



Designing and Evaluating the Performance of Full-scale Bioretention Cells in Indian Conditions

Aamir Ishaq Shah¹ · Mukesh Siag¹ · Samanpreet Kaur¹ · Sudhir Thaman¹ · Rakesh Sharda¹

Received: 5 April 2023 / Revised: 29 November 2023 / Accepted: 18 December 2023 / Published online: 10 January 2024
© The Author(s), under exclusive licence to Springer Nature Singapore Pte Ltd. 2024

Abstract

Urbanization leads to an increase in impervious area percentage and significantly alters the predevelopment hydrology. Bioretention cells are sustainable stormwater management techniques that mimic the natural soil system of an area and help in restoring the hydrological balance. Present study involved construction of full-scale bioretention cells and filling them with engineered filter media to assess the field performance. The filter media was prepared from coarse sand and topsoil mixed with rice straw–derived biochar and maize straw–derived compost. This study addresses the emerging need for effective stormwater management in urban areas by evaluating the performance of full-scale bioretention cells. The use of engineered filter media derived from rice and maize residues demonstrates innovation in stormwater management, and thus contributing to sustainable resource use. The bioretention cells were planted with plant varieties—*Thumbergia erecta*, *Haemelia patens* and *Tabernaemontana divaricata*. The bioretention cells were observed for pre- and post-plantation hydraulic conductivity and hydrologic performance. Full-scale bioretention cells reported a pre-plantation average hydraulic conductivity between 118.0 and 324.0 mm/hr. Post-plantation average hydraulic conductivity ranged between 341.6–562.0 mm/hr. The minimum and maximum pre-plantation hydraulic conductivity for bioretention cell 1 filled with compost were 112.5 and 136.5 mm/hr, respectively. The average hydraulic conductivity of 120.5, 211.1 and 241.4 mm/hr were observed for bioretention cells 1, 3 and 5 respectively. In the case of biochar-filled bioretention cells, the average hydraulic conductivity recorded for various rainfall events were 162.3, 175.5 and 190.3 mm/hr for bioretention cells 2, 4 and 6, respectively. Given the design parameters adopted for the field-scale bioretention cells, the time to empty based on minimum hydraulic conductivity values was 11 times faster than the recommended maximum time to empty for the bioretention cells. The volume and peak flow reduction of the full-scale bioretention cells ranged between 82.9–90.2% and 86.1–92.3%, respectively. The total contribution of 6 bioretention cells to the groundwater recharge in three recorded events was 18.2 m³.

Keywords Low impact development · Stormwater management · Bioretention cells · Water quality · Agricultural residues

Abbreviations

BOD biochemical oxygen demand
IWSZ Internal Water Storage Zone

TSS total suspended solids
DO dissolved oxygen
pH potential of hydrogen
EC electrical conductivity
Total N total nitrogen
Total C total carbon
PVC polyvinyl chloride
GPS Global Positioning System
LID low impact development
mm/hr millimetre per hour
mg/L milligram per litre
m³/s cubic meter per second

✉ Aamir Ishaq Shah
aishaq045@gmail.com

Mukesh Siag
siagmukesh@pau.edu

Samanpreet Kaur
samanpreet@pau.edu

Sudhir Thaman
sudhirthaman@pau.edu

Rakesh Sharda
rakeshsharda@pau.edu

¹ Department of Soil and Water Engineering, Punjab Agricultural University, Ludhiana, Punjab, India

Introduction

India has seen rapid urbanization due to the migration of people to urban areas. Around 34% of India's total population lives in urban areas, which is expected to double by 2050 [1]. Urbanization significantly increases the amount of stormwater runoff from a site, decreases infiltration and groundwater recharge and alters the natural drainage of an area [2]. Pollutant-loaded runoff accumulates on catchment surfaces and increased impervious areas prevent the stormwater from infiltrating and recharging the groundwater [3]. The occurrence of extreme weather events include droughts and floods resulting from the interaction of human and environmental systems [4]. Reducing vulnerability and exposure to present climate variability is the first step towards adaptation to future climate change. There is a need to adopt sustainable and long-term approaches to mitigate the adverse effects of climate change, especially on urban hydrology. It demands integrating various stormwater management practices with the existing urban infrastructure to overcome the challenges of climate change.

Several Indian cities have witnessed a decline in vegetation cover and an increase in impervious areas, resulting in generation of substantial volumes of stormwater runoff [5–7]. The conventional drainage system in India includes constructing drains and channels that often carry a mix of wastewater from both domestic and industrial sources, along with the stormwater. This dual-purpose design usually results in the failure of drainage network during heavy rainfall events leading to urban flash floods. The high sediment load carried by stormwater also leads to choking and reduction of the carrying capacity of drainage network. There is a need to adopt sustainable practices to reduce the load on urban drainage network, improve the surrounding aesthetics and contribute to groundwater recharge [8]. The adoption of LID (low impact development) practices such as bioretention cells emerges as a sustainable strategy to address the evolving demands of urban stormwater management in India. Ludhiana is one of the largest cities in India and was recently included in the list of smart cities. Groundwater is the primary source of its water supply [9]. However, its water table is falling rapidly due to groundwater overdraft and an increase in impervious areas. The lack of a proper stormwater drainage network often results in flooding in densely populated areas of the city during heavy rainfall events. Several stormwater management specialists have recognized the role of LID practices in stormwater management. LID approach is a radically different approach to conventional runoff water management. The runoff water generated is managed in small, cost-effective landscape features. The most popular LID practices include bioretention cells, rain

gardens, green roofs, rain barrels, cisterns, filters/buffers, green streets, infiltration trenches, permeable pavements and constructed wetlands [10]. LID can play a significant role in making the cities adaptable to changing climate, protecting biodiversity and improving the interaction between various groups of society through socialization at the physically accessible nested network of green spaces [11]. LID practices can also be adopted with the existing grey infrastructure to provide the benefits of stormwater management and prevent the heat island effect [12, 13]. The importance of stormwater management also increases in the context of changing precipitation extremes, such as erratic, uneven and high-intensity rainfall. It would also improve local ambience, biodiversity and groundwater recharge. There is a strong need for an anthropogenic modification of the environment in response to climate and weather over time and the development of “sustainable” engineering solutions.

Bioretention cells are excavated depressions in the ground, which are backfilled with filter media and planted with tolerant plant species acclimatized to the local conditions [14]. Bioretention cells are typically designed to treat, infiltrate and/or store a specific water quality volume from an area through filtration, adsorption, sedimentation and other natural processes [15]. Mitigation of peak flow and reduction of the total volume of runoff have been recognized as potential hydrologic benefits of bioretention cells. Groundwater recharge has been recognized as a hydrologic benefit of bioretention cells. Groundwater recharge can be a solution to lowering the water table; however, in industrial and commercial areas, the quality of water used for groundwater recharge is a major concern [16]. Bioretention cells provide a sustainable solution to these issues due to the ability to lower pollutant loads through various physical, chemical (denitrification, filtration, sedimentation and adsorption) and biological processes [17].

In northern India, most of the agricultural residues especially paddy and maize are burned, which causes large-scale air pollution. India, on an average, produces 500 million tons (Mt) of crop residue per year, according to the Indian Ministry of New and Renewable Energy [18]. A majority of the crop residue is used as fodder and fuel for domestic and industrial purposes, according to the same report. Despite this, 140 Mt of the surplus is left each year of which 92 Mt is burnt [18]. There have been several attempts to use paddy straw and maize straw for filtering wastewater as such as well as by turning them into secondary products such as biochar, bioethanol and compost [19]. However, their use as filter media in field-scale bioretention cells as secondary products has not been studied yet. Biochar, derived from rice straw, is known for its high porosity and water retention capacity

[20]. When incorporated into the filter media, it enhances infiltration rates by creating a porous structure that allows water to percolate through, reducing surface runoff. This is crucial for effective stormwater management. Both biochar and compost have adsorption capabilities, which help in removing pollutants from stormwater runoff [21–23]. The use of agricultural residues, such as rice and maize straw, for biochar and compost aligns with principles of sustainability. The choice of rice and maize straw acknowledges their abundance in northern India, where the study was conducted. Using locally available materials enhances the feasibility and cost-effectiveness of the engineered filter media, making the stormwater management solution more applicable and accessible for widespread adoption. This study would provide an alternative use of paddy straw and maize straw as an amendment for filter media preparation by turning them into biochar and compost, respectively. The research aimed to identify the performance of engineered filter media compositions suitable for bioretention cells in Indian conditions. The study also involved pre and post-plantation comparison of the hydraulic conductivity of engineered filter media.

Methodology

This section discusses the materials and methods applied in the design, construction and performance evaluation of the bioretention cells. The primary work involved the preparation of engineered filter media and the construction of bioretention cells based on actual and simulated runoff events. The whole methodology can be represented through a flow-chart, as depicted in Fig. 1.

General Description of the Site of Installation

The bioretention cells were constructed at the main campus of Punjab Agricultural University (PAU), Ludhiana, India (Fig. 2). Under the Köppen climate classification, the Ludhiana district can be classified as having a semiarid climate with a transitional climate between tropical wet and tropical dry. Bioretention cells are usually installed on the periphery of parking lots and roads, most preferably connected to the existing drainage network [24]. The present site was selected since it had a history of standing water during monsoon rains. The bioretention cells were constructed at the

Fig. 1 Research methodology

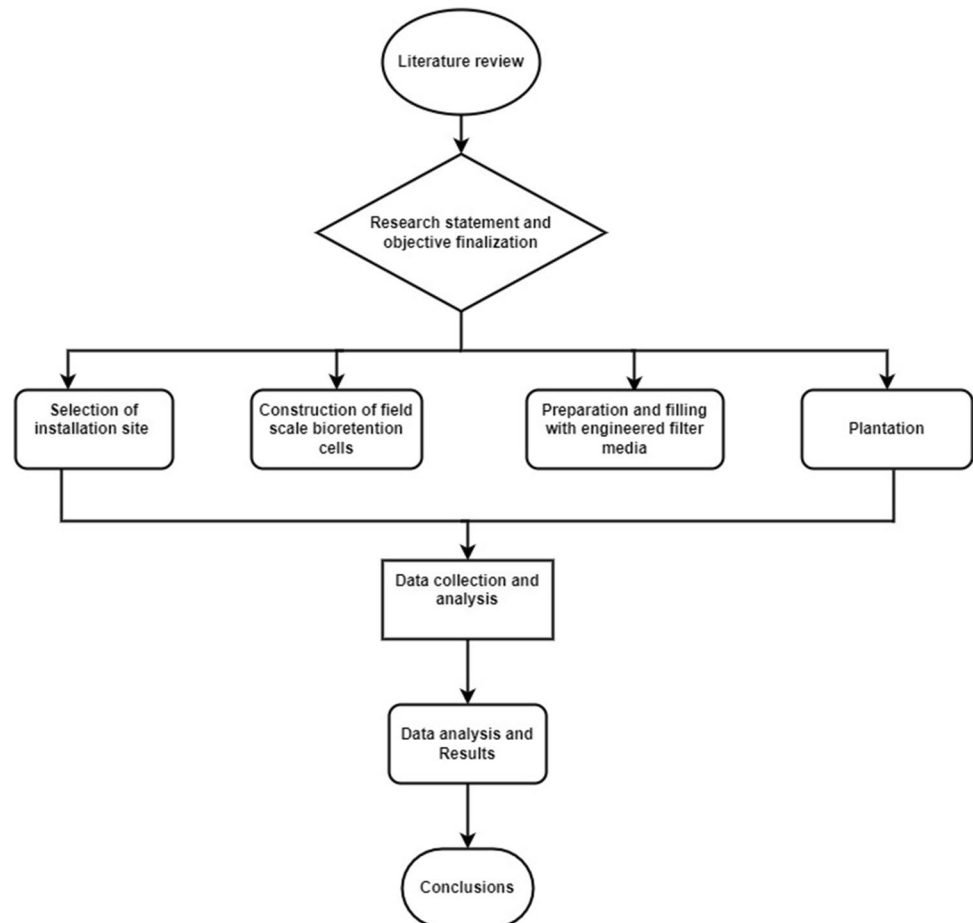


Fig. 2 Location of sites of installation of bioretention cells



present site to provide relief from water logging, recharge the intercepted water and reduce the sediment load of the stormwater. The exact Global Positioning System (GPS) coordinates giving the location of the bioretention cells lie at 30.89 N and 75.80 E.

Construction of Bioretention Cells

The construction of bioretention cells involved excavation up to a depth of 1.7 m. Masonry work using bricks and cement was done on the sides of each bioretention cell to prevent stormwater seepage. A small channel of length 25 m and width 0.4 m was constructed to collect the water from the sides of the road and divert it into the cells. The bioretention cells were filled with gravel to create a water storage zone and a monofilament nylon mesh was placed over the gravel layer. The underdrain was installed at 0.8 m depth above the gravel layer with perforation facing up. A sample chamber of 60 cm × 150 cm was provided in each bioretention cell. The design details of the constructed bioretention cells have been provided in Table 1. Each chamber was split into two sections—a sampling chamber and a collection chamber for receiving the effluent of the previous bioretention cells.

Preparation and Filling of Engineered Soil Mix

Conventionally, bioretention filter media consists of a mixture of 20–30% soil, 20–40% organic matter and 30–60% sand by volume [17, 25, 26]. The constituents of an engineered filter media are biochar, compost, coarse sand and topsoil [27]. Rice straw-derived biochar and

Table 1 Design details of the bioretention cells

S. no	Parameter	Value
1	Impervious catchment area (m ²)	1000
2	Length of each cell (m)	3
3	Width of each cell (m)	1.5
4	Total depth of each cell (m)	1.7
5	Surface area of bioretention (m ²)	4.5
6	Maximum ponding depth (m)	0.5
7	Depth of underdrain (m)	0.8
8	Depth of filter media (m)	0.5
9	Storage volume in ponding zone (m ³)	2.25
10	Porosity of gravel, filter media (%)	40, 25
11	Storage volume in the storage zone below underdrain (m ³)	1.44

maize straw-derived compost were used for preparation of filter media. The specific suitability of rice straw biochar and maize straw compost for the Indian context lies in their availability, physical and chemical properties, including particle size, porosity and nutrient content, contributing to sustainable stormwater management. These materials enhance adsorption, filtration and nutrient removal in bioretention cells. Due to higher porosity, the prepared filter media effectively maintains the hydraulic conductivity for an extended period [28]. Field studies evaluated two compositions of engineered filter media containing compost and biochar. Composition A had 60% sand, 20% compost and 20% topsoil; composition B had 70% sand, 10% biochar and 20% topsoil.

The addition of topsoil although has a negative impact on hydraulic conductivity; its presence in the filter

media is essential. It supports the vegetation and holds sufficient moisture to aid plant growth in the bioretention cell. The inflow runoff from the drainage area is directed into each bioretention cell through an inlet. An existing drainage channel or a pipe serves as an inlet [29]. For the present study, a polyvinyl chloride (PVC) pipe was used as an inlet. An outlet for draining the excess runoff is provided in all bioretention cells. A 4-inch PVC pipe was used to serve as an inlet and outlet. A sample from each material (biochar and compost) was taken for laboratory analysis and evaluated for the following parameters as in Table 2.

Each bioretention cell has three major zone—ponding zone, filter media zone and an Internal Water Storage Zone (IWSZ). Figure 3 shows the cross-section of a typical bioretention facility with an underdrain.

Table 2 Properties of the materials used in bioretention cells

Parameter	Biochar	Compost	Top soil
EC (dS/m)	11.2	3.56	0.10
pH	10	7.36	7.0
Total N (%)	0.20	0.85	0.12
Total C (%)	8.25	9.09	1.16
C:N ratio	41.2	10.7	9.7
Hydraulic conductivity	779.2	855.9	11.8

Selection of Plants

The plants play a very important role in keeping the bioretention cells functional by preventing the failure of the systems due to clogging [30]. Bioretention systems should support a range of plant species which increases the overall survivability of the plants as the drought-tolerant plants are gradually replaced by plants that prefer a wetter environment. The selection of plants was based on their suitability to survive in a wide range of soil moisture conditions expected in bioretention cells, ranging from ponded conditions during high rainfall events to dry conditions during no rainfall periods. Three hardy shrubs—*Thunbergia erecta*, *Hamelia patens* and *Tabernaemontana divaricata* were selected for planting in the bioretention cells based on their adaptability to a range of soil moisture conditions contributing to the overall survivability within the bioretention cells (Fig. 4). These shrubs expand their roots horizontally and vertically which contributes to maintain the hydraulic conductivity of the filter media [31].

Water Quality Parameters

The experimental procedures involved measurement of TSS concentration in inflow and the outflow stormwater from the bioretention cells. All the experiments involving the inflow and outflow treated stormwater were conducted as per the Standard Methods for Water and Wastewater Analysis

Fig. 3 Cross-sectional view of a typical bioretention cell

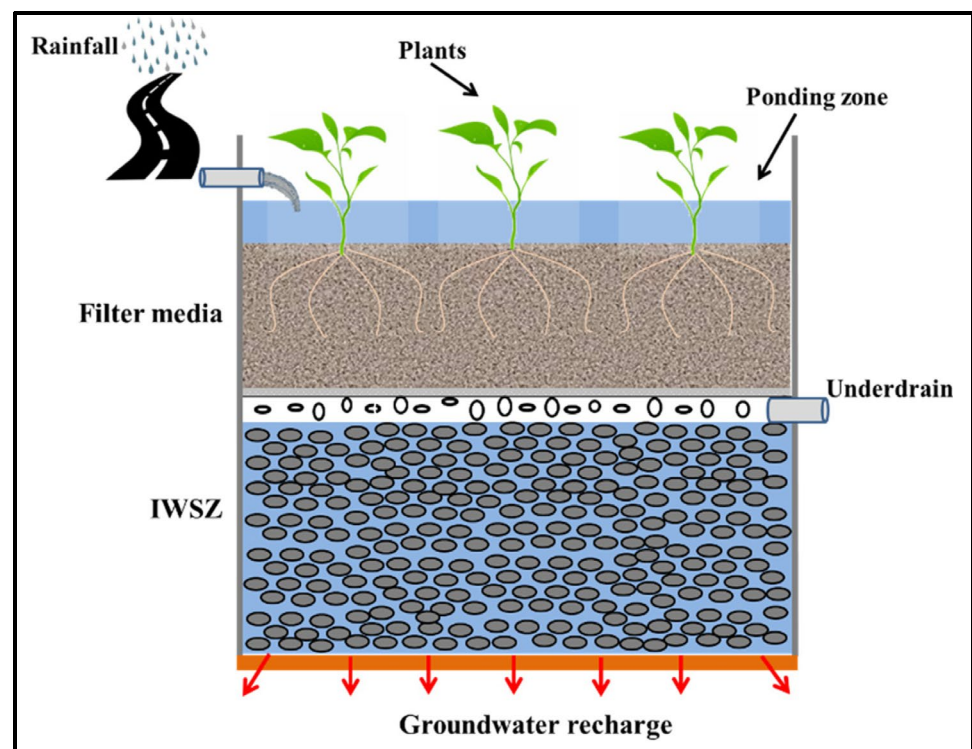


Fig. 4 Established plant varieties in the bioretention cells (*Tabernaemontana divaricata*, *Thunbergia erecta*, *Hamealia patens*)



guidelines [32]. Dissolved oxygen (DO) was measured using HI98193 and biochemical oxygen demand (BOD) was calculated as the difference between the initial and final DO concentrations after 5 days of incubation at 20°C. Water quality analysis indicating percentage pollutant removal from each event was evaluated as the difference between influent and effluent concentrations indicated in formula below.

$$R_i = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (1)$$

where R_i = percentage removal, C_{in} is the concentration of pollutant in influent (mg/L), C_{out} is the concentration of pollutant in effluent (mg/L).

Measurement of Hydrologic Response of Bioretention Cell

All relevant data was recorded manually during each runoff-producing rainfall event. The inflow rate and the rate of lowering of water level in the ponding zone were recorded for each bioretention cell. In the case of high runoff events, the runoff after filling IWSZ emerged from the outflow. The rate of outflow from underdrain was also recorded till the outflow stopped. The inflow and outflow data was recorded regularly using bucket-and-stopwatch method [33]. The water level in the ponding zone was recorded using a measuring scale (Fig. 5). Inflow and outflow rates were measured in litre/second, and the hydraulic conductivity was recorded in mm/hr.

The hydrologic response is expressed as the reduction in total runoff volume and peak runoff after the installation of bioretention cells. After filling to maximum ponding height, the behaviour of filter media was also evaluated during various recorded runoff-producing events. The measured value of the inflow rate into the bioretention cells was used to derive the inflow hydrograph. The outflow hydrograph is measured at the outlet (underdrain) similarly as the inflow. The time lag between of peak of the inflow hydrograph and the outflow hydrograph was also noted to represent the

buffering capacity of the bioretention system. The inflow and the outflow data was used to estimate the net volume of groundwater recharge during the rainfall events. In each bioretention cell, the volume of stormwater recharged was estimated from the stormwater inflow volume into ponding zone and the outflow volume from the IWSZ. In rainfall events where outflow was not observed, the groundwater recharge is the net volume of water inflow into the ponding zone of the bioretention cell.

Results and Discussions

The bioretention cells have been designed to facilitate sequential outflow integration. The outflow from each bioretention cell via underdrain collects in the collection chamber, from where it is conveyed through connecting pipes to the corresponding collection chamber of the subsequent bioretention cell (Fig. 6). This ensures a cumulative effect, wherein the outflow from each preceding bioretention cell contributes to the overall outflow from the succeeding cell in the bioretention train. Consequently, the outflow of the first bioretention cell (C1) combines with that of the second (C2), third (C3) and subsequent cells (4–6) resulting in collection of filtered stormwater. This final collected stormwater runoff in collection chamber of bioretention cell C6 is the total stormwater the urban drainage network is expected to handle. In a typical urban bioretention cell scenario where the bioretention cells are supplemented by the urban drainage network, the final overflow is diverted into an existing stormwater drainage network. Alternatively, the resultant outflow can be diverted into a groundwater recharge structure. The field-scale bioretention cells adopted in the present study represent a bioretention train design. The excess stormwater is diverted and the final outflow after passing



Fig. 5 Measurement of the rate of lowering of stormwater in ponding zone

through a series of bioretention cells can be diverted into the existing drainage network or recharged. The design is novel and can be adopted alongside roads with narrow sidewalks. The full design of the bioretention train is shown in Fig. 6.

The surface area of each bioretention cell based on the total length of 3 m and width of 1.5 m is 4.5 m². Given a drainage area of 1000 m² and a runoff coefficient of 0.90, a

design rainfall (*P*) of 20 mm will produce a runoff volume of 18 m³ in the first flush [34].

$$\text{First flush volume} = C \times P \times A \tag{2}$$

The calculations based on the maximum allowable ponding depth indicate that a volume of 2.25 m³ can be stored in the ponding zone between the upper surface of filter media and the maximum allowable ponding height of 0.5 m. For the given catchment of area (*A*) 1000 m²

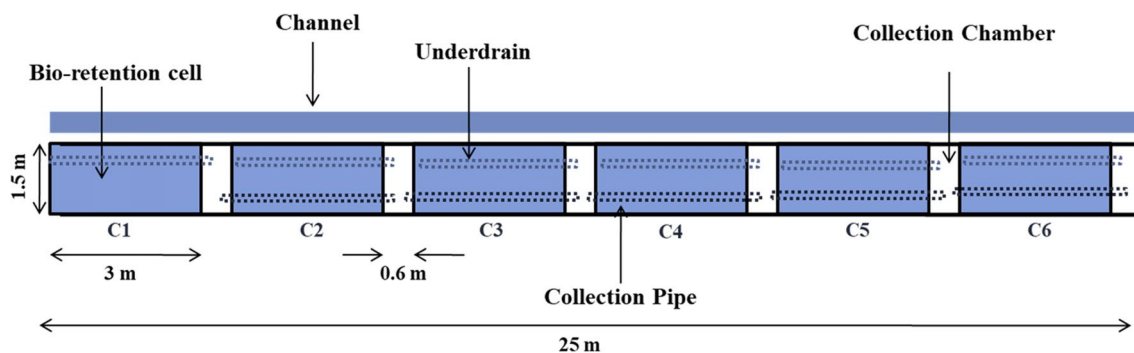


Fig. 6 Plan of the constructed bioretention cells (not to scale)

and runoff coefficient (C) 0.90, equation 2 can be used to calculate the maximum rainfall intensity that can be handled by the bioretention cells. If only the storage available in the ponding zone is considered, the ponding zones can handle all rainfall events of 15 mm or less. A rainfall event with a value greater than this should exceed the capacity of the bioretention cell. However, the filter media and the IWSZ also offer substantial storage in the pore spaces owing to the high porosity of the materials—gravel and engineered filter media. IWSZ with a total depth of 0.8 m accounts for storage of 1.44 m³, considering the porosity of gravel equal to 40%. IWSZ is located below the underdrain, so all the runoff collected in it is available for infiltration into the native soil. With a porosity of 25%, the engineered filter media is expected to provide 0.56 m³ of storage. Each bioretention cell in its storage zones offered a total storage volume of about 4.43 m³. If the maximum available ponding depth of 0.5 m is considered, the porous layers of bioretention cells offered nearly same storage as the surface storage offered by the ponding zone. Table 3 provides the distribution of storage in different storage elements of bioretention cells. The flow from the catchment area goes into 6 bioretention cells, and thus the total storage offered in the ponding zone, filter media and IWSZ fulfil the design criteria. A total 6 bioretention cells thus had a storage capacity of 26.59 m³. From equation 2, the bioretention cells based on additional storage offered by the IWSZ and the filter media could thus handle a rainfall event of 29.5 mm.

The time to empty the ponding zone is the ratio of the maximum allowable water level (m) in the ponding zone and the hydraulic conductivity of the filter media (mm/h). The hydraulic conductivity of engineered filter media significantly affects the time to completely empty the bioretention cells. Based on field data, the average hydraulic conductivity of bioretention cells varied between a minimum of 118 mm/h and a maximum of 324 mm/h before plantation. Time to empty based on maximum hydraulic conductivity values (324 mm/h) was calculated as 1.5 h. The design guidelines recommend the bioretention cells to empty within 24–48 h [35]. Given the design parameters adopted for the field-scale bioretention cells, the time to empty based

on minimum hydraulic conductivity values (118 mm/h) was 11 times faster than the recommended maximum time to empty (48 h) for bioretention cells. Post-plantation the average hydraulic conductivity of the 6 bioretention cells varied from a minimum of 330 to a maximum of 1457 mm/h, reducing the drawdown time substantially. Plantation negates the effect of clogging over a period of time and has a positive effect on the saturated hydraulic conductivity of the engineered filter media.

Hydraulic Performance of Engineered Filter Media

The maximum ponding achieved and the rate of lowering of water were recorded during each rainfall event. An overflow pipe bypassing the filter media was also provided to prevent the overtopping of the structure in case where the stormwater inflow exceeds the capacity of the ponding zone. The minimum and maximum pre-plantation hydraulic conductivity for bioretention cell 1, filled with compost, were 112.5 and 136.5 mm/h, respectively. The variation of hydraulic conductivity over the observation period is shown in Figs. 7, 8, 9, 10, 11 and 12. Bioretention cell 3 reported minimum hydraulic conductivity of 174 mm/h and maximum hydraulic conductivity of 257.5 mm/h. Similarly, minimum hydraulic conductivity of 198 mm/h and maximum hydraulic conductivity of 238 mm/h was recorded for bioretention cell 5. The average hydraulic conductivity of 120.5, 211.1 and 241.4 mm/h were observed for bioretention cells 1, 3 and 5 respectively. In the case of biochar-filled bioretention cells, the average hydraulic conductivity recorded for various rainfall events were 162.3, 175.5 and 190.3 mm/h for bioretention cells 2, 4 and 6, respectively. The maximum and minimum hydraulic conductivity for bioretention cell 2 were 116.3 and 256.7 mm/h, respectively. Bioretention cells 4 and 6 showed minimum hydraulic conductivity of 142.2 and 113.2 mm/h and maximum hydraulic conductivity of 200 and 212 mm/h, respectively. According to the

Table 3 Storage offered by different zones of bioretention cells

Storage zone	Depth (m)	Porosity (%)	Water storage (m ³)	Total storage in six bioretention cells (m ³)
Ponding zone	0.5	-	2.25	13.50
Filter media	0.5	25	0.56	3.37
IWSZ	0.8	40	1.44	8.64
Pea gravel	0.1	40	0.18	1.08
Total	1.6	-	4.43	26.59

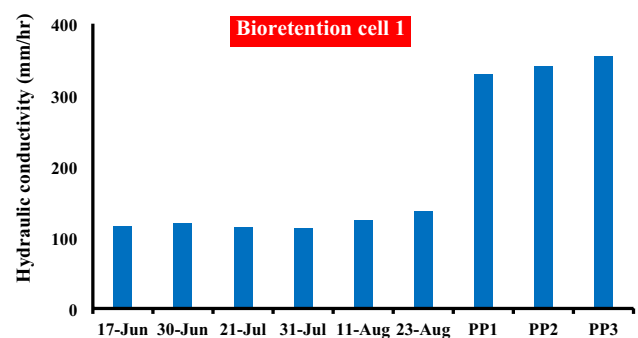


Fig. 7 Hydraulic conductivity variation in bioretention cell 1 (PP, post-plantation)

Fig. 8 Hydraulic conductivity variation in bioretention cell 2 (PP, post-plantation)

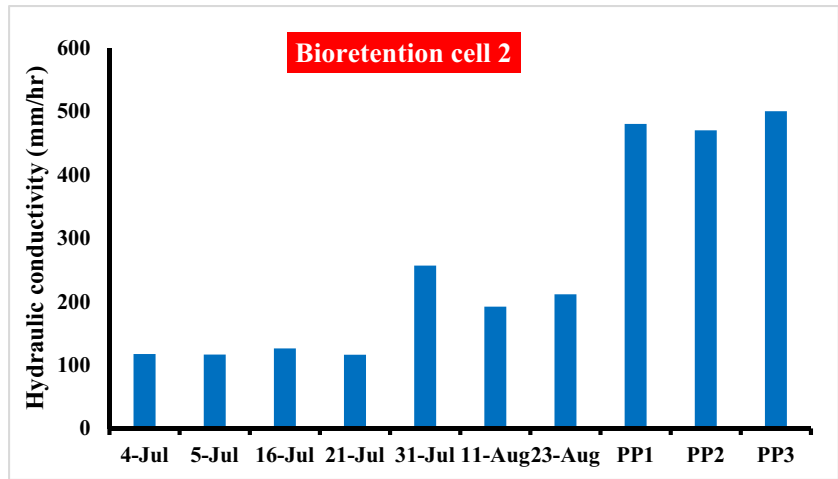


Fig. 9 Hydraulic conductivity variation in bioretention cell 3 (PP, post-plantation)

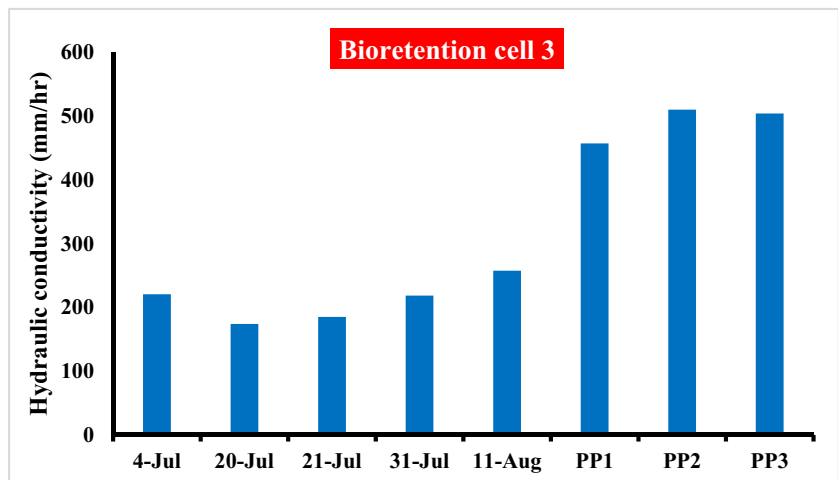
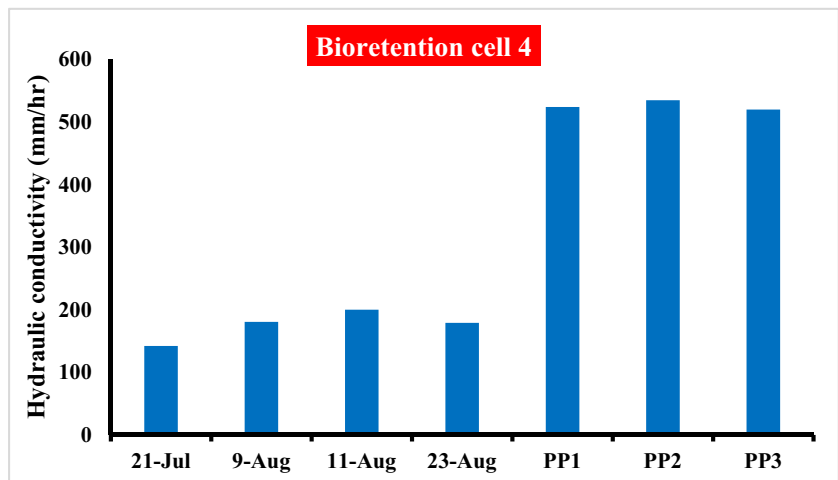


Fig. 10 Hydraulic conductivity variation in bioretention cell 4 (PP, post-plantation)



results, the drawdown values observed in all bioretention cells fall within the ranges reported and suggested in the previous studies and existing design manuals [36–38]. The observed pre-plantation hydraulic conductivity values are consistent with the variability reported in previous

studies. Field-scale bioretention cells reported hydraulic conductivity in the range of 115 to 864 mm/h [39]. Despite factors such as compaction and deposition affecting hydraulic conductivity, all the values were well above the design target hydraulic conductivity of 25 mm/h [40].

Fig. 11 Hydraulic conductivity variation in bioretention cell 5 (PP, post-plantation)

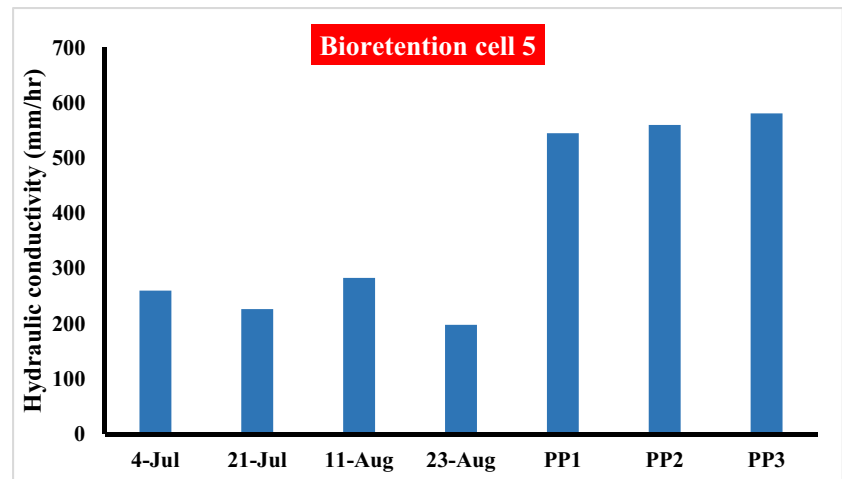
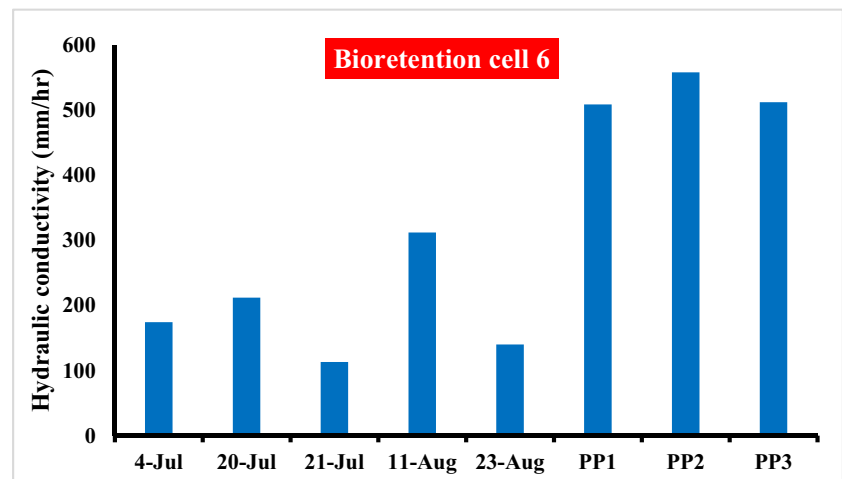


Fig. 12 Hydraulic conductivity variation in bioretention cell 6 (PP, post-plantation)



Similarly, the time to empty the ponding zone was also noted in all bioretention cells. For the recorded rainfall events, bioretention cell 1 reported an average 30 to 205 min to completely drain ponding depths between 6 and 21 cm in the ponding zone. In bioretention cell 2, the average time to empty minimum and maximum ponding depths of 2.1 cm and 25 cm was 10 and 105 min, respectively. An average of 65 and 110 min were required for bioretention cells 3 and 4 to empty their maximum ponding depths of 24 and 30 cm, respectively. Bioretention cell 5 took 95 min to empty a maximum ponding of 30 cm. In order to empty the ponding depth of 30 cm, bioretention cell 6 took a total of 225 min. This is mainly due to variations in the hydraulic conductivity on the particular dates the ponding depth observations were made. The total time to empty the ponding zone of all bioretention cells was thus within the design guidelines.

Effect of Plant Establishment on Hydraulic Conductivity of Filter Media

Multiple studies have shown that silt builds in bioretention media over time and plugs the pores, thereby decreasing infiltration rate and porosity [41–43]. Vegetation plays a significant role in countering the effects of media clogging and maintaining porosity through root turnover. Certain plant varieties develop up to six secondary root sets to a depth of 0.6 m which counteracts the clogging of pores [44]. Bioretention cells 1–6 planted with different shrub varieties were observed for any changes in hydraulic conductivity post-establishment. A significant reduction in the time to empty and a substantial increase in hydraulic conductivity was observed in all bioretention cells. Post-plantation with *Thunbergia erecta* bioretention cells 1 and 4 recorded an

average hydraulic conductivity of 341.6 and 526.3 mm/h. A 64.7 and 66.3% increase in the average hydraulic conductivity was observed post-establishment. Bioretention cells 3 and 6 after plantation with *Hamalia patens* observed an average hydraulic conductivity of 490.3 and 526.2 mm/h. Average hydraulic conductivity in bioretention cells 3 and 6 increased by 56.9 and 69.8%, respectively after plantation. Bioretention cells 2 and 5 post-plantation with *Tabernaemontana divaricata* observed an average hydraulic conductivity of 483.3 and 562.0 mm/h showing an increase of 66.3 and 56.9%. Hydraulic conductivity values after the establishment of plants thus showed a positive correlation with vegetation growth. Similar results were reported by Paus et al. [29]. This is because the growth of the secondary and tertiary roots makes the soil porous as compared to soil with no plants [45]. Bioretention cells with high initial hydraulic conductivities (>200 mm/h) maintained it within guideline values even with a 25–50% reduction due to clogging [46]. Bioretention cell 1 reported an empty time of 29 min to drain maximum storage of 20 cm completely. Post-establishment of plants, bioretention cells 2 and 3 recorded a time of 33 and 22 min to empty a maximum ponding of 30 and 20 cm, respectively. The time to empty a maximum ponding of 30 cm in bioretention cell 4 was 30 min. Similarly, bioretention cells 5 and 6 in order to completely drain a maximum ponding of 25 and 30 cm, took an empty time of 24 and 34 min, respectively. The improvement in hydraulic conductivity post-plantation is crucial for maintaining the inflow of stormwater and enhancing the overall performance of the bioretention cells. The observed changes suggest that the selected plant varieties contribute significantly to maintaining the hydraulic conductivity over time. Plants also play a significant role in preventing clogging and failure of the bioretention systems [47]. Based on the improved values of hydraulic conductivity post-plants, it can be concluded that the root systems of the *Thumbergia erecta*, *Haemelia patens* and *Tabernaemontana divaricata* likely contribute to the maintenance of pore spaces in the bioretention cells. These results highlight the positive impact of plant-induced changes on the overall performance and thus reducing the risk of failure in the bioretention cells over time.

Hydrological Analysis

Hydrological analysis involved evaluating the peak flow and runoff reduction potential of bioretention cells for different rainfall events. The inflow measurement into the bioretention cells 1–6 was recorded during various rainfall events. Out of the total of 11 recorded rainfall events, outflow measurements were made for 3 rainfall events each in 6 bioretention cells. All rainfall events were used to evaluate the hydrological behaviour of bioretention cells in terms of peak flow reduction, volume reduction and groundwater recharge.

The peak outflow from the bioretention cell recorded during the rainfall events and the peak inflow rate into bioretention cell was used to estimate the peak flow reduction achieved by bioretention cell. Outflow was observed in bioretention cells 2 and 3 during a rainfall event on 31-July and 21-July, respectively. All the outflow recordings were observed in bioretention cells 4, 5 and 6 on 11-August. The peak outflow recorded for bioretention cell 2 was 0.22 litres/s against a peak inflow of 1.58 litres/s. A peak flow reduction of 86.07% was thus achieved for bioretention cell 2. In a study in Australia, peak flow reduction of 80% was observed in bioretention cells without an IWSZ [48]. A 60 cm IWSZ in three bioretention cells were able to achieve a peak flow reduction between 24 and 96% in a clay soils [49]. Peak flow mitigation of 65% was achieved in bioretention cells in Connecticut, USA [17, 49]. About 80–90% in reduction in peak runoff was reported in Australia [50]. Bioretention cells with IWSZ and built on native soil having high infiltration rates reported higher volume reduction 96–100% in sandy soil and 75–87% for sandy clay loam soils [25]. Water in bioretention cells is stored in active storage and IWSZ. Stormwater in IWSZ below underdrain depth will remain in storage until all the inflow water is infiltrated. Given an underdrain depth of 0.8 m, a substantial reduction in peak flow was thus observed. Higher peak inflows result in greater peak flow reduction due to a hydraulics principle known as routing. In a controlled outdoor study of four bioretention cells, it was found that greater organic content reduced the peak flow more than a higher sand content [51]. The hydraulic performance of bioretention cells decreases as the rainfall depth and duration increase [52]. High intensity rainfall events provide limited time to capture stormwater volume in bioretention cells. The performance of bioretention cells is best in the case of small rainfall events since most of the precipitation events are below the design depth of 13 mm or 25 mm rainfall. An average rainfall event, for example for a city like the Greater Toronto area of Canada is 5 mm [53]. During events with 1-year design rainfall intensities, peak flow reduction varied from 24 to 96% with the best mitigation during events [49]. A study by [54] reported that residential rainwater harvesting structures resulted in peak flow reduction potentials for the sub-basins between 2.7 and 14.3%. Peak inflow rates observed during different rainfall events are shown in Table 4. Peak flow reductions achieved are given in Table 5.

Groundwater Recharge

The total inflow volume against recorded rainfall events is given in Table 6. In each bioretention cell, the volume of stormwater recharged was determined by subtracting the net volume of stormwater outflow from the net volume of inflow. During three recorded rainfall events for bioretention cell

Table 4 Peak inflow into bioretention cell during different recorded events

Event B. Cell 1	Peak inflow (l/s)	Event B. Cell 2	Peak inflow (l/s)	Event B. Cell 3	Peak inflow (l/s)
17/06/2022	0.96	04/07/2022	1.55	04/07/2022	1.65
30/06/2022	0.29	05/07/2022	0.77	21/07/2022	1.69
23/08/2022	0.64	31/07/2022	1.58	11/08/2022	1.24
Event B. cell 4	Peak inflow (l/s)	Event B. Cell 5	Peak inflow (l/s)	Event B. Cell 6	Peak inflow (l/s)
09/08/2022	1.10	04/07/2022	0.91	04/07/2022	0.99
11/08/2022	1.60	11/08/2022	1.86	11/08/2022	1.95
23/08/2022	0.90	23/08/2022	0.71	23/08/2022	0.75

Table 5 Peak flow reduction observed in bioretention cell

Bioretention cell	Event	Peak inflow (l/s)	Peak outflow (l/s)	Peak flow reduction (%)
2	31/07/2022	1.58	0.22	86.1
3	21/07/2022	1.69	0.21	87.6
4	11/08/2022	1.60	0.20	87.5
5	11/08/2022	1.86	0.20	89.2
6	11/08/2022	1.95	0.15	92.3

1, a total volume of 1787.5 litres (1.79 m³) was recharged. Bioretention cell 2 contributed a net volume of 3713.7 litres (3.71 m³) to groundwater recharge. Bioretention cell 3 after deducting the outflow from underdrain contributed a total volume of 3898.5 litres (3.89 m³) to groundwater recharge. The contribution of bioretention cell 4, cell 5 and cell 6 to groundwater recharge was estimated as 3249.0, 2460.0 and 3091.2 litres, respectively. Thus, the contribution of bioretention cells to groundwater recharge is quite evident. During the three recorded rainfall events, each bioretention cell contributed in the range of a minimum of 297 litres (0.29 m³) and a maximum of 1657.5 litres (1.66 m³). During the three rainfall events for which inflow–outflow data were recorded, the bioretention cells contributed 18196.9 litres (18.2 m³) to groundwater recharge. The results establish the potential of bioretention cells for ground water recharge.

A study in semiarid region found that nearly 100% of the inflow volume was recharged via bioretention cells [55].

Bioretention cells can reduce peak flow and volume depending on the size and permeability of the filter media [56]. The total volume of the bioretention cell can be divided into ponding volume, filter media volume and the IWSZ volume. The total volume of stormwater entering and leaving the bioretention cells during different rainfall events was noted to calculate the stormwater volume reduction potential. While bioretention cell 2 produced a net outflow volume of 258 l against an inflow volume of 1915.5 litres, giving a total volume reduction of 86.5%. The total volume reduction potential of bioretention cells 3, 4, 5 and 6 was found to be 82.9%, 83.7%, 87.9% and 90.2% respectively (Table 7). IWSZ, however, plays a crucial role in runoff volume reduction. Peak flow and stormwater volume reduction,

Table 7 Observed runoff volume reduction potential of bioretention cell

Rainfall event	Bioretention cell	V _{IN} (l)	V _{OUT} (l)	Reduction (%)
31/07/2022	2	1915.0	258	86.5
21/07/2022	3	1900.5	324	82.9
11/08/2022	4	1803.0	297	83.7
11/08/2022	5	1773.0	213	87.9
11/08/2022	6	1728.9	168	90.2

Table 6 Net inflow stormwater volume/ ground water recharge during different rainfall events

Event B. cell 1	Inflow volume (litres)	Event B. cell 2	Inflow volume (litres)	Event B. cell 3	Inflow volume (litres)
17/06/2022	831.3	04/07/2022	1572.0	04/07/2022	945.0
30/06/2022	488.2	05/07/2022	484.2	21/07/2022	1900.5–324=1576.5
23/06/2022	468.0	31/07/2022	1915–258=1657.5	11/08/2022	1377.0
Event B. cell 4	Inflow volume (litres)	Event B. cell 5	Inflow volume (litres)	Event B. cell 6	Inflow volume (litres)
09/08/2022	828.0	04/07/2022	603.0	04/07/2022	742.8
11/08/2022	1803–297=1506.0	11/08/2022	1773–213=1560.0	11/08/2022	1728.9–168=1560.9
23/08/2022	912.0	23/08/2022	297.0	23/08/2022	787.5

as observed in this study, plays a pivotal role in reducing the load on drainage systems by mitigating the impact of high stormwater flow volumes [57]. Runoff volume reduction in the range of 50–90% were reported from bioretention facilities [58, 26]. Peak flow and volume reduction greater than 80% has been reported by different studies [59, 16]. Despite low infiltration underlying soils, IWSZ reduced runoff by 59%, 42% and 36% over the monitoring period [49]. The depth of filter media and exfiltration rate are primary factors that determine the volume reduction performance of a bioretention cell. At full vegetation, a green roof can as much as 75% of precipitation as compared to 20 to 40% during the winter months [60]. Green roofs as a part of LID have also been found to reduce runoff volume by 29% in Vancouver, 55% in Shanghai and 100% in Kelowna [61].

A lag between the time stormwater reaches inflow and the time outflow appears from the underdrain was recorded. For all the observed events, an average lag time of less than 2 h was observed between the inflow and stormwater emerging from the outflow. A lag of 45 min was observed between the peak inflow and peak outflow from the inflow–outflow hydrographs of bioretention cell 2 (Fig. 13 a). Bioretention cell 3 observed a lag of 70 min between peak inflow and peak outflow (Fig. 13 b). In bioretention cells 4 and 5 for rainfall event on 11/08/2022, a lag of 45 min each was observed (Fig. 14 c, d). From the inflow–outflow hydrograph of bioretention cell 6 (Fig. 15), a lag time of 30 min was observed. The lag time can range from 30 min to 30 h [62]. The results suggest that the constructed bioretention cells could store and withstand the design rainfall intensity in

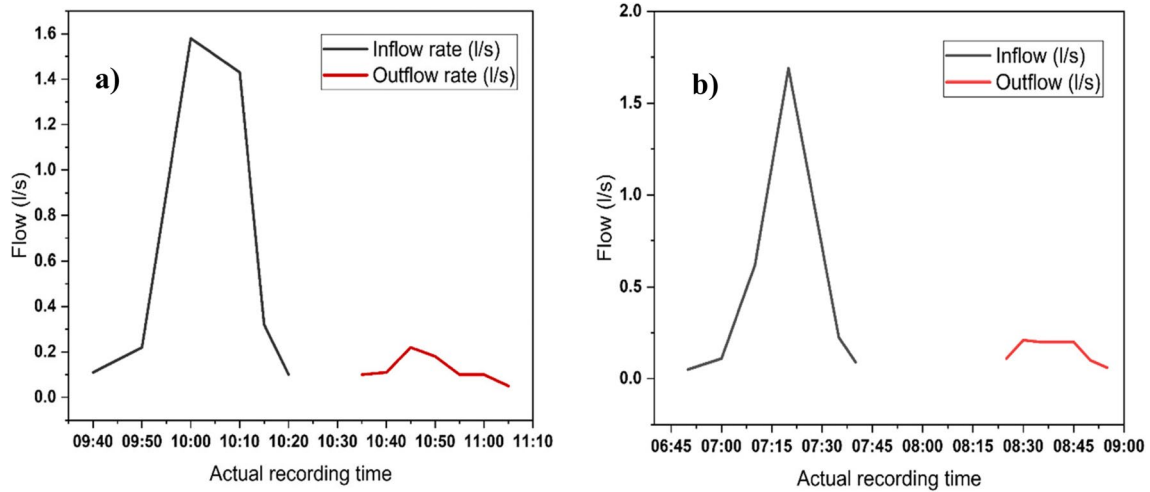


Fig. 13 Inflow vs. outflow hydrographs **a** bioretention cell 2: 31/07/2022; **b** bioretention cell 3: 21/07/2022

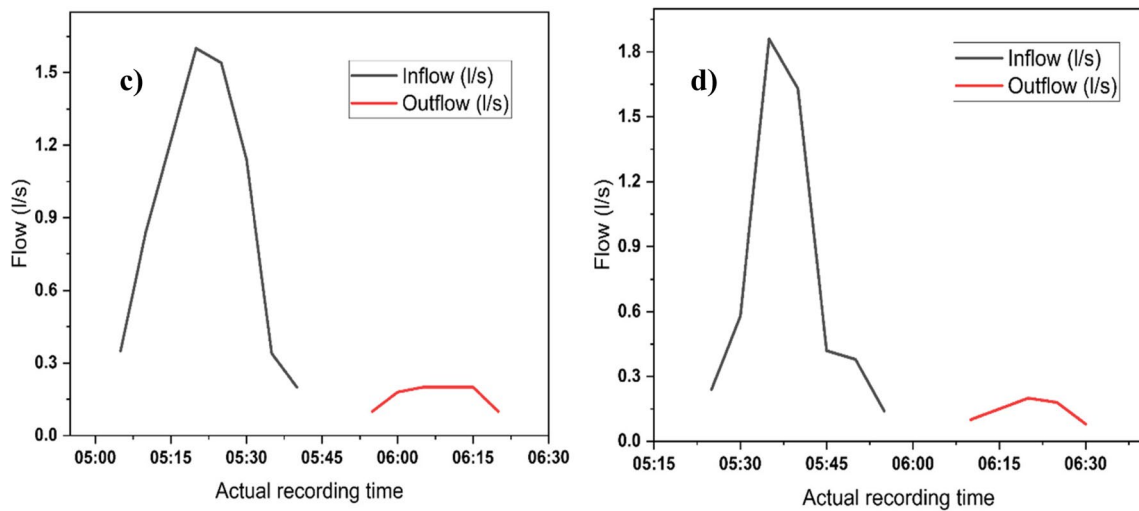


Fig. 14 Inflow vs. outflow hydrographs **c** bioretention cell 4:11/08/2022; **d** bioretention cell 5:11/08/2022

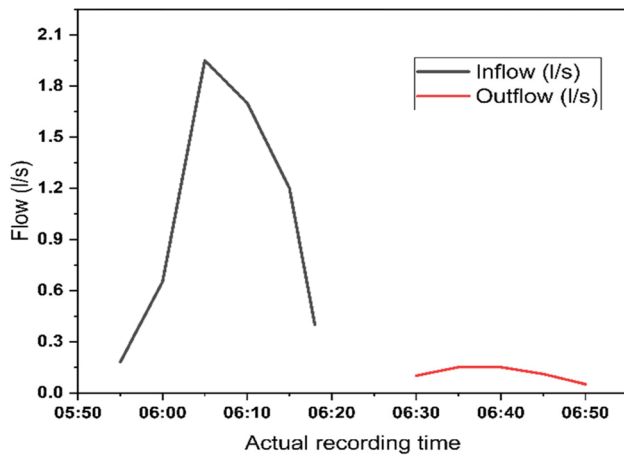


Fig. 15 Inflow vs. outflow hydrographs of bioretention cell 6:11/08/2022

the ponding and storage zone. In monsoon semiarid climate zone in Shaanxi Province of China, a study reported that the bioretention cells were quite effective for in reducing peak flow and runoff volume by over 75% [63]. A study used decentralized hydrological model and observed that bioretention cells could achieve urban flooding reduction rate of higher than 70% [64]. Due to the increase in hydrostatic pressure within the bioretention cells, it was discovered that

a deeper ponding depth resulted in less peak flow treatment and a decrease in lag time [51]. A low capture rate in high rainfall events decreases the hydraulic performance of bioretention cells [52].

Water Quality Performance of Bioretention Cells

TSS Removal

Water sampling was done on five rainfall events. While monitoring the inflow and outflow stormwater from bioretention cell 1, an average TSS removal of 87.2% was observed. The results also revealed that the mean and median outflow concentrations were 156.5 and 155 mg/L, respectively. Bioretention cell 2 had an average TSS removal percentage of 82.9% and the mean TSS of outflow was reported 143 m/L. Similarly, bioretention cells 3 and 4 reported average TSS removal of 82.73 and 83.96% for the observation period (Table 8). The mean TSS concentration in the outflow of bioretention cells 3 and 4 was 145.5 and 124 mg/L, respectively. All the field-scale bioretention cells reported an average TSS removal rate above 80 % which is the recommended removal rate suggested for an efficient bioretention facility (Fig. 16, Fig. 17). An average TSS removal rate of 82.0 and 85.1% were observed for bioretention cell 5 and 6, respectively. Several studies have

Table 8 Average TSS removal recorded on different rainfall events

Bioretention	28-May	17-Jun	20-Jun	30-Jun	04-Jul	Average TSS Removal (%)
Cell 1	87.50	84.88	89.82	83.72	90.10	87.20
Cell 2	79.17	82.20	85.45	85.27	82.41	82.90
Cell 3	83.33	83.25	83.27	81.40	82.41	82.73
Cell 4	84.17	78.53	85.64	85.27	86.17	83.96
Cell 5	80.00	84.29	80.73	80.62	84.63	82.05
Cell 6	87.50	85.34	86.00	81.40	85.06	85.06

Fig. 16 Average TSS removal on different dates against various inflow TSS concentrations

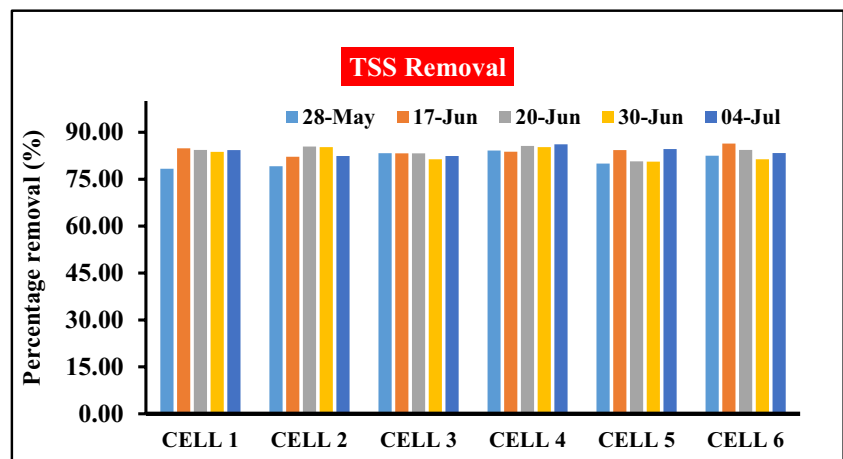
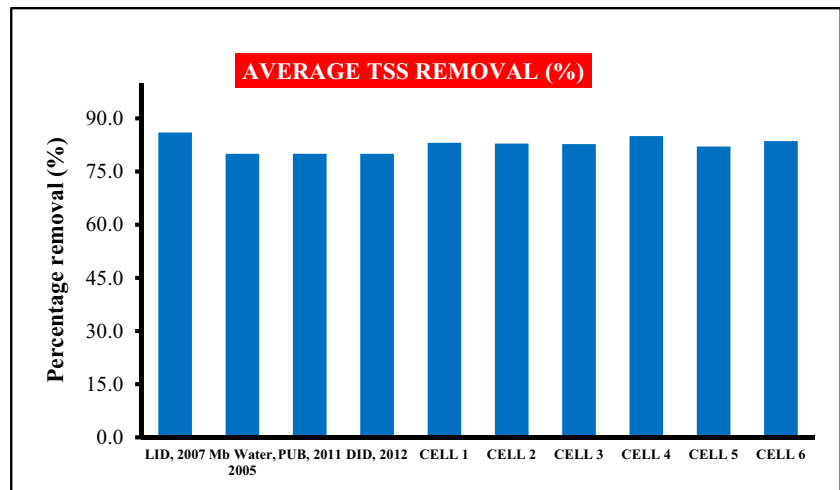


Fig. 17 Average TSS removal performance of bioretention cells



reported above 80% TSS removal efficiency of bioretention cells [65, 66]. The bioretention cells are usually designed to achieve a recommended TSS reduction greater than 80% [67]. A study by [36] suggests that hydraulic conductivity of bioretention filter media in the range of 50–150 mm/h is sufficient for total suspended solids (TSS) and pathogens removal. The outflow from bioretention cells 5 and 6 had a mean outflow concentration of 149.5 and 137.7 mg/L. TSS concentration in the inflow ranged between 322.5 and 1462.75 mg/L with a mean and median concentration of 957.0 and 1025 mg/L. The water quality standard for TSS for all freshwater streams and tributaries is established at 100 mg/L [68]. A varying filter media composition and coarse sand resulted in deposits of 65–75% runoff sediments in the bioretention cells [69]. The deposition may clog the filter media; however, scraping or raking the sediments on top of filter media plays a significant role in restoring the hydraulic conductivity. TSS is mainly removed by physical filtration that mainly depends on the hydraulic conductivity and other properties of filter media [70]. Given the purpose, bioretention cells should be designed to achieve the targeted hydraulic and water quality performance goal within site constraints [48].

Temperature

Thermal pollution is an underrated form of pollution in urban areas. When it rains over an urban catchment, the stormwater runoff moves as sheet flow over roads, roofs and parking lots. As a result of the maximization of the contact surface area between the impervious surface and the stormwater, sheet flow accelerates heat energy transfer [22]. The temperature of stormwater runoff is thus typically high especially the first flush. This high temperature runoff enters the water bodies, which can harm aquatic life. The present study observed the ability of full-scale bioretention cells to lower the temperature of inflow stormwater. Mean temperature reduction of 2.1, 2.3 and 2.4°C was observed for bioretention cells 1, 2 and 3, respectively during the 5 recorded rainfall events. The outflows from bioretention cells 4, 5 and 6 had a mean temperature reduction of 2.3, 2.4 and 2.2°C respectively (Table 9). These findings are in line with results of [71] who on based on monitoring inlet, outlet and soil temperatures during natural rainfall events observed significant reduction in temperature of outflow water from bioretention cells. A total of four bioretention cells in western North Carolina reported an average temperature reduction of 8.8°C. The cooling of inflow stormwater

Table 9 Mean outflow temperature during different natural rainfall events

Bioretention	28-May	17-Jun	20-Jun	30-Jun	04-Jul	Mean temperature reduction (°C)
Cell 1	2.0	2.4	2.1	2.0	1.9	2.1
Cell 2	1.9	2.5	2.4	2.2	2.0	2.3
Cell 3	2.9	2.4	2.3	2.1	2.8	2.4
Cell 4	2.2	2.3	2.4	2.2	2.1	2.3
Cell 5	2.1	2.6	2.4	2.0	2.5	2.4
Cell 6	2.4	2.2	2.5	2.2	2.0	2.2

occurs during passage through filter media, infiltration and heat exchange in the IWSZ [72].

The temperature of inflow during five rainfall events ranged between 29 to 31°C. Outflows from bioretention cells 1, 2 and 3 had an average temperature of 27.9, 27.8 and 27.5°C. Bioretention cells 4, 5 and 6 also lowered the average inflow temperature from 30°C to 27.8, 27.7 and 27.8°C respectively. DO values vary from 15 mg/L at 0°C to 8 mg/L at 30°C [73]. At temperatures of 20 and 30°C, the level of saturated DO is 9.0–7.0 mg/L. Low oxygen in water can kill fish and other organisms present in water. Thus, a small reduction in temperature of outflow stormwater can have a significant effect on the dissolved oxygen in water. A minimum outflow temperature of 27.0, 27.1 and 26.1°C was observed from bioretention cells 1, 2 and 3 respectively on 17-June. On the same date, lowest outflow temperatures of 26.1, 26.8 and 26.9°C were observed from bioretention cells 4, 5 and 6 respectively.

Dissolved Oxygen

The amount of oxygen present in water in dissolved form is referred to as dissolved oxygen (DO). It is an indicator of overall health of water. The amount of DO present in water is a function of water temperature, salinity and turbulence. DO

concentrations in surface water varies between 5 and 14.5 mg O₂ per litre [74]. Since the dissolved and temperature reading were taken in situ, the values of DO were highly temperature dependent. The DO in the inflow stormwater runoff ranged between 5.03 to 5.68 mg/L (Table 10). Outflow from bioretention cells 1, 2 and 3 observed a mean DO of 5.92, 6.76 and 6.71 mg/L respectively. Similarly, mean DO concentrations of 6.66, 6.49 and 6.47 mg/L were observed in the outflows from bioretention cells 4, 5 and 6 respectively. Optimum DO values between 4 and 6 mg/l have been suggested to support aquatic life [75, 76].

Mean BOD concentration in the outflows from bioretention cells 1, 2 and 3 were 1.76, 1.52 and 1.56 mg/L respectively. The BOD concentration in the inflow stormwater ranged between 2.31 to 3.15 mg/L. Outflows from bioretention cells 4, 5 and 6 observed mean BOD of 1.52, 1.55 and 1.43 mg/L for recorded five natural rainfall events. The BOD of drinking water lies between 1 and 2 mg/L. Moderately, clean water have BOD in the range of 3–5 mg/L. BOD value of polluted waters lies between 6 and 9 mg/L. The high BOD value in polluted waters is mainly due to the presence of organic wastes. It can be observed from Table 11 that the values of BOD reported are well within the reported limits for clean water, and thus the water can be released into natural water bodies without harming the aquatic life.

Table 10 Average DO concentration of inflow and outflow from bioretention cells

Sample	28-May	17-Jun	20-Jun	30-Jun	04-Jul	Mean DO (mg/L)
Inflow	5.03	5.68	5.59	5.42	5.55	5.45
O1	6.36	4.56	6.77	5.77	6.12	5.92
O2	6.96	6.52	7.18	6.05	7.10	6.76
O3	6.80	6.01	7.20	5.85	7.70	6.71
O4	6.94	6.08	7.22	6.15	6.92	6.66
O5	6.68	5.77	7.20	5.76	7.04	6.49
O6	7.03	5.85	7.11	5.54	6.82	6.47

*O1, O2, O3, O4, O5 and O6 are outflows from bioretention cells 1, 2, 3, 4, 5 and 6, respectively

Table 11 Mean BOD concentration in outflow vs. inflow

Bioretention	28-May	17-Jun	20-Jun	30-Jun	04-Jul	Mean BOD (mg/L)
Inflow	2.60	2.56	2.38	2.31	3.15	2.60
O1	1.50	1.72	1.91	1.86	1.80	1.76
O2	1.72	1.31	1.38	1.94	1.27	1.52
O3	1.69	1.50	1.67	1.14	1.78	1.56
O4	1.69	1.41	1.45	1.41	1.64	1.52
O5	1.44	1.57	1.38	1.84	1.52	1.55
O6	1.38	1.48	1.40	1.56	1.32	1.43

*O1, O2, O3, O4, O5 and O6 are outflows from bioretention cells 1, 2, 3, 4, 5 and 6, respectively

Table 12 Inflow vs. outflow pH values during different dates

Bioretention	28-May	17-Jun	20-Jun	30-Jun	04-Jul	Average pH
Inflow	6.6	7.2	7.2	7.0	6.9	7.0
Cell 1	7.0	7.0	7.2	6.9	7.2	7.1
Cell 2	8.4	7.2	7.4	6.9	7.1	7.4
Cell 3	7.2	7.1	7.1	7.1	6.8	7.1
Cell 4	7.3	7.6	7.1	7.0	7.3	7.2
Cell 5	7.1	7.1	7.0	7.0	7.0	7.0
Cell 6	7.2	7.5	7.2	7.2	7.0	7.2

pH of Inflow and Outflow Water

Inflow stormwater had a pH in the range of 6.6 to 7.2, indicating that it was slightly acidic to nearly neutral. Stormwater runoff passing through engineered filter media had little or no effect on effluent pH. After passage through engineered filter media, slightly acidic solutions became neutral or slightly basic in nature. The stormwater entering the ponding zone of the bioretention cells had pH in the range of 6.6 to 7.2. After passage through engineered filter media, the stormwater runoff outflow from bioretention cell 1 had pH in the range of 6.9–7.1. The average pH of the stormwater outflow from bioretention cell 1 was 7.1. The outflows from bioretention cells 2 and 3 had an average outflow pH of 7.4 and 7.1, respectively. Similarly, bioretention cells 4 and 5 had average outflow pH of 7.2 and 7.0, respectively. Bioretention cell 6 observed an average outflow pH of 7.2. The results indicated that the sand filter basin did not alter significantly the pH of the stormwater ($p > 0.05$ in both tests). The average inflow pH into the bioretention cells on different dates is 7.0 ± 0.26 . The average value of outflow pH on different dates are 7.1 ± 0.14 , 7.4 ± 0.56 , 7.1 ± 0.15 , 7.2 ± 0.23 , 7.0 ± 0.07 and 7.2 ± 0.18 for bioretention cells 1, 2, 3, 4, 5 and 6 respectively. The average inflow vs outflow pH values from different bioretention cells is given in Table 12. The range of pH achieved in the outflow is consistent with the typical pH values of stormwater obtained in other studies [77].

Conclusions

Indian cities have experienced rapid population growth and increase in impervious area in the last few decades. Due to faulty and insufficient drainage network/capacity, the frequency of urban flash flood has increased significantly. Integrating bioretention cells in the urban drainage network will reduce the load on urban drainage network, prevent choking due to suspended solids, increase groundwater recharge and reduces the incidences of urban floods. The engineered filter media and plant establishment contribute to efficient drainage, mitigating the risk of flooding during

heavy rainfall events in Indian urban areas. One significant contribution of bioretention cells to urban stormwater management is the reduction of peak flow. The property of reducing the peak flow decreases the frequency and chances of occurrence of flash floods. The data on field-scale bioretention cells reveal an average peak flow reduction between 86.1 and 92.3% was observed in the bioretention cells. Another essential hydrological benefit associated with adopting bioretention cells is stormwater volume reduction. Based on the inflow and the corresponding outflow hydrographs, it was found that the bioretention cells can result in 82.95–90.28% stormwater volume reduction. The peak flow and volume reductions achieved surpass the stormwater management goals. Implementing bioretention cells can significantly reduce the impact of stormwater runoff, minimizing the strain on existing drainage systems and mitigating the risk of urban flooding. All the bioretention cells performed exceedingly well, allowing the stormwater to infiltrate the native soil. The total contribution of 6 bioretention cells to the groundwater recharge in three recorded events was 18.2 m^3 . In Indian urban areas, where groundwater depletion is a concern, bioretention cells can play a vital role in replenishing aquifers, supporting sustainable water resource management. The TSS removal percentage ranged between 82.0 to 87.2%. The findings suggest that adopting bioretention cells with engineered filter media and appropriate vegetation can be a viable and effective stormwater management strategy in Indian urban areas. In future, there is a need to investigate the long-term performance and sustainability of vegetated bioretention cells in varied Indian climatic conditions. Integrating the bioretention cells with existing drainage systems to optimize stormwater management also needs to be explored. It is essential to investigate the economic viability and scalability of introducing bioretention cells in densely populated urban areas, while actively involving local governing bodies.

Author Contributions Aamir Ishaq Shah: original manuscript drafting and writing; Mukesh Siag: manuscript draft, supervision; Samanpreet Kaur: technical guidance, data analysis; Sudhir Thaman: manuscript data verification, references; Rakesh Sharda: supervision, technical support and resources.

Declarations

Competing interests The authors declare no competing interests.

References

- Dirks S, Keeling M (2009) A vision of smarter cities: how cities can lead the way into a prosperous and sustainable future, vol 8. IBM Institute for business Value
- Miller JD, Hutchins M (2017) The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. *J Hydrol: Reg Studies* 12:345–362
- Chow MF, Yusop Z, Shirazi SMM (2013) Environmental assessment of bioretention cells. *Environ Assess* 185:8321–8331
- IPCC: Climate Change (2014) Synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland, p 151
- Ramachandra TV, Bharath HA, Gouri K, Vinay S (2017) Green spaces in Bengaluru: quantification through geospatial techniques. *Indian forester* 143(4):307–320
- Fernandes S, Chatterjee B (2017) World environment day: Mumbai lost 60% of its green cover in 40 years, Hindustan Times. Retrieved from <https://www.hindustantimes.com/mumbai-news/40-years-of-development-cost-mumbai-60-of-its-green-cover-65-of-water-bodies-study/story-ySgLLxkoNbBALP3u28X9TI>. Accessed 12 Feb 2023
- Mankikar US, Driver B (2021) Blue-green infrastructure: an opportunity for Indian cities. ORF Occasional Paper 317. May. Observer Research Foundation. Retrieved from: <https://www.orfonline.org/research/blue-green-infrastructure-an-opportunity-for-indian-cities/>. Accessed 11 Feb 2023
- Demuzere M, Orru K, Heidrich O, Olazabal E, Geneletti D, Orru H et al (2014) Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. *J Environ Manage* 146:107–115
- Kulkarni H, Shah M, Shankar PV (2015) Shaping the contours of groundwater governance in India. *J of Hydrology: Regional Studies* 4:172–192
- Ohio Department of Natural Resources (ODNR) (2014) Division of soil and water conservation. In: Mathews J (ed) Rainwater and land development: ohio's standards for stormwater management, low impact development, and urban stream protection, third edition
- Paul J, Parthasarathy S, Gupta P (2017) Exporting challenges of SMEs: a review and future research agenda. *J World Business* 52(3):327–342
- Elmqvist T, Setälä H, Handel SN, van der Ploeg S, Aronson J, Blignaut JN, de Groot R (2015) Benefits of restoring ecosystem services in urban areas. *Curr Opin Environ Sustain* 14:101–108
- Jayasooriya VM, Ng AWM (2014) Tools for modeling of stormwater management and economics of green infrastructure practices: a review. *Water Air Soil Pollut* 225:1–20
- Coffman LS, Siviter T (2004) Advanced bioretention technology. In: Proc 7th Water Res Symp. University of Ohio, p 163
- United States Environmental Protection Agency (USEPA) (2008) Reducing storm-water costs through low impact development strategies and practices. Rep. No. EPA 841-F-07-006. EPA, Washington, D.C. Accessed Feb 2012. <http://www.epa.gov/nps/lid/>
- Davis AP (2009) Field performance of bioretention: hydrology impacts. *J Hydrol Engg* 13:90–95
- Dietz ME, Clausen JC (2007) A field evaluation of rain garden flow and pollutant treatment. *Water Air Soil Pollut* 167:123–138
- NPMCR (2019) Accessed on 6 March; Available online: http://agricoop.nic.in/sites/default/files/NPMCR_1.pdf
- Bhattacharyya P, Bisen J, Bhaduri D, Priyadarsini S, Munda S, Chakraborti M, Nimbrayan P (2021) Turn the wheel from waste to wealth: economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. *Sci Total Environ* 775:145896
- Mohanty SK, Valenca R, Berger AW, Iris KM, Xiong X, Saunders TM, Tsang DC (2018) Plenty of room for carbon on the ground: potential applications of biochar for stormwater treatment. *Sci Total Environ* 625:1644–1658
- Xiong J, Liang L, Shi W, Li Z, Zhang Z, Li X, Liu Y (2022) Application of biochar in modification of fillers in bioretention cells: a review. *Ecol Eng* 181:106689
- Thompson DW, Kennedy JJ, Wallace JM, Jones PD (2008) A large discontinuity in the mid-twentieth century in observed global-mean surface temperature. *Nat* 453(7195):646–649
- Tian J, Jin J, Chiu PC, Cha DK, Guo M, Imhoff PT (2019) A pilot-scale, bi-layer bioretention system with biochar and zero-valent iron for enhanced nitrate removal from stormwater. *Water Res* 148:378–387
- Jarrett A (2016) Rain gardens (bioretention cells): a stormwater BMP. Penn State Extension extension.psu.edu/rain-gardens-bioretention-cells-a-stormwater-bmp
- Brown RA, Line DE, Hunt WF (2012) LID treatment train: pervious concrete with subsurface storage in series with bioretention and care with seasonal high-water tables. *J Environ Engg* 138:689–697
- Hunt WF, Smith JT, Jadlocki SJ, Hathaway JM, Eubanks PR (2008) Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC. *J Environ Engg* 134:403–408
- Minnesota Pollution Control Agency (MPCA) (2008) Minnesota stormwater manual. St. Paul, Minnesota, USA. <http://www.pca.state.mn.us/index.php/water/water-types-and-programs/storm-water/stormwater-management/minnesotas-stormwater-manual.html>. Accessed 14 Mar 2023
- Olson NC, Gulliver JS, Nieber JL, Kayhanian M (2013) Remediation to improve infiltration into compact soils. *J Environ Manage* 117:85–95
- Paus KH, Morgan J, Gulliver JS, Leiknes T, Hozalski RM (2015) Assessment of the hydraulic and toxic metal removal capacities of bioretention cells after 2 to 8 years of service. *Water Air Soil Pollut* 225:1–12
- Skorobogatov A, He J, Chu A, Valeo C, van Duin B (2020) The impact of media, plants and their interactions on bioretention performance: a review. *Sci Total Environ* 715:136918
- Gibbens RP, Lenz JM (2001) Root systems of some Chihuahuan Desert plants. *J Arid Environ* 49(2):221–263
- Baird RB, Eaton AD, Clesceri LS (2012) In: Rice EW (ed) Standard methods for the examination of water and wastewater, vol 10. American public health association, Washington, DC
- Shrestha A, Shrestha SM, Pradhan AMS (2023) Assessment of spring water quality of Khandbari Municipality in Sankhuwasabha District, Eastern Nepal. *Environ Sci Pollut Res* 30(43):98452–98469
- OEPA (2013) Ohio nutrient reduction strategy. Ohio EPA, Columbus, OH
- Southeast Michigan Council of Governments (SEMCOG) (2008) Low impact development manual for Michigan: a design guide for implementers and reviewers.
- Denich C, Bradford A, Drake J (2013) Bioretention: assessing effects of winter salt and aggregate application on plant health, media clogging and effluent quality. *Water Qual Res J Canada* 48(4):387–399

37. Hunt WF, Davis AP, Traver RG (2012) Meeting hydrologic and water quality goals through targeted bioretention design. *J Environ Engg* 138(6):698–707
38. Luell SK, Hunt WF, Winston RJ (2011) Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff. *Water Sci Technol* 64(4):974–979
39. Asleson BC, Nestingen RS, Gulliver JS, Hozalski RM, Nieber JL (2008) Performance assessment of low impact stormwater practices. In: *World Environ and Water Res Congress: AHupua'A*, pp 1–11
40. PGC (1993) Design manual for use of bioretention in stormwater management. In: *Prince George's County (MD) Government Department of Environmental Protection Watershed Protection Branch, Landover, MD*
41. Le Coustumer S, Fletcher TD, Deletic A, Barraud S (2007) Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies. *Water Sci Technol* 56:93–100
42. Kandra HS, McCarthy D, Fletcher TD, Deletic A (2014) Assessment of clogging phenomena in granular filter media used for stormwater treatment. *J Hydrol* 512:518–527
43. Segismundo EQ, Kim LH, Jeong SM, Lee BS (2017) A laboratory study on the filtration and clogging of the sand-bottom ash mixture for stormwater infiltration filter media. *Water* 9:32
44. Houdeshel CD, Hultine KR, Johnson NC, Pomeroy CA (2015) Evaluation of three vegetation treatments in bioretention gardens in a semi-arid climate. *Lands and Urban Plann* 135:62–72
45. Rachman A, Anderson SH, Gantzer CJ, Alberts EE (2004) Soil hydraulic properties influenced by stiff-stemmed grass hedge systems. *Soil Sci Soc Am J* 68(4):1386–1393
46. Fassman-Beck E, Wang S, Simcock R, Liu R (2015) Assessing the effects of bioretention's engineered media composition and compaction on hydraulic conductivity and water holding capacity. *J Sustain Water Built Environ* 1(4):04015003
47. Muerdter C, Özkök E, Li L, Davis AP (2016) Vegetation and media characteristics of an effective bioretention cell. *J of Sustainable Water in the Built Environ* 2(1):04015008
48. Hatt BE, Fletcher TD, Deletic A (2009) Hydrologic and pollutant removal performance of stormwater biofiltration systems at field scale. *J Hydrol* 365:310–321
49. Winston RJ, Dorsey JD, Hunt WF (2016) Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Sci Total Environ* 553:83–95
50. Lucke T, Nichols PW (2015) The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. *Sci Total Environ* 536:784–792
51. Gulbaz S, Kazezyılmaz-Alhan CM (2017) Experimental investigation on hydrologic performance of LID with rainfall-watershed-bioretention system. *J Hydrol Engg* 22(1):D4016003
52. Li H, Sharkey LJ, Hunt WF, Davis AP (2009) Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland. *J Hydrol Engg* 14(4):407–415
53. Behera PK, Papa F, Adams BJ (1999) Optimization of regional storm-water management systems. *J Water Res Plan Manage* 125(2):107–114
54. Custódio DA, Ghisi E (2023) Impact of residential rainwater harvesting on stormwater runoff. *J Environ Manage* 326:116814
55. Heiberger JR (2013) Infiltration and potential groundwater recharge performance of stormwater bioretention designed for semiarid climates. *The University of Utah*
56. Khan UT, Valeo C, Chu AV, Van Duin B (2012) Bioretention cell efficacy in cold climates: Part 1—hydrologic performance. *Canadian J of Civil Engg* 39(11):1210–1221
57. Lucas WC, Sample DJ (2015) Reducing combined sewer overflows by using outlet controls for Green Stormwater Infrastructure: case study in Richmond, Virginia. *J Hydrol* 520:473–488
58. Heasom W, Traver RG, Welker A (2006) Hydrologic modeling of a bioinfiltration best management practice 1. *JAWRA J of the American Water Res Association* 42(5):1329–1347
59. Ermilio JR, Traver RG (2006) Hydrologic and pollutant removal performance of a bio-infiltration BMP. In: *World Environmental and Water Resource Congress 2006: examining the confluence of environmental and water concerns*, pp 1–12
60. Sepehri M, Malekinezhad H, Ilderomi AR, Talebi A, Hosseini SZ (2018) Studying the effect of rain water harvesting from roof surfaces on runoff and household consumption reduction. *Sustain Cities Soc* 43:317–324
61. Roehr D, Laurenz J, Kong Y (2009) Green envelopes: contribution of green roofs, green facades, and green streets to reducing stormwater runoff, CO₂ emissions, and energy demand in cities. In: *Low impact development for urban ecosystem and habitat protection*, pp 1–8
62. Kratky H, Li Z, Chen Y, Wang C, Li X, Yu T (2017) A critical literature review of bioretention research for stormwater management in cold climate and future research recommendations. *Front Environ Sci Eng* 11:1–15
63. Liu N, Wang M, Zhou F, Zhai H, Qi M, Liu Y et al (2021) Selenium bioavailability in soil-wheat system and its dominant influential factors: a field study in Shaanxi province, China. *Sci Total Environ* 770:144664
64. Liao KH, Deng S, Tan PY (2017) Blue-green infrastructure: new frontier for sustainable urban stormwater management. In: *Greening cities: forms and functions*. Singapore, Springer Singapore, pp 203–226
65. Hsieh CH, Davis AP (2005) Evaluation and optimization of bioretention media for treatment of urban storm water runoff. *J Environ Engg* 131(11):1521–1531
66. Bratieres K, Fletcher TD, Deletic A, Zinger Y (2008) Nutrient and sediment removal by stormwater biofilters: a large-scale design optimization study. *Water Res* 42:3930–3940
67. ANZECC, ARMCANZ (2000) Australian and New Zealand guidelines for fresh and marine waters. *National Water Quality Management Strategy Paper No 4*. Australian and New Zealand Environment and Conservation Council & Agriculture Resource Management Council of Australia and New Zealand, Canberra
68. Oregon DEQ (2004) Oregon Administrative Rules, Chapter 430, Division 041. In: *Water Quality Standards: beneficial uses, policies, and criteria for Oregon*
69. Jenkins JKG, Wadzuk BM, Welker AL (2010) Fines accumulation and distribution in a storm-water rain garden nine years post construction. *J Irri Drain Engg* 136(12):862–869
70. Blecken GT, Zinger Y, Deletić A, Fletcher TD, Hedström A, Viklander M (2010) Laboratory study on stormwater biofiltration: nutrient and sediment removal in cold temperatures. *J Hydrol* 394(3–4):507–514
71. Jones MP, Hunt WF (2009) Bioretention impact on runoff temperature in trout sensitive waters. *J of Environ Engg* 135(8):577–585
72. Barbis J, Welker AL (2010) Stormwater temperature mitigation beneath porous pavements. In: *World Environmental and Water Resources Congress 2010: Challenges of Change*, pp 3971–3979
73. Wetzel RG (2001) *Limnology: lake and river ecosystems*, 3rd edn. Academic Press, London, p 1006
74. Shah KA, Joshi GS (2017) Evaluation of water quality index for River Sabarmati, Gujarat, India. *App Water Sci* 7(3):1349–1358
75. Leo ML, Dekkar M (2000) *Hand book of water analysis* (1–25, 115–117, 143, 175, 223–226, 261, 273, 767). Marcel Dekker, New York
76. Eichler PP, Eichler BB, de Miranda LB, da R M Pereira E, Kfourri PB, Pimenta FM, Vilela CG (2003) Benthic foraminiferal response to variations in temperature, salinity, dissolved oxygen and organic carbon, in the Guanabara Bay, Rio de Janeiro, Brazil. *Anuário do Instituto de Geociências* 26:36–51

77. Barańkiewicz D, Chudzińska M, Szpakowska B, Świerk D, Gołdyn R, Dondajewska R (2014) Storm water contamination and its effect on the quality of urban surface waters. *Environ Monit Assess* 186:6789–6803

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.