings of a review of the scientific literature on the long-term performance of SBS are presented in this paper. The findings show that only a few studies have investigated the performance of SBS and its change over time, and that the results of laboratory and field experiments differed due to the presence of plants, regular maintenance, and some uncertain environmental factors. Based on the existing knowledge gaps in this field, the main challenges observed was the lack of long-term field data series, and the existing mathematical models are not able to accurately forecast the long-term performance of SBS. This could be owing to the difficulties in monitoring activities, the high costs involved and the unpredictability around the operational timeframe. Future study should concentrate on the implementation of simulation and modeling-based research in pilot and full-scale SBS, and the inclusion of new performance indicators should be considered as a priority.

1. Introduction

Rapid urbanization has resulted in a continuous increase in the urban population, a vigorous expansion of urban land use, a significant increase in impervious areas, a serious deterioration of the living environment, and a slew of urban problems (Liang et al., 2019; Wu and Chen, 2013). The expansion of the urban impervious and hardened underlying surface has accelerated the hydrological cycle, resulting in increased flood frequency and intensity. The pollutants carried by urban roads (tire wear, pedestrian shoe sole friction, dust in the air, industrial and construction waste, etc, among others (He, 2011; Li and Zuo, 2013; Zuo et al., 2011a,b) are discharged into rivers and/or directly infiltrated into the soil during periods of rainfall. Not only is the water quality of rivers and lakes affected, but the quality of groundwater has also shown to deteriorate (Hansen et al., 2016). As a result, reducing urban rainwater runoff and removing pollutants from runoffs are critical challenges in urban water management as well as in the field of municipal and environmental sciences (Chen et al., 2013).

Faced with severe problems of waterlogging, pollution, and a lack of groundwater recharge caused by urbanization, innovative urban stormwater management approaches, e.g. the sustainable urban drainage systems (SUDS) in the United Kingdom and low impact development (LID) in the United States, have been developed and implemented to address these multiple objectives in the design and decision-making stages. Many research and pilot projects have been conducted around the world in recent years to test and/or demonstrate rain gardens in residential and commercial areas, green roofs in high-density urban areas (Besir and Cuce, 2018; Cascone et al., 2018; Shafique et al., 2018), bio-swales or bioretention cells along the urban roads for the collection and purification of urban runoffs (Besir and Cuce, 2018; Cascone et al., 2018; Shrestha et al., 2018; Yang et al., 2019, 2020). These facilities/infrastructures are inexpensive and offer numerous advantages (Kousky et al., 2013; Yu et al., 2018). While grey infrastructure is intended to transport urban stormwater runoff away from impermeable areas, green infrastructure reduces and treats stormwater runoff before it is delivered to the surface and ground water, which has significant social and economic benefits (Alves et al., 2019; Derkzen et al., 2017; Xu et al., 2019).

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In recent years, SBS implementation has been widely spread throughout the world, and much research and extensive field work has been conducted to study the performance of SBS, including both the hydraulic (Kluge et al., 2018; Le Coustumer et al., 2009; Li and Davis, 2008) and pollutants removal performance (Al-Ameri et al., 2018; Mullane et al., 2015; Youngblood et al., 2017). However, from a practical perspective, there are some limitations to these technologies, as well as a need to better understand their long-term performance. First and foremost, there is an inherent disparity between laboratory and field experiment results (Lopez-Ponnada et al., 2020). It is widely acknowledged that it is not completely possible to replicate field conditions in the laboratory, such as temperature fluctuations, plant growth, animal and human activities (Lopez-Ponnada et al., 2020). For example, the accelerated aging tests designed to mimic natural weathering processes in the laboratory ignores the effects of vegetation growth (Hatt et al., 2011; Thomas et al., 2015). Furthermore, field data are limited, particularly those pertaining to the long-term behavior by considering the inflow and outflow volume/pollutant concentrations, pollutant concentrations in the soil, vegetation growth and maintenance activities. Field data are important in understanding how SBS systems work under natural conditions; however, monitoring at the field scale is more difficult than it is done in controlled laboratory conditions (Liu et al., 2017). Because of the complexity of the systems operational process and the lack of long-term field data (Goh et al., 2019; Skorobogatov et al., 2020), it is difficult to predict/model the long-term behavior (Liu et al., 2017, 2018), Therefore, most of the existing models have used limited data to establish the relationship between the environmental indicators, parameters of interest and predicted the performance of SBS.

The specific objectives of this review can be stated as follows: (i) to review the existing literatures and summarize the results and limitations of laboratory and field-scale SBS experiments; (ii) to determine the current limitations of predicting/modeling the long-term performance of SBS; (iii) to identify the challenges/limitations and provide future research directions in order to maintain long-term (high) performance of SBS.

2. Research on long-term performance of SBS

2.1. Hydraulic performance

Hydraulic conductivity is an important indicator of a SBS systems hydraulic performance. Table 1 shows the key results achieved in previous studies concerning the long-term hydraulic conductivity of SBS. A field study in Australia focused on the hydraulic conductivity of 37 biofilter systems, after 0.5–3 years of operation, and the results revealed that only 43% were within the recommended range of 50–200 mm/h. Some with high initial hydraulic conductivity (>200 mm/h) showed a significant reduction; however, most of them maintained an acceptable value, whereas others with low initial hydraulic conductivity (20 mm/h) did not change significantly over time (Le Coustumer et al., 2009). Another study with two stormwater filtration systems reported that the hydraulic conductivity decreased significantly over 5–7 years of operation, but remained within the acceptable limits (212.4–504 mm/h) (Haile et al., 2016). A 7-year-old bioretention system in Blacksburg (USA) also performed well in terms of runoff infiltration (Willard et al., 2017). According to a study from Germany, the hydraulic conductivity of most bioretention systems still met technical guidelines after 11–22 years of operation (Kluge et al., 2018). Paus et al. (2014) investigated the long-term performance of the infiltration function of bioretention cells and reported that the infiltration capacity of bioretention cells did not change noticeably for more than six years, which could be attributed to routine maintenance and large variability in efficiency between storm events. However, different types of SBS and external conditions may result in different hydrologic performance over time. For example, a 9 and 14-year-old grassed swale were completely clogged when there was no maintenance (Al-Rubaei et al., 2015). Long-term lab experiments using SBS has also been reported to simulate real conditions. During 20 years equivalent lab-based runoff loading test of a bioretention column (initial value of 81 mm/h), a significant decrease (>90%) of hydraulic conductivity was observed during the first 4 years (Khan et al., 2012) and the authors concluded that the results were different from the actual field tests.

2.2. Pollutant removal

2.2.1. Heavy metals

The suspended solids concentration has a significant impact on the hydraulic conductivity of the SBS system, and particle binding causes the heavy metals to accumulate in the soil over the operational time. Many lab experiments, as well as accelerated tests, have investigated the mechanism of heavy metal removal. Li and Davis (2008) proposed a three-layer theory to describe particulate capture in the bioretention system filter media, and according to the modeling results of their work, field inspection should be performed once or twice per year, media maintenance should be performed every 5 years, and a 5–20 cm top media replacement should be performed in order to maintain the high performance of the system.

Heavy metal concentrations above a certain range (Pb 500 mg/kg, Cu 2000 mg/kg, Zn 14,000 mg/kg, cd 40 mg/kg) are harmful to humans, and the SBS has proven to perform well in containing and retaining them within the system (Hatt et al., 2011). However, according to the results from the lab accelerated loading test, Cd, Cu, and Zn had accumulated in

Table 1
Literature reports on the long-term hydraulic conductivity of SBS.

Reference	SBS type	Scale	Operation time	No. of studies	Hydraulic conductivity
Le Coustumer et al. (2009)	Biofilter systems	Field. less than 40 m^2	0.5–3 years	37	Recommended initial hydraulic conductivity: 50–200 mm/h; after operation: approx. 17–40%
Khan et al. (2012)	Bioretention	Field (32 m^2) and laboratory (0.25 m^2)	An equivalent 20 years of loading test	One field and 4 columns	Cold condition performance: Saturated hydraulic conductivity decreased over the first 4 equivalent years
Paus et al. (2014)	Bioretention	Field (28–93 m^2)	2–8 years	6	Results showed that there is a strong positive correlation of saturated hydraulic conductivity (K_{sat}) with service time: slope $= 10.2 \pm 2.4$ cm/h per year, $R^2 = 0.6$
Al-Rubaei et al. (2015)	Concrete pavement and grassed swales	Field (pavement: 600 × 400 × 100 mm, swales: 1.5 m and 3)	1–14 years	12	All 12 infiltration systems showed a reduction in hydraulic conductivity
Willard et al. (2017)	Bioretention	Field (4.6 × 7.6 × 1.8 m)	7 years	1	Bioretention cell performed well and reduced the storm flow after 7 years
Haile et al. (2016)	Stormwater filtration system	Field (40.5 and 65.5 m^2)	5–7 years	2	Whole layer: 3.5×10^{-6} m/s and 4.8×10^{-5} m/s; Filter media layer: 5.9×10^{-5} m/s and 1.4×10^{-4} m/s; Fresh filter media: 3.8×10^{-4} to 5.2×10^{-4} m/s
Kluge et al. (2018)	Bioretention	Field (10 cm top soil/20 cm sub soil)	11–22 years	22	Predominantly sandy systems: 9.2×10^{-4} to 5.6×10^{-7} m/s; Sandy loam/silty loam systems: 7.5×10^{-5} to 6.9×10^{-7} m/s

the filter media and their concentrations exceeded the human health level and/or ecological regulatory guidelines even after 12–15 years (equivalent) of operation (Hatt et al., 2011). However, in another study, the results from accelerated Cu and Zn loading test of a media filter drain showed that there was little or no decrease in sorption after the equivalent of 14–22 years of operation, achieving removals >90% for both Cu and Zn (Thomas et al., 2015). Bates (2014) reported no varying trends in metal reduction removal efficiency in a 13-year-old rain garden. According to Jones and Davis (2013), analysis of soil samples taken from a four-year-old bioretention system revealed that Cd, Cu, and Zn concentrations in the filter media had increased sharply but remained below the regulatory clean-up thresholds (Maryland residential cleanup: Pb 400 mg/kg, Cu 310 mg/kg, Zn 2300 mg/kg; EPA residential cleanup: Pb 400 mg/kg, Cu 3100 mg/kg, Zn 23,000 mg/kg). Table 2 summarizes some of the important results achieved for heavy metals and nutrients using SBS.

A field test of several bioretention cells (11–22 years old) in Germany yielded a similar result, revealing that most heavy metal was accumulated in the top 20 cm of the media and their concentrations decreased rapidly with a depth increase. Besides, after depths of 30 cm, it was also observed that most of the heavy metals were only slightly water soluble, allowing for a longer service life (Kluge et al., 2018). However, there was a hypothesis that heavy metals were not captured and/or removed by the soil during high-intensity rainfall events, and that only a small portion of heavy metals accumulated in the filter media after a long period of operation (10 years) (Lucke and Nichols, 2016). The drainage

Table 2
Literature reports on the removal of heavy metals and nutrients using SBS.

Reference	SBS type	Pollutants type	Scale	Operation time	No. of studies	Key results from the study
Hatt et al. (2011)	Bioretention	Heavy metals	Laboratory (0.15 m height, 0.025 m diameter)	12–15 equivalent years	6 columns	Breakthrough of Zn can occur, while the breakthrough of Cd, Cu, Pb will not occur during the service life
Jones and Davis (2013)	Bioretention	Heavy metals	Field (25 m^2 × 0.9 m)	4 years	1	Metal concentrations (Pb, Cu, and Zn) increased, but they never exceeded the regulatory thresholds
Bates (2014)	Rain garden	Heavy metals	Field (144 m^2 × 0.25 m)	13 years	1	The rain garden was effective at reducing heavy metals (copper, chromium, lead, cadmium, and zinc) in stormwater runoff
Thomas et al. (2015)	Media Filter Drains	Heavy metals	Field and laboratory (0.1 m height, 0.15/0.2 m diameter)	14–22 equivalent years	2 filed sites, 6 columns	14 to 22 equivalent years of copper and zinc loading test showed little or no decrease in sorption capacity
Wang et al. (2016)	Bioretention	Heavy metals	Laboratory (0.1 m height)	Not mentioned	4 columns	The migration rate of Cd was: sand < fine sand < quartz < zeolite; adsorption and accumulation of Cd are more significant than the migration
(Nichols and Lucke, 2016)	Bioretention	Heavy metals	Field (1.2 m depth)	10 years	5	Heavy metal accumulated mainly in the top 0–50 mm soil layers; the concentration was below the detectable limits
Kluge et al. (2018)	Bioretention	Heavy metals	Field	11–22 years	22	Vertically, heavy metals are usually accumulated in the top 0–20 mm soil layers, then their concentrations tend to decrease with increasing depth. Horizontally, heavy metal accumulation often occurred near the inlet section
Al-Ameri et al. (2018)	Bioretention	Heavy metals	Field (1.44–860 m^2)	9–16 years	78	Concentration of heavy metals in industrial areas were higher than residential areas, and concentration of Zn was higher than Cd, Cu and Pb
Uusi-Kämppä (2005)	Buffer zones	Nutrients	Field (70 m × 18 m)	10 years	6	In cold climates, loss of molybdate-reactive P from the natural vegetation buffers was high due to P leaching from the top soil and decaying grass residues during the spring season
Uusi-Kämppä and Jauhiainen (2010)	Buffer zones	Nutrients	Field (70 m × 18 m)	17 years	6	The capacity of buffer zones in retaining P during the summer and autumn months were better than during spring
Komlos and Traver (2012)	Rain garden	Nutrients	Field (144 m^2 × 0,25 m)	9 years	1	The system removed ortho-phosphate, and it was accumulated in the top 0–10 cm soil layer
Payne et al. (2014)	Stormwater Biofiltration System	Nutrients	Mesocosm (0.15 m diameter and 0.23/0.6 depth)	18 months	2	Assimilation was the primary fate for NO_3^- in biofilter columns which containing the most effective plant species, while denitrification was the major role in columns which have fewer effective species
Willard et al. (2017)	Bioretention	Nutrients	Field (4.6 m × 7.6 m × 1.8 m)	7 years	1	Denitrifying bacteria were mainly present in the top filter layers, while the submerged zone facilitated denitrification
Lucke et al. (2017)	Bioretention	Nutrients	Field	10 years	4	Bioretention system showed positive effect on TN and TP removal; only one test showed negative effect on TN removal
Lopez-Ponnada et al. (2020)	Bioretention	Nutrients	Field (1.22 m × 0.457 m × 0.97 m)	Not mentioned	2	First long-term field comparison of a conventional and modified (submerged zone with wood chips) bioretention system. The modified system showed better efficiency in removing nitrogen, and some field result was also different from lab-experiments
Zhang et al. (2011)	Bioretention	Microbial contamination	Laboratory (0.025 m diameter, 0.23 m height)	18 months	5 columns	The initial removal efficiency of a conventional bioretention system for *E. coli* was 72%, and thereafter it was >97% after six months of operation. The growth of indigenous protozoa enhanced the removal efficiency
Shen et al. (2020)	Stormwater biofilters	Microbial contamination	Laboratory	Not mentioned	2	Two Real Time Control (RTC) strategies for storm water harvesting and reuse of stormwater was demonstrated using biofilters

area's land use type was an important factor that affected heavy metal concentrations in soil and their mobility; Bioretention systems in industrial areas had elevated heavy metal concentrations that would exceed the threshold for both soil quality and ecological guidelines, whereas SBS in residential areas are unlikely to exceed the soil quality threshold for human health (Al-Ameri et al., 2018).

It is noteworthy to mention that, the migration rate of heavy metals varies depending on the type of filter media used, and sand has been shown to perform well in the capture/removal of heavy metals (Wang et al., 2016). However, when clogging occur as a result of the accumulation of heavy metals and suspended solids, the removal of soluble heavy metals decreased because there was more time for metal desorption as well as the breakdown of the accumulated sediments (Zhang et al., 2018b). This clearly explain why, even after a long-term operation, heavy metal concentrations were not high because more heavy metals flowed and dissipated through the system into the surface/groundwater.

2.2.2. Nutrients

Nitrogen and phosphorus are the two most abundant nutrients in stormwater runoff, and SBS has proven to be highly effective at removing them (Goh et al., 2019; Osman et al., 2019). Nitrogen was thought to be temporarily stored by plants or microorganisms, or transformed into N_2 gas by bacteria, and then permanently removed through the process of denitrification in the SBS (Payne et al., 2014). Phosphorus is removed by plants and microbial uptake or absorbed by the filter media (Marvin et al., 2020). Many studies focused on the efficacy and the mechanism involved in nitrogen (Jiang et al., 2017; Tian et al., 2019; Wu et al., 2017) and phosphorus (Chang et al., 2019; Zhang et al., 2018a) removal, but few studies have examined the long-term performance in SBS (Table 2). Previous research suggested that SBS could reduce nutrients after a long-term operation. In Blacksburg (USA), a 7-year-old bioretention cell performed well in reducing nitrogen and phosphorus (TN from 0.27 to 4.07 to 0.29–1.30 mg/L; TP from 0.01 to 0.38 to 0.02–0.32 mg/L), and this study also emphasizes that most biochemical processes, such as denitrification, occurred at the top 30 cm of the filter media (Willard et al., 2017).

In some situations, the pollution removal performance of bioretention systems could also be attributed to the mere transfer of pollutant from one phase to other (e.g. by adsorption). Komlos and Traver (2012) studied the long-term orthophosphate reduction efficacy in a 9-year-old rain garden, and the results showed no residual P in the treated water. Lopez-Ponnada et al. (2020) constructed a conventional and a modified bioretention system to assess the N removal performance. The results from their study showed that both the systems were efficient at removing NH_4^+ (83% modified, 74% conventional), but the removal pattern of NOx (NO_2^--N and NO_3^--N) was different (81% modified, 29% conventional). Besides, it was also reported that the antecedent dry conditions (0–13 days) had no discernible effect on the DOC or TN removal and the efficacy varies depending on the season. For example, Uusi-Kämppä (2005) conducted a study to investigate agricultural phosphorus reduction by buffer zones that was operated for 10 years in Finland. The results showed that the performance in summer and autumn was better than in spring, which could be attributed to vegetation growth. The vegetation buffers reduced the annual total phosphorus loss by 40% compared to no buffers. Another study of a 17-year-old buffer zone conducted by Uusi-Kämppä and Jauhiainen (2010) found that the retention capacity of phosphorus was reduced in spring, and the reason was the high phosphorus content present in the surface soil due to frozen plant matters tissue destruction.

2.2.3. Fecal indicator bacteria (FIB)

Microbial pathogen contamination of groundwater (including drinking water supply) is still a global concern (Theron and Cloete, 2002). Animal feces and wastewater may contain pathogenic microorganisms such as *E. coli*, which are released into the environment during the transmission process (Brennan et al., 2010). Furthermore, fecal indicator bacteria are widely used as a sanitary index/criterion for ascertaining the water quality (Cao et al., 2011). Many studies have been conducted to investigate the efficacy of fecal indicator bacteria (FIB) removal using SBS (Kranner et al., 2019; Mei et al., 2020; Peng et al., 2016; Rahman et al., 2020). Zhang et al. (2011) conducted a bioretention column test to evaluate the long-term removal efficiency of removing *E. Coli*. During the 18-month loading test, the removal efficiency was 72% initially and then it increased to >97% after six months of operation.

In a recent study, Shen et al. (2020) developed two Real Time Control (RTC) strategies to evaluate the removal efficiency of *E. Coli* for different requirements; one of which was to keep the water in the biofilter for at least two days, and the other was to drain and collect the water in the submerged zone for at least two days. The first strategy resulted in a 62.3% reduction and 28.4% treated water, whereas the second strategy resulted in only 5.4% treated water.

2.2.4. Influence of Cl^- accumulation

Since the early 1900s, sodium chloride has been widely used as a deicing agent (Kelly, 2008). The Cl^- produced by deicing is highly soluble, difficult to degrade (Ramakrishna and Viraraghavan, 2005), and it easily leaches from the bioretention systems (Søberg et al., 2014). Besides, the Cl^- could also be accumulated in the bioretention systems during the winter season and released to the surface water with runoff during other seasons (Géhéniau et al., 2015).

Casey et al. (2013) conducted a study to investigate the spatial and temporal distribution of chloride and conductivity, and the findings revealed that the conductivities were high in surface and ground waters in long hydroperiod retention (45 mS cm^{-1}) and one short hydroperiod detention ponds (25 mS cm^{-1}), respectively. The peak conductivities of another short hydroperiod detention ponds was around 4.5 mS cm^{-1}. During the summer months, the conductivity of pond ground water usually remains high. Previous research has shown that winter road maintenance salts have a significant impact on the removal of water contaminants in bioretention cells (Kratky et al., 2017). For example, it can reduce the ability of vegetation to uptake the heavy metals (Szota et al., 2015) and according to the results of another study, the removal efficiency of nitrogen and phosphorus was enhanced under the influence of 15 years of long-term saline runoff (Denich et al., 2013). The long-term performance of metal accumulation under salt application necessitates further research in this field.

2.3. Influence of vegetation

The SBS's hydrologic and pollutant removal performance are both influenced by vegetation (Skorobogatov et al., 2020). On the one hand, vegetation can intercept rainfall, reduce stormwater runoff erosion, relieve soil medium clogging, maintain long-term infiltration capacity, and reduce total stormwater volume through transpiration. Vegetation, on the other hand, influences various pollutant removal processes, such as vegetation utilization and rhizosphere microbial transformation (Muerdter et al., 2018). Table 3 summarizes the key findings from previous literatures on SBS performance under the influence of vegetation.

2.3.1. Hydrologic function

In a bioretention cell and other SBS, media clogging is the primary limitation of its service life (Kandra et al., 2014). On the one hand, vegetation reduces the water flow rate and traps more solids in the soil medium (Hunt et al., 2012). The total suspended solids (TSS), on the other hand, enters the system continuously with stormwater runoff and clogs the media during long term operation. The macrospores and root channels formed in the soil media by vegetation roots can improve infiltration and prevent clogging. Furthermore, greater root coverage and a faster rate of vegetation growth will increase the soil media

Table 3
Literature reports on the SBS performance under the influence of vegetation.

Reference	SBS type	Impact type	Scale	Operation time	No. of studies	Vegetation species and key results
Hatt et al. (2009a)	Stormwater biofiltration systems	Hydraulic	Field (10 m × 1.5 m × 0.7 m)	2 years	3	Vegetation species: *Carex appressa, Carex tereticaulis, Lomandra longifolia, Isolepis nodosa, Caleocephalus lacteus*, and *Juncus* spp
Le Coustumer et al. (2012)	Bioretention	Hydraulic	Laboratory (0.375 m diameter and 0.9 m height	72 weeks	75 columns	Vegetation species: *Carex appressa, Dianella revoluta, Microleana stipoides, Leucophyta brownie* and *Melaleuca ericifolia*
Hart (2017)	Bioretention	Hydraulic	Field (12.4–26 m^2)	14 months	2	Different root characteristics increases the infiltration rate at different depths. Larger-root biomass are more effective in increasing the infiltration capacity
Gonzalez-Merchan et al. (2014)	Stormwater infiltration system	Hydraulic	Field (8000 m^2)	More than 30 years	1	Vegetation species: *Arundinacea, Polygonum mite, Rumex crispus*; Some species (*Phalaris arundinacea*) are more appropriate to avoid clogging
Muthanna et al. (2007)	Bioretention	Pollutant removal	Mesocosms (1.09 m × 0.882 m × 0.9 m)	Not mentioned	1	Vegetation species: *Lythrum salicaria, Iris pseuacorus, Vinca minor* and *Hippophaë rahmnoides*; Plant uptake of heavy metals: 2–7%
Bratieres et al. (2008)	Bioretention	Pollutant removal	Laboratory (0.375 m diameter, 0.3–0.7 m depth)	7 months	125 columns	*Carex appressa* and *Melaleuca ericifolia* enhanced nitrogen removal
Barrett et al. (2013)	Bioretention	Pollutant removal	Laboratory (0.2 m diameter and 0.61 m depth)	9 months	12 columns	Plant species: *Buchloe dactyloides* and *Muhlenbergia Lindheimeri*; Removal of TN: 59–79% and TP: 77–94%
Houdeshel et al. (2015)	Bioretention	Pollutant removal	Field (4.3 m × 2.4 m × 1.2 m	15 months	3	Vegetation species: Upland cell: *Schizachyrium scoparium, Bouteloua gracilis, Sorghastrum nutans, Amelanchier utahensis, Cercocarpus ledifolius, Cercocarpus montanus, Artemisia cana*; Wetland cell: *Juncus effuses, Dactylis glomerata, Typha* sp., *Phragmites* sp., *Salix exigua, Medicago sativa.* Wetland vegetation in the bioretention cell reduces the nutrients, but it requires supplementary irrigation; The regionally native upland vegetation captures less nutrient, but does not require additional irrigation
Rycewicz-Borecki et al. (2017)	Bioretention	Pollutant removal	Mesocosms (0.425 m × 0.324 m × 0.232 m)	9 months	1	*Phragmites australis, Carex praegracilis*, and *Carex microptera* uptake more TP and TN than *Typha latifolia, Scirpus validus*, and *Scirpus acutus*
Payne et al. (2018)	Stormwater biofilters	Pollutant removal	Laboratory (0.15 m high and 0.3 mm deep)	6 months	220 columns	Vegetation species: Velvetene, Palmetto Soft Leaf Buffalo, *Poa labillardieri, Poa sieberiana, Carex appressa, Gahnia sieberiana, Juncus pallidus, Dianella revolute, Dianella tasmanica, Allocasurina littoralis, Leptospermum continentale, Hakea laurina, Sporobolus virginicus, Austrodanthonia caespitosa, Poa poiformis, Cyperus gymnocaulis, Juncus kraussii, Gahnis trifida, Cares tereticaulis, Melaleuca incana, Astartea scoparia, Hypocalymma angustifolium*

infiltration over time (Muerdter et al., 2018). A field study conducted in Australia reported the link between plant growth and media infiltration, specifically demonstrating that root growth and senescence mitigated compaction and clogging (Hatt et al., 2009a,b). According to Le Coustumer et al. (2012), vegetation with thick roots performed well in maintaining the hydraulic conductivity of a bioretention system. Similarly, Hart (2017) also reported that, root morphology was beneficial for increasing the infiltration capacity of bioretention systems, and those with abundant root biomass increased the infiltration rate of the soil media.

According to Beven and Germann (2013), vegetation roots can produce macrospores in as little as two years, promoting soil media infiltration. Gonzalez-Merchan et al. (2014) conducted a field study in France and envisaged that the infiltration capacity of a stormwater infiltration system with actively growing vegetation was 2–4 times greater than that without vegetation. Although vegetation was shown to improve the clogging process and the service life of SBS, more in-depth research and data is still required to investigate the mechanism and quantify its influence on long-term SBS performance.

2.3.2. *Pollutant removal*

The service life of a SBS is also affected by the pollutants accumulated in the media. The presence of vegetation in SBS usually increases its N uptake capacity compared to unplanted conditions (Goh et al., 2017; Houdeshel et al., 2015). The N removal efficiency can also be influenced/affected by the plant age and type (Palmer et al., 2013). Muerdter et al. (2018) emphasized that the N removal may be higher in well-established bioretention sites, while in some research the N removal was reported to be low due to the lack of time for the vegetation to grow. The growth of plant root was considered to be an important reason for the increase of N removal, i.e. the vegetation with elaborate root networks are more conducive to N removal (Barrett et al., 2013; Bratieres et al., 2008). However, during long-term operation, due to the aging of vegetation, N can also be released, causing secondary pollution. Therefore, it has been recommended to include a practically feasible troubleshooting/maintenance strategy during the design of SBS in order to extend the longevity of its operation (Mullane et al., 2015).

The presence of vegetation can also slightly improve the P removal capacity of the bioretention system, because the system without plants already had a high P removal value (Bratieres et al., 2008), while plants mainly uptake the dissolved form of P from water environments (Rycewicz-Borecki et al., 2017). Besides, heavy metals are largely trapped in the media of SBS via the filtration and/or adsorption processes. Heavy metals such as Zn, Cu, Mn, Ni, among others can be directly absorbed by plants as micronutrients (Tangahu et al., 2011). This phenomenon clearly indicates that a fraction of the heavy metals can be permanently removed by vegetation harvesting (Table 3) (Muthanna et al., 2007). Therefore, the harvesting of vegetation in SBS during the withering period should also be considered during the maintenance step. This strategy will prevent the pollutants that had been absorbed by vegetation from being released into the system again, and prolong/extend the service life of SBS.

2.4. Model simulation

SBS is widely used to address urban water ecological problems; therefore, a comprehensive model that can assist city managers in deciding which type of SBS to use, scale-up, and evaluate its performance after implementation is required. Most of the existing models can achieve these goals and accurately predict the short-term hydraulic or water quality performance; however, there is lack of literature on models that can be used to predict/forecast the long-term performance of complex natural process such as SBS (Kaykhosravi et al., 2018).

2.4.1. Hydrologic model

For SBS design and performance prediction, the hydrologic model is widely used (Table 4). However, some of these models lack the ability to simulate the performance over the long-term operational time, and others lack long-term field monitoring data to calibrate the model (Brown et al., 2013). Brown et al. (2013) used DRAINMOD (Skaggs, 1978, 1982, 1985; Wayne Skaggs, 1999) to simulate the performance of four bioretention cells with varying initial conditions, and the modeling results demonstrated high reliability in predicting the bioretention cell's hydraulic performance over time. However, because the monitoring period was only for two years, it is possible that the infiltration capacity of bioretention cells did not change significantly. The Long-Term Hydrologic Impact Assessment Model (L-THIA LID) (Kaykhosravi et al., 2018) compares the difference in runoff volume, with and without low impact development (LID) facilities, before and after the development using the Curve Number (CN) method (Cronshey et al., 1985), but the model does not consider the efficiency change caused by LID. Liu et al. (2015) and Liu et al. (2015b) improved the L-THIA-LID model's capability to simulate the diversity of BMPs and LID practices, as well as the impacts of BMPs and LID practices implemented in series. The L-THIA-LID (2.0 and 2.1) model is widely used for assisting the decision-making process by determining the environmental impacts and identifying cost effective BMP/LID practice strategies/plans at the watershed scales; however, it cannot predict the life of BMP/LID practices or provide maintenance recommendations for long-term operation. Abualfaraj et al. (2018) quantified the long-term rainfall-runoff response of the Javits Convention Center (JJCC) green roof (USA). In that study, four years of rooftop monitoring data was collected and compared with the EPA-SWMM model simulation, and the model results showed a 20 + 10% increase in total runoff volume and a 15 + 25% increase in peak runoff rates compared to the baseline. However, the detailed analysis of these four years of monitoring data, as well as model optimization, were not considered in this study.

The age and maintenance requirements are important factors in determining the long-term SBS performance, and these factors are closely related to the physical clogging process. William et al. (2019) proposed a probability-based method, using EPA-SWMM, to estimate the frequency of maintenance based on the probability of failure when the rain garden retains 80% of the inflow (by volume), which would reduce the impact of clogging. That study also emphasizes the importance of inflow pretreatments in reducing clogging, and recommended that the reliability-based method (such as volume retention) is more holistic than saturated hydraulic conductivity in evaluating the hydrological performance of rainwater gardens. However, the role of plants and microorganisms was not considered in this method, which will prolong the clogging process during long term operations.

2.4.2. Water quality models

Previous studies on water quality models were mostly based on short-term data and they focused on heavy metal removal. When compared to a hydrologic model, it is more difficult to determine the pollutant removal process using a water quality model (Table 4), which

Table 4
Literature reports on modeling the long-term performance of SBS.

Reference	Model type	Model details	Key results
Brown et al. (2013)	DRAINMOD/ Hydrology	DRAINMOD, a widely-accepted agricultural drainage model, first developed in the 1970s at North Carolina State University, to simulate the hydraulic performance of a bioretention cell	Improvements: (1) Models the mechanism in the submerged zone and (2) accounts for the soil–water content
(Liu et al., 2015a; Liu et al., 2015b)	Long-Term Hydrologic Impact Assessment –LID (L-THIA LID)/ Hydrology and water quality Version 2.0 and 2.1	L-THIA LID, first developed in 2000 at Purdue University. The model simulates runoff and non-point source pollution combined with LID practices	Improvements: Diversity of the simulation, ability to estimate the runoff volume reduction, water quality, and simulating the impacts of BMPs and LID practices
Abualfaraj et al. (2018)	Environmental Protection Agency Stormwater Management Model (EPA-SWMM)/Hydrology and water quality	EPA-SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from urban areas	This study used EPA-SWMM to predict the total runoff volume and event peak runoff rates of a green roof. No model improvement was involved in this study
William et al. (2019)		EPA-SWMM (Same as above)	This study proposed a probabilistic method to determine the maintenance frequency which can reduce the impact of clogging in rain gardens
Kabir et al. (2017)	Heavy metal removal	This model describes the breakdown rate, accumulation, and leaching of heavy metals in stormwater biofilters	The leached concentrations of Cu and Pb was linearly correlated to the hydraulic conductivity, equilibrium and kinetic rate constants; Zn leaching concentration was correlated to these parameters by a power law equation
Zhang et al. (2018b)	Heavy metal Removal	This model was developed to predict the long-term removal of heavy metals by porous pavements by simulating the adsorption and desorption processes	The model demonstrated the highest accuracy in predicting the release of Al and Cu, followed by Fe and Pb; however, it was not capable of predicting the release of Zn and Mn
Shen et al. (2018)	Microbial removal	This model simulated the long-term microbial removal by stormwater biofilters, based on a 'three-bucket' approach, and the	The model's prediction was not sensitive to all parameters, presumably due to the lack of data rather than the

(continued on next page)

Table 4 (*continued*)

Reference	Model type	Model details	Key results
		one-dimensional advection-dispersion equation	uncertainty of the model structure
Liu et al. (2018)	Long-term effectiveness model (hydraulic and water quality)	The model framework consists of the establishment period efficiency, starting efficiency, efficiency for each storm event, efficiency between maintenance, and efficiency over the life cycle	This is the first study that quantifies the efficiency and the changing trend of LID practices during different stages of its life cycle

increases the difficulty in model calibration as well as its reliability for practical use. Kabir et al. (2017) proposed a mechanistic model that describes the breakdown rate, accumulation, and leaching of heavy metals in stormwater biofilters by integrating the dynamics of ecohydrology and metal geochemistry. However, the test data used in that study were from a 100-day experiment, and the influence of vegetation was not considered; this clearly fortifies the fact that additional data are required by considering all the possible (transient) variations in performance. Zhang et al. (2018b) developed a pollutant treatment model that simulates the adsorption and desorption processes to predict the long-term removal of heavy metals by porous pavements. The results show that the model has the highest accuracy in predicting the release of Al and Cu, followed by Fe and Pb, but not for Zn and Mn.

Shen et al. (2018) created a new model to simulate the long-term removal of microorganisms by stormwater biofilters, which is based on a "three-bucket" approach and it uses the one-dimensional advection-dispersion equation to represent microbial transport and fate under various design and operational conditions. The model was calibrated using data from 44 weeks of laboratory columns experiments. The results showed that model prediction efficiency was insufficient in terms of parameter sensitivity, which was largely due to a lack of data rather than the uncertainty of the model structure. Hence, in order to assess SBS's long-term effectiveness and it change over time, Liu et al. (2018) created a high-level and forward-thinking long-term impacts modeling framework, by including the establishment period efficiency, starting efficiency, efficiency for each storm event, efficiency between maintenance periods, and efficiency over the entire life cycle. For model framework validation, the total phosphorus removal data from a grass buffer and bioretention system were used, and it was shown that the model results fitted reasonably well with the experimental data. According to the authors, this modeling framework explains five processes in the SBS's life cycle, as well as possible trends of efficiency changes at various stages, and provides a good starting point for future research.

3. Current challenges and future research directions

3.1. Current challenges

SBS systems should be better managed and the design engineers should have a clear understanding of its long-term performance in order to maximize benefits, manage risk, and provide satisfactory levels of service to the public. To better assess the long-term SBS performance, the underlying complex hydrologic and pollutant removal processes, particularly the effects of aging, vegetation, seasonal changes, land-use pattern, etc, among others must be understood. However, these processes are difficult to replicate in the laboratory and in field scale experiments, such as lysimeters, which are time consuming and will take years to produce useful data. To investigate the performance of SBS systems, lab and field experiments have been carried out by researchers from many countries, but there is a knowledge gap between the two, which resulted in model simulation/prediction results that were uncertain (data-based). In almost all the cases, the monitoring system was not integrated with the SBS systems while the project was being built. Besides, by considering the frequency and period of monitoring the SBS performance, it is difficult to point out the most important or reliable parameter for accessing the system performance.

3.1.1. Data collection

SBS has been used in some developed countries for more than 20 years, but long-term monitoring data is still scarce. Meanwhile, due to individual differences in the design, type of construction, purpose of the SBS and the monitorable physico-chemical and biological parameters, there are many different types of data storage modes. For example, the stormwater runoff, outflow volume, pollutant loads, installation details, vegetation conditions, rainfall event characteristics, and maintenance activities are examples of basic parameters. This necessitates the development of a comprehensive data monitoring and collection strategy, as well as the establishment of a standardized SBS database. First, the design and installation details of the SBS should be mentioned, followed by the site-specific conditions (e.g. soil, land use type, vegetation, and climate). Second, for long-term hydrologic monitoring, continuous rainfall, temperature, SBS inlet water volume/level, outlet water volume/level, overflow volume/level, and surface water level data are required, and all of these data should be time-coupled. Besides, the inlet and outlet water samples during every rainfall event should be tested for different pollutants e.g. heavy metals and nutrients (N, P, K), DOC). The soil samples must also be tested to determine whether the concentration of heavy metals exceeds the target value. Third, the majority of SBS are vegetated, and vegetation plays an important role in the long-term performance of SBS; hence, the SBS operational strategy should also include a period maintenance phase (e.g. after the winter season). Maintenance can improve SBS performance (vegetation, harvesting, surface garbage cleaning, plumbing); therefore, the frequency of maintenance and the exact time must be recorded. Finally, the length of the monitoring period may be a significant challenge in collecting long-term data; this necessitates additional research on the long-term performance of SBS, updating monitoring methods, reducing costs, and optimizing models.

3.1.2. Monitoring

Monitoring is critical in managing SBS systems, and the following factors should be considered before developing a monitoring strategy: (i) connecting outcomes (key performance indicators) to actions (investment, policy, and operations); (ii) risk assessment (environmental, economic, social, and political); (iii) monitoring the service quality in response to investment decisions; (iv) capturing externalities (e.g. carbon footprint); (v) understanding total life costs; and (vi) implementing best operational and management practices (e.g. ISO 55000) (Fig. 1). It is noteworthy to mention that, monitoring a full-scale project is far more difficult than those monitored under lab-scale conditions. Considering the need to develop a feasible long-term monitoring strategy, automatic sampling may be the only option and the monitoring system could be integrated with models that would require real-time data.

The following are some of the current challenges confronting SBSs (Fig. 1): (i) The goal of SBS system management is to maximize benefits, manage risk, and provide satisfactory levels of service to the public in a sustainable manner by building, operating, maintaining, renewing, replacing, and disposing of systems; (ii) Lab experiments were mostly reported in previous research, and they were generally short-term studies in which accelerated loading tests were frequently used to simulate long-term processes under controllable environmental conditions; (iii) Field experiments, primarily long-term studies, were less reported, but the results were mixed due to uncontrollable environmental conditions; (iv) In current full-scale applications, there may not be (enough) space to install the monitoring device, the parameters to be

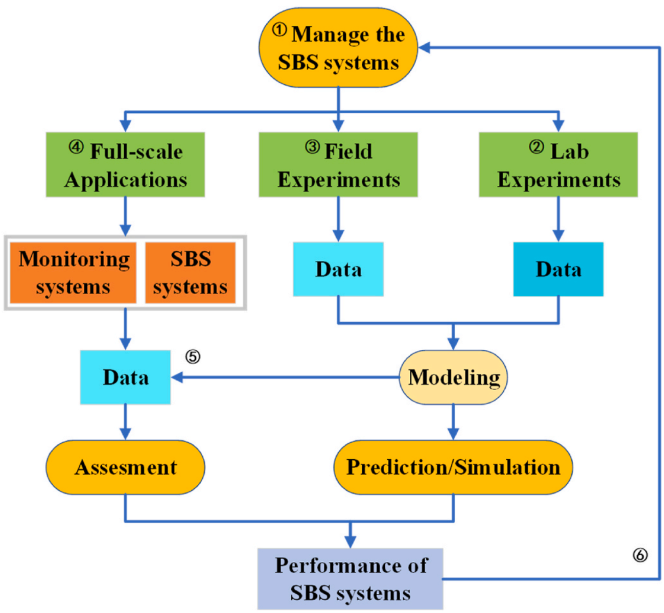

Fig. 1. Current status of monitoring and modeling the performance of SBS systems.

monitored, and the frequency; (v) Based on the modeling results, some recommendations for monitoring parameters and their frequency can be made by considering the local conditions; however, these models should be validated at the real-scale, under harsh environmental conditions; and (vi) Future research should focus on ascertaining the water quality, removing pollutants, ascertaining the hydraulic behavior, and expanding the performance indicators (e.g. temperature, biodiversity/ecosystems service, livability) in order to better manage the SBS systems.

3.2. *Future research directions*

3.2.1. *Long-term performance*

SBS without vegetation is governed by simple hydrologic and pollutant removal processes and behaves similarly to a permeable pavement. As a result, accelerated laboratory loading tests can reasonably well simulate the impact of aging on the performance of these inorganic systems. However, when vegetation is present, the process becomes more complex, e.g. the interactions between the root system of a plant and the soil media. Anew, as suspended solids continue to enter the system via stormwater runoff, the permeability of the soil media decreases gradually, but plant root growth restores the soil media's permeability. Hence, the vegetated SBS has a longer service life than the non-vegetated SBS.

The removal of pollutants in the SBS is related to the contact time between the stormwater runoff and the soil media, implying that the removal efficiency is related to the hydraulic conductivity of the soil media. As a result, vegetation indirectly influences the SBS removal efficiency. It may also change seasonally and annually. On the other hand, the changes in soil media permeability due to changing seasons might also affect the hydrologic performance of the SBS. At the same time, vegetation can absorb a large portion of the nutrients; thus, the nutrient removal efficiency of SBS varies with vegetation growth period. Heavy metals are primarily adsorbed by the soil media, with vegetation absorbing only a small portion. The long-term migration and distribution of heavy metals in the soil medium and the transport mechanism of the non-adsorbed/non-removed heavy metals to the ground water table should also be studied under real environmental conditions.

3.2.2. *New model development and performance indicators*

A model is generally used to aid the decision-making process; however, due to its limitations in simulating the long-term performance of SBS, there is a deviation between the original design and the actual effect, and these errors will have a direct impact on the SBR operation and the decision-making process. It is therefore recommended to collect and use long-term data to improve the model's prediction accuracy. Furthermore, there is no guideline/protocol for sample collection, model validation and monitoring activities. To assess the representativeness of the existing data, a model network should be established. The model network can provide monitoring guidance for the data paucity conditions, such as monitoring parameters, monitoring frequency, and monitoring duration.

In some instances, when data is limited and to reduce the model's data dependence, the existing data analysis methods have been modified or new methods were developed to maximize the effect. Hakimdavar et al. (2016) developed a water balance approach to evaluate the long-term hydrologic performance of green roofs. The model input only includes rainfall, soil moisture content, and the maximum water storage capacity of the soil, while the model output includes runoff and evapotranspiration (ET). The authors recommended that the data should be recorded every 6–24 h to yield the best results. Physical parametric models such as EPA-SWMM (Rosa et al., 2015), HYDRUS1-D (Wyatt, 2019), and PROM (Sun et al., 2013) have been successful in predicting the hydrologic behavior of SBS. Besides, the calibration parameters such as site and soil specific data, which are difficult to obtain or measure, are also required. In the literature, some simpler and less data intensive conceptual water balance models have also been successfully developed to predict the hydrologic behavior of SBS (Locatelli et al., 2014; Sherrard and Jacobs, 2012).

Previous research studies have identified the main performance indicators as hydraulic effect and pollutant removal. For example, in the on-going China's Sponge City project, the volume capture ratio of annual rainfall and the rate of non-point source pollution reduction are the only two indicators used to evaluate the performance of SBS systems. However, when the purpose of implementing a SBS has multiple objectives, then more performance indicators should be considered, e.g. temperature, biodiversity/ecosystem service, and sustainability.

4. Conclusions

A review of the existing literature on the performance of SBS revealed that few studies have examined the performance of SBS and its evolution over time, and that laboratory and field experiments produced inconsistent results due to the presence of plants, regular maintenance, and uncertain environmental factors. Further research will require long-term, high-quality field data that combines online monitoring of important parameters. However, the monitoring infrastructure and sampling strategies in place today are suboptimal and should be upgraded through the use of online sensors, real-time monitoring analytical instruments, data storage, and analysis tools. As long-term monitoring requires additional investment and is not always feasible in developing countries, future research should also focus on the application of simulation and modeling to pilot and full-scale SBS, with performance indicators including biodiversity, urban climate, landscape, ground and surface water quality, ecosystem services, and liveability.

Uncited references

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Declaration of competing interest

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

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