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Unit-scale- and catchment-scale-based sensitivity analysis of bioretention cell for urban stormwater system management

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ABSTRACT

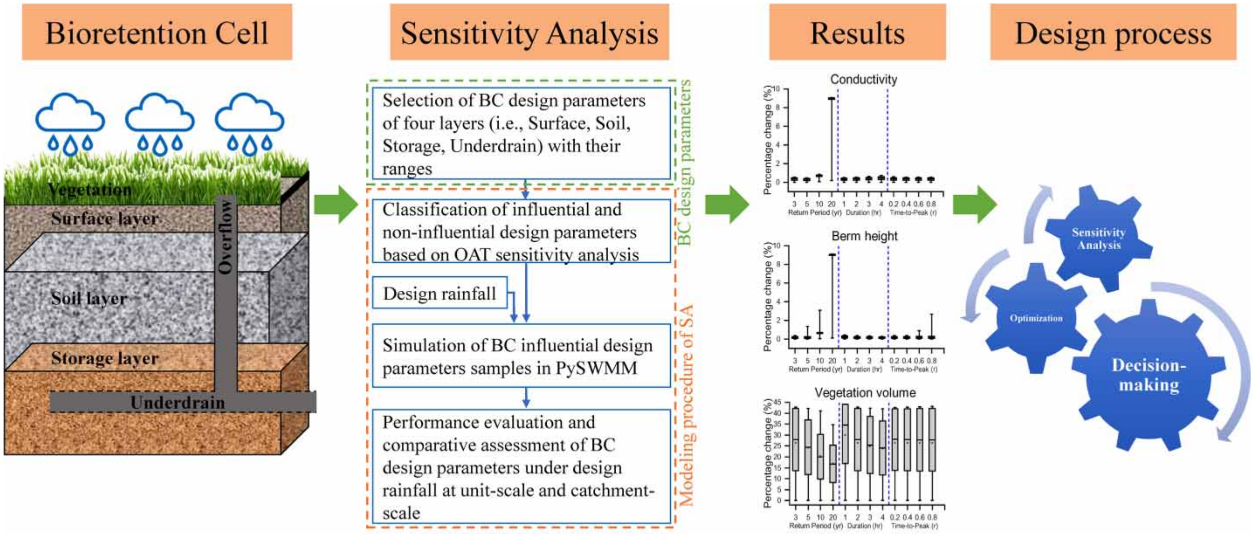
An improved understanding of bioretention cell (BC) design configuration at both the unit scale and catchment scale is necessary for critical insight into dynamical behaviors of design parameters, which resultantly guides and improves the effectiveness and efficiency of a BC. A comprehensive sensitivity analysis (SA) of BC design parameters was conducted in this study by using the Stormwater Management Model (SWMM) which is globally used for BC's modeling. The preliminary screening of various design parameters is conducted by the one-factor-at-a-time (OAT) SA method and the key influential parameters (i.e., conductivity, berm height, vegetation volume, suction head, porosity, wilting point, and soil thickness) are selected for further SA. To this end, 1,000 random uniformly distributed samples of each sensitive design parameter are simulated by a Python wrapper of SWMM (PySWMM) under different design storms at the unit scale and catchment scale, respectively. Unit-scale SA results found unique characteristics of each design parameter under different storm scenarios, and their behaviors toward different model responses dynamically change within their factor spaces. Catchment-scale SA results conclude vegetation and soil layers design parameters have significant impacts on controlling stormwater at the catchment scale, and optimal selection of design parameters of vegetation (type, density, and height) and soil (type, layer thickness, and void ratio) is necessary for significantly improving the effectiveness of the BC at the catchment scale.

Key words: bioretention cell, hydrological performance, sensitivity analysis, unit and catchment scales, urban stormwater system

HIGHLIGHTS

- Improved understanding of the hydrological performance of design parameters of bioretention cells at unit and catchment scales.
- Enhanced hydrological responses of bioretention design parameters toward different model outputs.
- Optimal retrofitting of bioretention cell configuration for improving urban stormwater management.

GRAPHICAL ABSTRACT



Conclusions: The findings of this study recommend the precise selection of bioretention design parameters especially berm height, vegetation volume, and soil thickness in soil and storage layers, and other influential design parameters during modeling and construction considering local climate dynamics and design guidelines for improving bioretention cell design efficiency.

1. INTRODUCTION

Low-impact developments (LIDs) including bioretention cells (BCs) have been globally accepted as sustainable green infrastructure solutions to potentially contribute to coping with quantitative and qualitative problems escalating under climate change impacts (Nasseri *et al.* 2018; Loáiciga *et al.* 2019; Samouei & Özger 2020; Prettyman *et al.* 2021). In the past two decades, hydrological performance evaluation of LIDs under different hydro-meteorological and topographical conditions have proved their effectiveness in controlling stormwater's quantitative and qualitative parameters, which had been gradually triggered by recent upsurges in population and urbanization patterns (Yang & Chui 2018; Tansar *et al.* 2023). Resultantly, impervious areas severely increased in urban catchments disrupted the natural hydrological cycle, and increased surface and peak flows which caused stormwater management problems including urban flooding and accumulation of pollutants and debris loads (Liu *et al.* 2015; Palla & Gnecco 2015). Retrofitting LIDs against impervious regions in urban catchment significantly changes the hydrological response of catchment and effectively makes an effort to mimic pre-development hydrological conditions and control pollutants generated by non-point sources during storms (Guo *et al.* 2019).

Over recent years, numerous research studies have been conducted to evaluate the performance of LIDs in individual or in combinations with grey infrastructures to optimize location and scale by retrofitting LIDs, with consideration of various design factors including retrofitting life cycle costs against qualitative and quantitative advantages, and evaluation of optimal designs to mitigate future extreme storms impacted by climate change (Zhang & Chui 2018; Gao *et al.* 2022; Wang *et al.* 2023). A significant number of research studies conclude combined application of LIDs and grey infrastructure is the most cost-effective and sustainable solution, as the benefits of both types of systems superimpose their individual effects, which help to support stormwater management with an efficient approach (Islam *et al.* 2021). The majority of research studies discussed the efficiency and effectiveness of LIDs to mitigate stormwater management problems considering available resources (i.e., construction costs, location, and scale, etc.); however, limited research studies are conducted to understand hydrological dynamics of different design parameters under different storm conditions to better understand design configurations of LIDs/BC at the unit scale (Brunetti *et al.* 2018; Madrazo-Uribeetxebarria *et al.* 2021; Tansar *et al.* 2023), especially with the Stormwater Management Model (SWMM), as the SWMM is the most globally used hydrological-hydraulic model for planning, designing, modeling, optimization, and performance evaluation of LIDs within urban catchment.

The SWMM is preferred over other models because it is freely available open-source software, and it is an integrated platform to run hydrologic, hydraulic, and water quality simulations (i.e., single event and long term), especially in urban areas (also can be used for non-urban areas) for qualitative and quantitative evaluations of stormwater and wastewater for better planning and management. Furthermore, some previous research studies have used global sensitivity methods (e.g., variogram analysis of response surface (VARS) method, Sobol method, etc.) for parametric study of the BC or other LID design parameters (Brunetti *et al.* 2018; Korgaonkar *et al.* 2020; Madrazo-Uribeetxebarria *et al.* 2021; Tansar *et al.* 2023), although these methods help to do a more deep study of design parameters of the BC, its responses and underlying processes; however, these methods are also more complex, need higher computational resources and time, and mostly the modelers need to prepare a set-up to couple hydrological model (i.e., PySWMM or SWMM) with the global sensitivity method by using any coding language, which sometimes faces limitations (i.e., may need larger time and more skills) during applications. The methodology presented in this paper is more simple and more readily applicable to studying and developing an appropriate understanding of design parameters and their impacts on model responses. Moreover, other studies also used sensitivity analysis (SA) methods and rainfall forecasting by using artificial neural networks (ANNs) in combination with hydrological models (Nasseri *et al.* 2008; Nasseri & Asghari 2015). Recently recognized different machine learning techniques (Yuan *et al.* 2018; Adnan *et al.* 2020, 2021, 2023; Ikram *et al.* 2022a, 2022b, 2022c) can be used for a better understanding of the BC water balance and how its design can be improved for enhancing its efficiency for flood reduction at a catchment scale.

The BC is selected from among other LIDs because of its higher effectiveness to control stormwater (Tansar *et al.* 2022) and hydrological performance evaluation of its design parameters for improved understanding of the response of design configurations under different storm conditions at the unit scale and catchment scale. Limited attention is paid in previous research studies to the understanding of potentials and contributions of design parameters in response to different model outputs and rainfall conditions at the unit scale, and how it helps to better understand the dynamical characteristics of each design parameter and its effects on the water balance of the BC. The main novel contribution of this paper is to improve understanding of parametric response on different model outputs (i.e., surface infiltration, surface outflow, storage, and peak flow) under different storm conditions in the SWMM helps to select optimal values of design parameters for improving efficiency and effectiveness of the BC at the unit scale.

Furthermore, the insights gained from parametric analysis of BC modeling in the SWMM at the unit scale can potentially contribute to the decision-making of optimal selection of different design parameters of the BC for its practical implementation in the urban catchment. For example, the effective range of depth of different layers (i.e., surface, soil, and storage layers), physical properties of vegetation (i.e., type, density, and height, etc.), design characteristics of soil (i.e., type, size, shape, and other hydrological properties of soil such as conductivity, porosity, residence time, and water retention capacity), and impacts of underdrain on hydrological dynamics of the BC. Resultantly, an optimally designed BC with higher efficiency and effectiveness in terms of higher infiltration and storage capacity would not only be helpful in cost-effectiveness but also contribute to enhancing achieving target design goals (i.e., surface and peak flow control, urban flood control, and pollution load control) of the BC at a larger scale, (i.e., catchment scale). The selection of optimal values of different design parameters is one of the main problems for improving the efficiency of the BC. Considering this, this paper originally contributes to improving the effectiveness and efficiency of the BC by enhancing understanding of its design configurations at the unit scale and catchment scale through SA of its design parameters for different model responses and rainfall conditions, which would be helpful in the future for stormwater managers, green infrastructure modelers, practitioners, and researchers for accurate selection of their optimal values.

To fill the above-mentioned research gaps, the main objectives of this research study are: (1) to categorize influential and non-influential design parameters of bioretention cell and (2) to do an SA of bioretention design parameters at the unit scale and catchment scale for improved understanding of design configurations of the BC under different storms and model responses.

2. STUDY AREA

Sensitivity analysis of the BC is conducted at two scales: (a) unit scale and (b) catchment scale. A unit scale of the BC is based on a single hypothetical sub-catchment of 1 km^2 (1,000 m $\times$ 1,000 m) with 5% treatment of the impervious area with the BC. The conceptual BC model in the SWMM is based on three vertical layers: (1) surface layer, (2) soil layer, and (3) storage layer, as shown in Figure 1(a). The surface layer receives precipitation and runoff drained from other nearest impervious areas which distribute into outflow, evaporation, and infiltration. The infiltrated flow in the first layer passed through the soil layer and percolates to the storage layer. An optional underdrain layer system is placed at the gravel storage bed which received exfiltration from the storage layer and outflowed to the drainage system. Furthermore, the underdrain layer is also connected to an overflow pipe which can overflow during the higher rate of exfiltration. A synthetic urban drainage catchment of 7.2 km^2, having 8 sub-catchments, 13 conduits, 13 junctions, and an outfall is selected for hydrological performance evaluation of the BC at the catchment scale, as shown in Figure 1(b). The percentage of the BC decided between 10 and 30% on all sub-catchments to represent diverse hydrological characteristics of the catchment, and 50% impervious area of each sub-catchment was retrofitted with the BC.

3. METHODOLOGY

We present a simple and computationally efficient SA method employed at unit scale and catchment scale for improved understanding of hydrological behaviors of influential design parameters of the BC toward different model responses at the unit scale (e.g., surface infiltration volume, surface outflow volume, and storage volume) and catchment scale (e.g., surface runoff volume, peak runoff volume, storage volume, and outflow volume of catchment) under different design rainfall conditions (e.g., return period, storm duration, time-to-peak). The main goal of SA at both scales is to better understand the hydrological dynamics and effectiveness of the BC at the unit scale and how it contributes to control different stormwater routing parameters at the catchment scale.

Figure 2(a) represents step-by-step methodology used in this study. In the first step of the methodology, the OAT method is employed on 18 BC design parameters for the classification of influential and non-influential parameters, and only seven influential parameters including conductivity, berm height, vegetation volume, suction head, porosity, wilting point, and soil thickness were found to be sensitive (as shown in Figure 3) and chosen for further evaluation. The next step is to decide factor spaces (ranges) of design parameters based on BC design guidelines from the SWMM reference manual (Rossman & Huber 2016), and the Technical Guide of Sponge City Construction of Low Impact Development (MOHURD 2014), and represented in Table 1. Following that, a uniform random sampling technique is adopted for generating 1,000 random samples of each sensitive design parameter across the factor space for equal representation of every part of the parameter's design space, which may also have an acceptable probability of engineering accuracy (Tung *et al.* 2006). Furthermore, the Python wrapper of SWMM (PySWMM) (McDonnell *et al.* 2020) is used for iterative simulations of design parameters' samples at unit-scale and catchment-scale models and different hydrological performance evaluation indices were calculated at both scales.

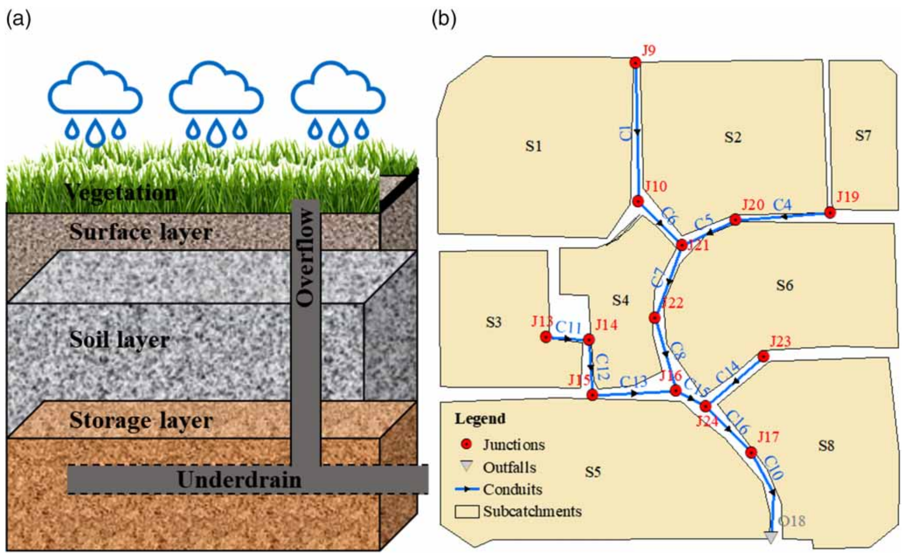


Figure 1 | (a) Bioretention cell and (b) map of synthetic study area.

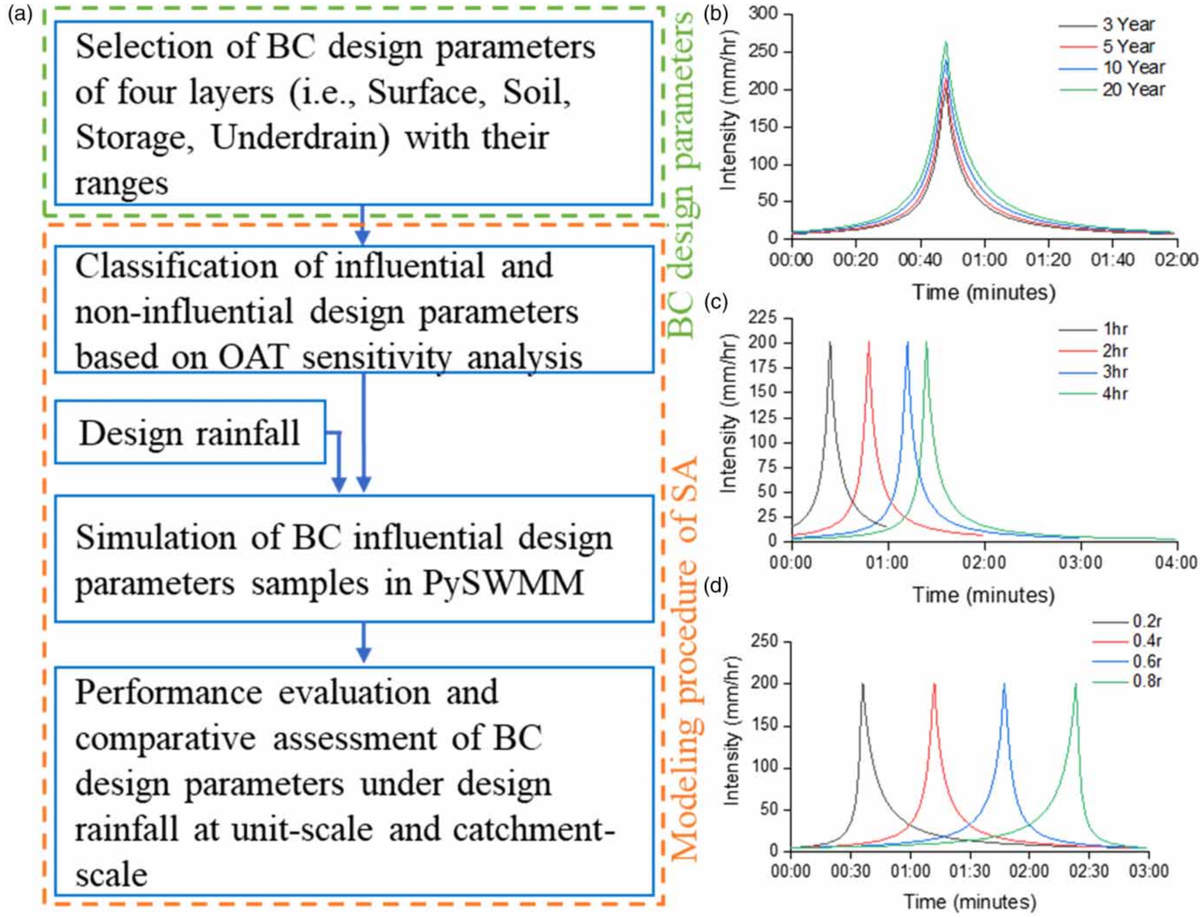


Figure 2 | (a) Methodological framework of SA. Design rainfall for (b) return period, (c) storm duration, and (d) time-to-peak.

Furthermore, four design rainfalls of each scenario (i.e., intensity, storm duration, time-to-peak) were considered, with return periods (e.g., 3, 5, 10 and 20 years), storm durations (e.g., 1, 2, 3, and 4 h), and time-to-peaks (e.g., 0.2, 0.4, 0.6, and 0.8*r*), as represented in Figure 2(b)–2(d), respectively. Here, *r* is a parameter that represents ratio of time-of-peak to total storm duration. The Chicago design storm method (Keifer & Chu 1957) together with the Shanghai rainstorm IDF formula (Shanghai Municipal Engineering Design Institute 2003; Tansar *et al.* 2022) was used for designing synthetic rainfall and hyetograph of synthetic rainfall was formulated by using an alternating block method. The 3-year design rainfall was selected for analysis of the hydrological response of the BC against storm duration and time-to-peak scenarios. Readers are referred to Tansar *et al.* (2023) for detailed technical background and modeling set-up of bioretention cells in the SWMM.

4. RESULTS AND DISCUSSION

Seven out of 18 design parameters of the BC are selected during the OAT SA method for three model responses, i.e., surface infiltration volume, storage volume, and surface outflow volume, as represented in Figure 3. The sensitivity of design parameters linearly changes according to percentage-based variations in design parameters' values (i.e., +5, +10, +15, +20, and −5, −10, −15, −20) with respect to base value. Overall, berm height, conductivity, and porosity performed better than the other four design parameters including wilting point, vegetation volume, suction head, and soil thickness. Furthermore, all design parameters are highly sensitive to surface infiltration volume and storage volume compared to surface outflow volume.

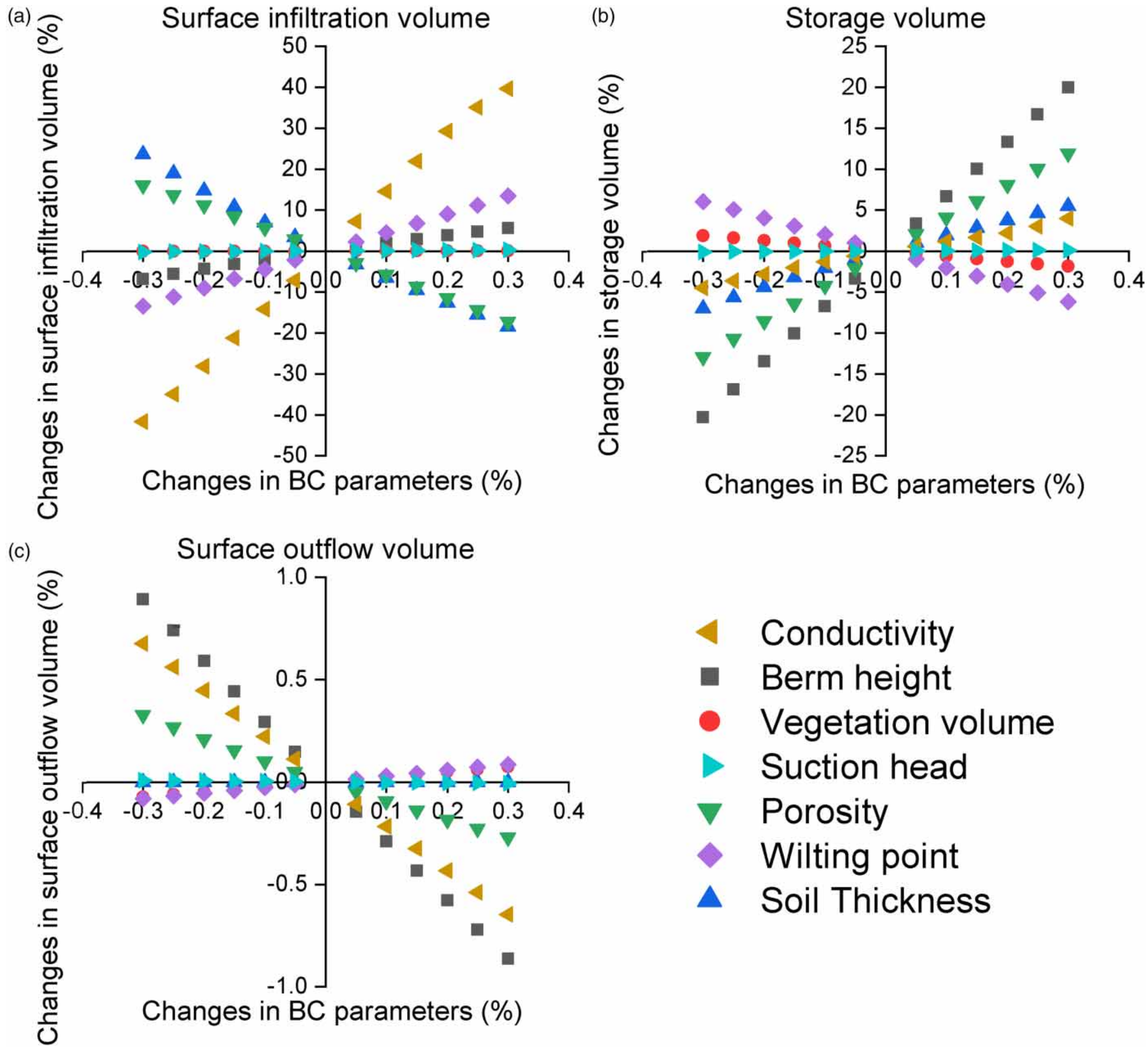


Figure 3 | One-factor-at-time (OAT) SA results of bioretention cell parameters for (a) surface infiltration volume, (b) storage volume, and (c) surface outflow volume.

4.1. Sensitivity analysis of BC design parameters at the unit scale

Sensitivity analysis of the BC at the unit scale with variations of different design parameters improves understanding about the characteristics and variation scale of different BC responses under different rainfall conditions. Considering this, three model responses such as surface infiltration volume, storage volume, and surface outflow volume were selected to understand the extent of variations of these design parameters with variations of parameters' values across the factor spaces.

4.1.1. Surface infiltration volume

Hydrological response of each parameter against variation of parameter values within its design space represents unique patterns under different rainfall conditions, as shown in Figure 4. For example, conductivity represented a gradual rise in its median and interquartile range (IQR) from lower to higher and shorter to longer storm events, however, a reversal effect was noticed for time-to-peak storms. Results explain that the sensitivity of conductivity parameter increases for higher return periods and longer storm events compared to lower intensity and shorter rainfall events. However, earlier peak storm events represented more variability in infiltration volume compared to later peak storms. It indicates that the identical

Table 1 | BC designed parameters with their ranges

Layers	Design parameters	Range
Surface	Berm height (mm)	100–300
	Vegetation volume (fraction)	0–1
	Surface roughness (Manning's *n*)	0–0.24
	Surface slope (%)	0–5
Soil	Thickness (mm)	450–900
	Porosity (volume fraction)	0.45–0.60
	Field capacity (volume fraction)	0.15–0.25
	Wilting point (volume fraction)	0.05–0.14
	Conductivity (mm/h)	0.25–120
	Conductivity slope	30–60
	Suction head (mm)	49–320
Storage	Thickness (mm)	150–900
	Void ratio (voids/solids)	0.2–0.4
	Seepage rate (mm/h)	127–381
	Clogging factor	–
Underdrain	Drain coefficient (mm/h)	0–0.5
	Drain exponent	0–0.5
	Drain offset height (mm)	0–305

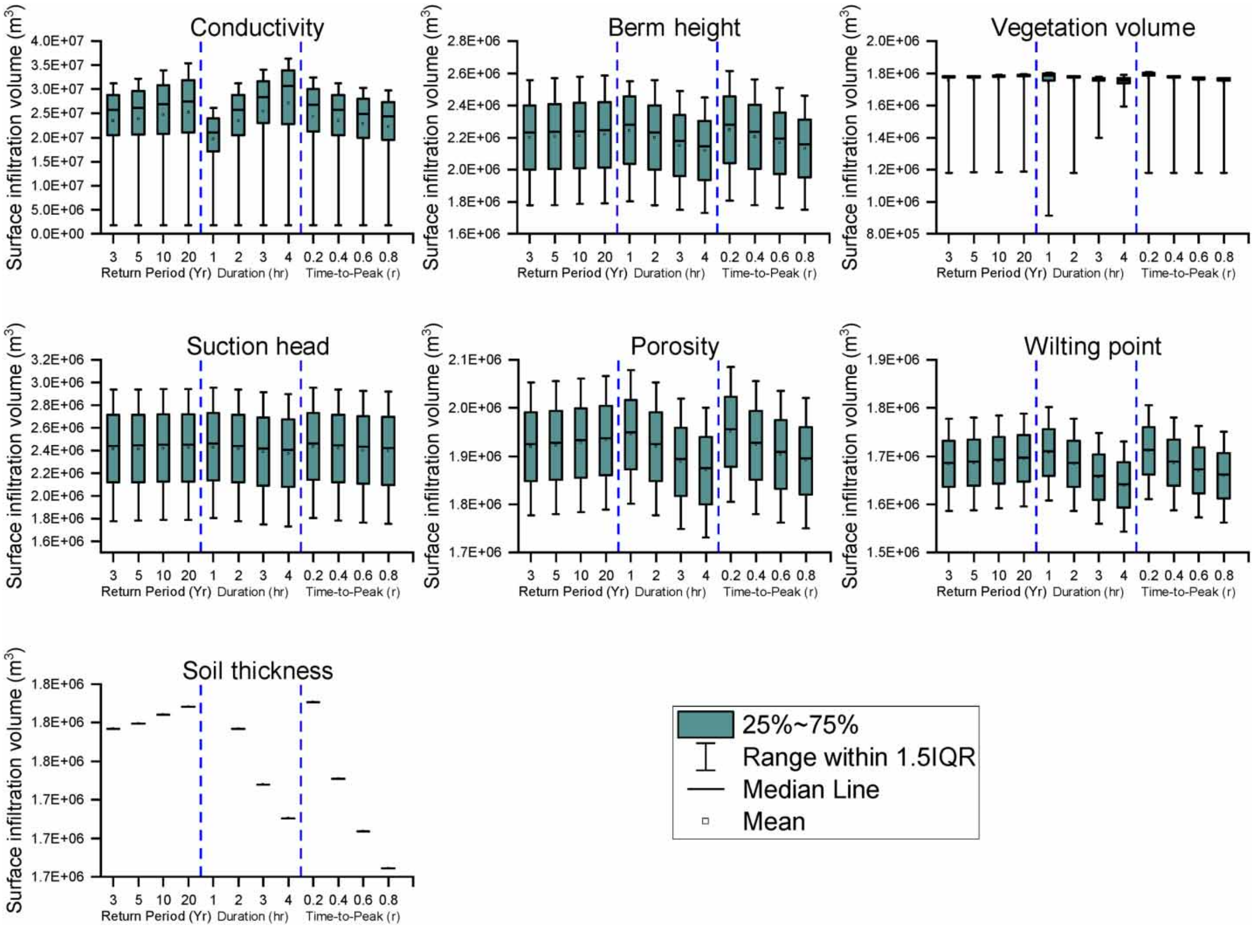


Figure 4 | Unit-scale hydrological response of different BC design parameters on the surface infiltration volume under return period, storm duration, and time-to-peak scenarios.

variation in design parameters results in larger changes in infiltration volume in sensitive storms compared to less sensitive ones. Apart from rainfall effects, the response of the design parameter also varies within its design space, as some part of the factor space is more sensitive compared to others.

In the case of conductivity, the first quartile of infiltration volume represents larger variations (as the first quartile (Q1) has larger spread characteristics), however, the remaining part of volume showed less variation in infiltration volume (as upper quartiles' results (Q2–Q4) are in concentrated form). These results are showing dynamic characteristics of parameter behavior within the design space, with 25% of the total design space producing lower infiltration volume with larger variability and the remaining 75% portion generating higher infiltration volume with less variability. In the case of other design parameters, berm height, porosity, and wilting point represented limited variation in their median and IQR for return period scenarios; however, the gradual reduction in their median infiltration volume from shorter to longer durations and earlier to later peaks highlight their maximum potential of water infiltration and storage which can be exploited because of maximum available storage capacity of soil layer (i.e., empty void spaces). In addition, these three parameters exhibited roughly equal representations of the parameter's design space for infiltration volume. The suction head's median and IQR exhibited minimal variation, and its design space has an equal sensitivity level of infiltration volume within its design space. Vegetation volume represents significant variation for only 25% of its design space and other portions of the design space represent limited variation in infiltration volume. Soil thickness represented no significant variation in infiltration volume by changing depth within its design range.

4.1.2. Storage volume

The distinctive pattern of hydrological behaviors of design parameters in response to variation of its design space for storage volume under different storm conditions was observed, as shown in Figure 5. Taking conductivity as an example, the first quartile (Q1) of storage volume has significant variations, while the remaining three quartiles (Q2–Q4) showed limited variations in all storm scenarios. Moreover, a consistent expansion and reduction in the first quartile of storage volume for lower to higher intensity and earlier to later peak storms, respectively, represent the dynamical behavior of design parameters within its design space under different storm conditions. However, the expansion of storage volume around its median from shorter to longer storms indicates an increase in sensitivity of 75% of the design parameters' factor space, which contributed to the variation of storage volume of upper quartiles (Q2–Q4). Berm height showed limited storage volume for return period scenarios and gradual median and IQR reduction from shorter to longer and earlier to later peak storms. Vegetation volume showed very insignificant variations in storage volume for all rainfall scenarios.

Moreover, each portion of the parameter design space for both parameters (berm height and vegetation volume) showed equal potential for storage volume. The suction head's storage volume increased gradually from lower to higher return periods and decreased significantly from shorter to longer and earlier to later peak storm events. Porosity and wilting point had a similar effect on a storage volume, with a gradual increase from lower to higher return periods and a significant decrease from shorter to longer and earlier to later peak storm events. Furthermore, the design space outputs of both parameters are constrained to limited ranges of storage volume. In terms of soil thickness, there is a clear upward trend in infiltration volume from lower to higher storm events, as well as a downward trend from shorter to longer and earlier to later peak storm events (like its results of surface infiltration volume). The results, however, show that soil depth has an equal effect on storage volume within its design space.

4.1.3. Surface outflow volume

Generally, conductivity, berm height, and vegetation volume demonstrated significant impact and suction head, porosity, and wilting point showed an insignificant effect on surface outflow volume by variation of parameter values within their design spaces, as shown in Figure 6. Conductivity demonstrated a significant increase in outflow volume from lower to higher return periods, but only a limited increase from shorter to longer and earlier to later peak storm events. Furthermore, the comparison of the first three quartiles (Q1–Q3) with the fourth represents larger variations in later quartiles. Berm height and vegetation volume both represented a significant increase in outflow volume from lower to higher and shorter to longer storm events, respectively, with no variation observed for time-to-peak scenarios. Berm height showed larger variations in outflow volume within its design space, whereas vegetation volume was relatively smaller. Other three parameters, including suction head, porosity, and wilting point, demonstrated a similar pattern of results with significant incremental variation during return periods and storm duration scenarios, but no significant change was observed for time-to-peak scenarios.

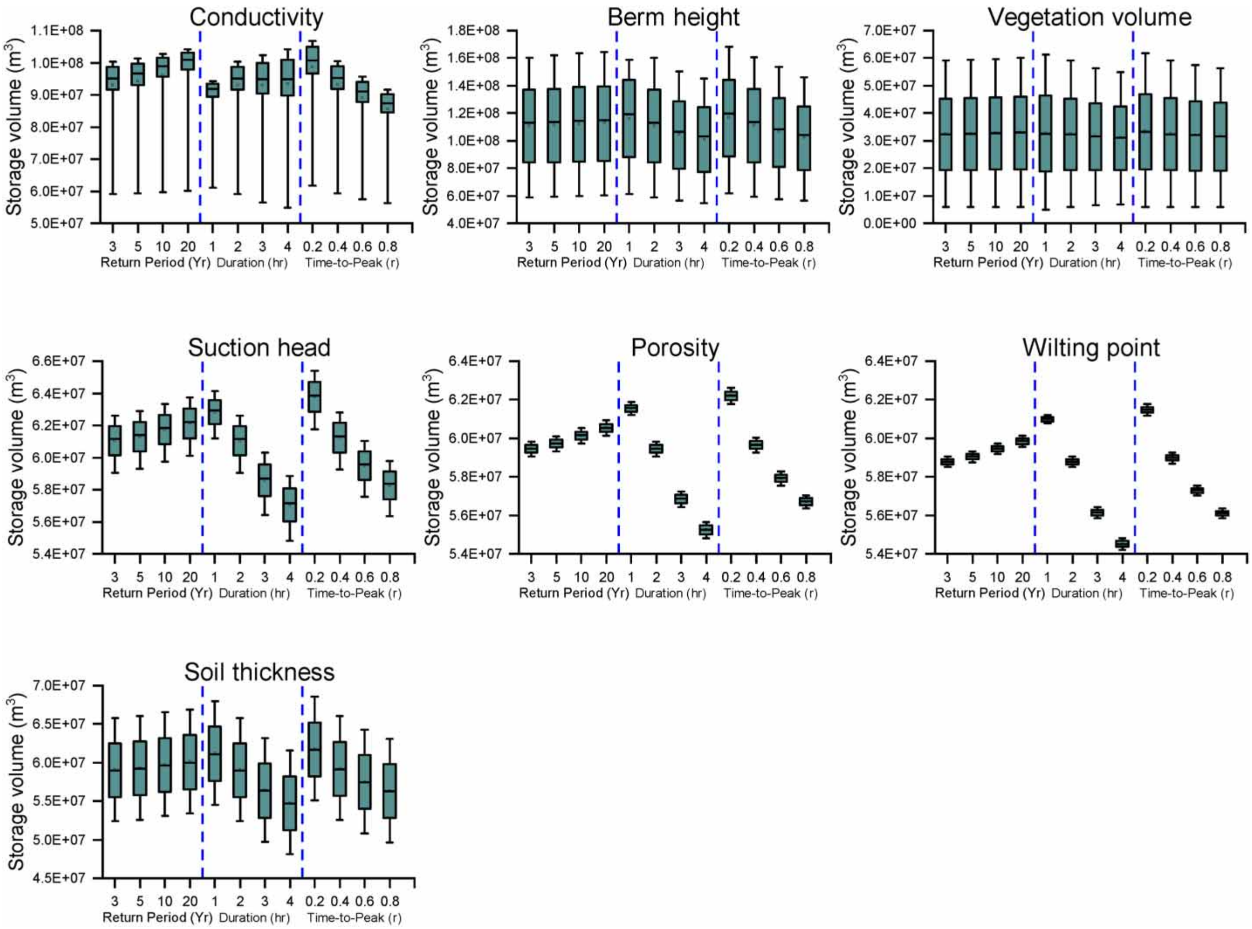


Figure 5 | Unit-scale hydrological response of different BC design parameters on the storage volume under return period, storm duration, and time-to-peak scenarios.

Furthermore, in the overall design parameter space, these three design parameters showed no significant variation in surface outflow volume. With a variation in soil thickness parameter, higher and longer storms overflow more runoff than lower and shorter storms; however, no countable effects on outflow volume were measured by the variation in storm peak. Results explain that the sensitivity of conductivity increases from highly intense storms providing evidence of its significance for stormwater control, where optimal values of conductivity and other design parameters are very important for improving efficiency and effectiveness to achieve target design goals, as an incorrect value of conductivity or other parameters during modeling and designing of the BC may produce false estimates.

The findings of SA of BC design parameters at the unit scale made a classification of design parameters as influential and non-influential. Every design parameter represented unique characteristics in response to different hydrological outputs and storm conditions, explaining their potentials, contributions, and impact on total outputs against their variations within their pre-defined factor spaces. The selection of optimal BC design parameters is important as it has a significant impact on different outputs at the unit scale, which ultimately contributes to compound variations at the catchment scale. Most previous research studies and government development programs discussed planning, designing, and optimization of BC's scale and location and its impact on different responses (i.e., qualitative and quantitative), and guidance for the selection of design parameters of three layers of the BC mostly used either from the SWMM reference manual (Rossman & Huber 2016) or previously published research studies or with small modifications of local design guidelines (MOHURD 2014). However, because each region or catchment has its climatic dynamics, soil characteristics, groundwater table conditions, local design guidelines, and target outputs, BC design parameters cannot be generalized at a larger scale (global).

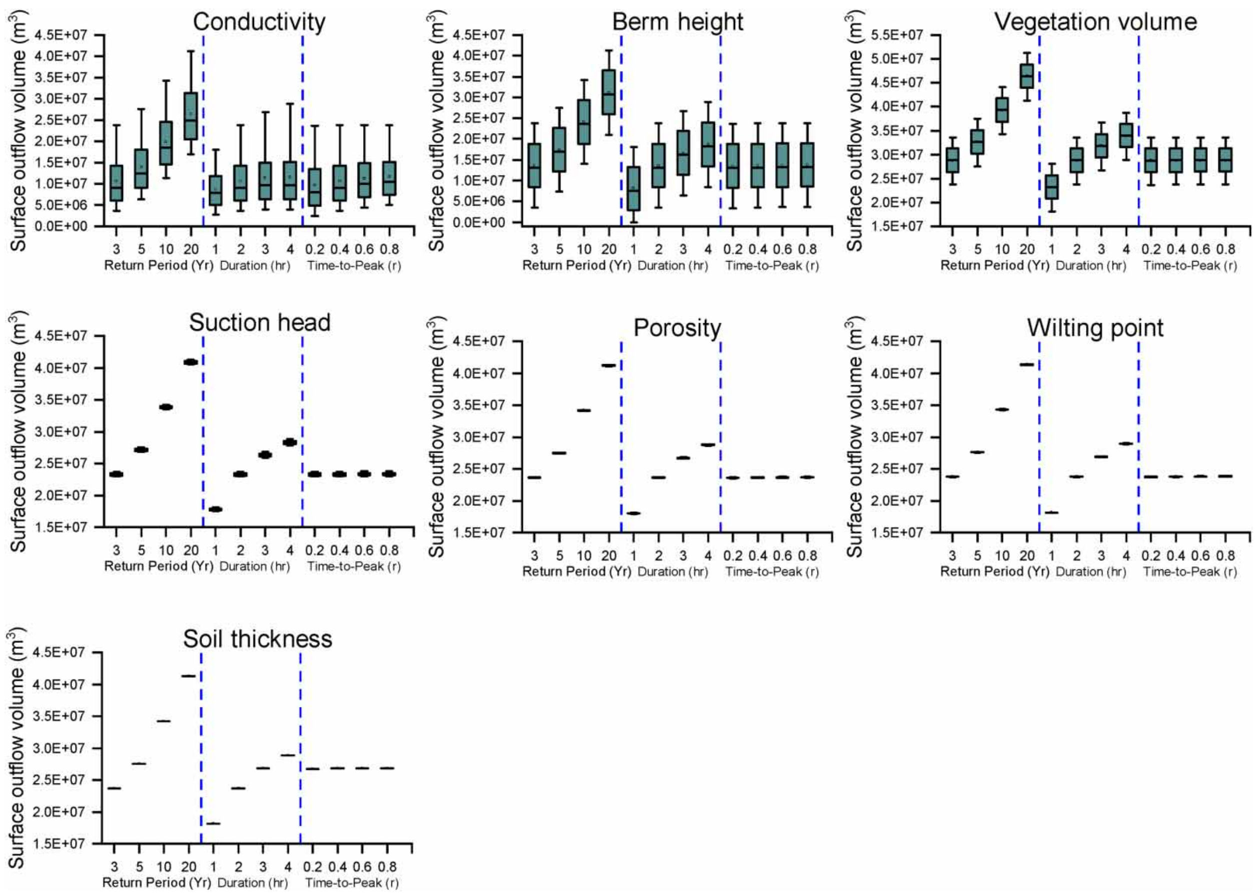


Figure 6 | Unit-scale hydrological response of different BC design parameters on the surface outflow volume under return period, duration, and time-to-peak scenarios.

4.2. Sensitivity analysis of BC design parameters at the catchment scale

Evaluation of the hydrological response of BC design parameters at the catchment scale is conducted for understanding the potential contributions of each design parameter for changing different stormwater routing parameters at the catchment scale. This analysis contributes to improving understanding of the extent to which each design parameter's capability to vary stormwater routing parameters (e.g., surface runoff volume, peak runoff volume, storage volume, and outflow volume), and results are discussed in terms of the percentage change. Like unit-scale analysis, catchment-scale evaluation was performed for seven influential design parameters which were selected based on an OAT analysis, as shown in Figure 3.

4.2.1. Surface runoff volume

Results clearly demonstrate that vegetation volume has a far greater impact on runoff generation compared to other design parameters, as shown in Figure 7. Particularly, the vegetation volume's effect on runoff volume gradually decreases from lower to higher and shorter to longer storms, and no significant impact was observed for time-to-peak storms. The gradual reduction in change of runoff by variation of vegetation volume parameter explains that larger and longer storms decrease the effectiveness of vegetation and may result in a significant reduction in its hydrological performance for stormwater control.

Considering these results, it is important to highlight that selection of type and growing density of vegetation on BC's surface should also be considered during the construction of the BC considering local weather patterns, design guidelines, and availability of resources. Interestingly, the other five design parameters including conductivity, berm height, suction head, porosity, and wilting point showed only limited effects on variation of runoff within their factor spaces. For example, overall, less than 1% variation in runoff was observed by testing the sensitivity of full factor spaces of conductivity and berm height, and

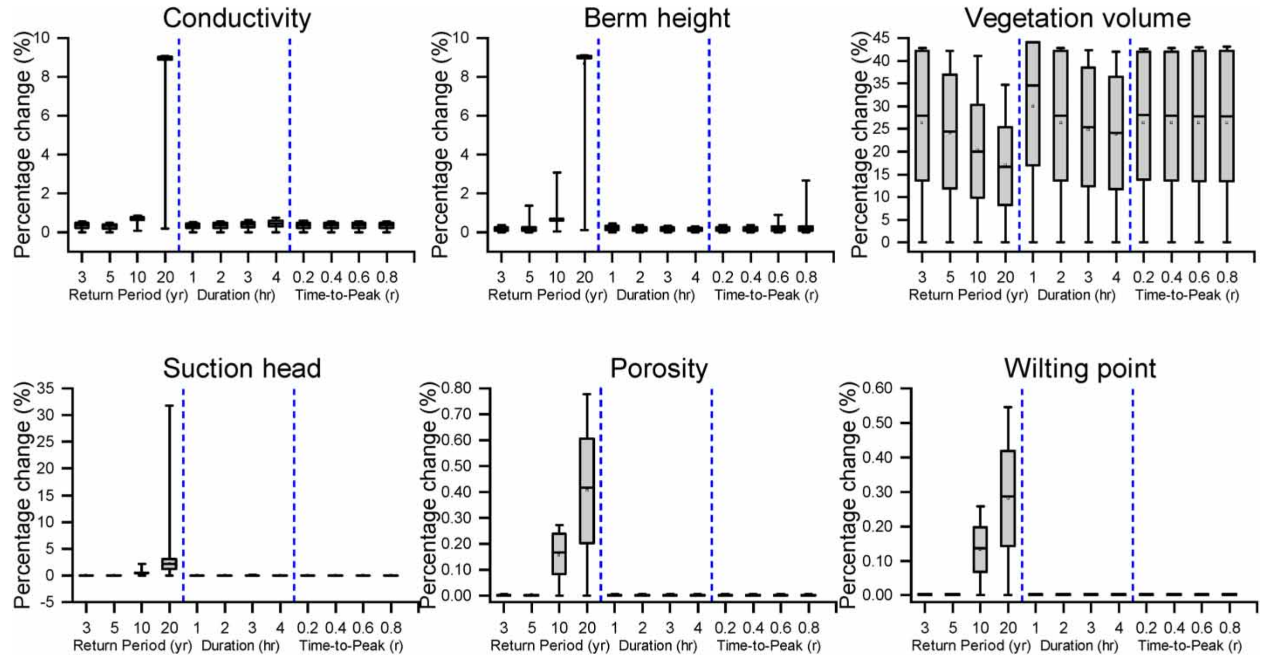


Figure 7 | Catchment-scale hydrological response of different BC design parameters on the surface runoff volume under return period, duration, and time-to-peak scenarios.

the other five design parameters demonstrated limited impacts on runoff changes. However, the sensitivity of design parameters increased for higher design storms. Soil thickness represented no effect on runoff variation.

4.2.2. Peak runoff volume

Understanding the impacts of design parameters on peak runoff is very important, as assessment and reduction of hydrograph's peak at flood hot spots within urban catchment reduce urban flood risk during peak storm periods. Figure 8 represents an evaluation of SA results of influential design parameters on peak flow generated from all sub-catchments. Similar to surface runoff, vegetation volume is the main design parameter among all parameters that represented significant impacts on controlling stormwater's peak. In particular, vegetation showed significantly higher impacts for lower return periods, shorter durations, and earlier peak storms and which gradually reduced for higher return periods, longer durations, and later peak storms. It is inferred from these results that optimal selection and design of vegetation on the BC, which is homogeneously distributed within urban catchment considering available spaces and sizes may significantly contribute to reducing minimize peak of catchments having rainfall of less than 10-year return periods and 2-h duration. In the case of other design parameters including conductivity, berm height, suction head, porosity, and wilting point, a limited effect on peak runoff was observed for each storm condition. Moreover, conductivity represented a higher impact on controlling peak runoff for lower return periods, shorter durations, and earlier peak storms in comparison to higher return periods, longer durations, and later peak storms, however, the overall impact is insignificant. Soil thickness demonstrated no influence on the variation of peak flow.

4.2.3. Storage volume

Storage efficiency of a bioretention cell is mainly dependent on the optimal selection and design of its construction materials, for example, type and density of vegetation, type of soil and its thickness, berm height, depth of each layer, etc. A well-designed BC with higher storage efficiency and its replication at the catchment scale provides better opportunities for a significant reduction in generating runoff and peak flows and urban drainage system flooding and is highly cost-effective compared to a poorly designed BC. Based on catchment-scale SA of influential design parameters, conductivity, vegetation volume, wilting point, and soil thickness represented significantly better effects on the variation of catchment-scale stormwater storage compared to other design parameters, as shown in Figure 9.

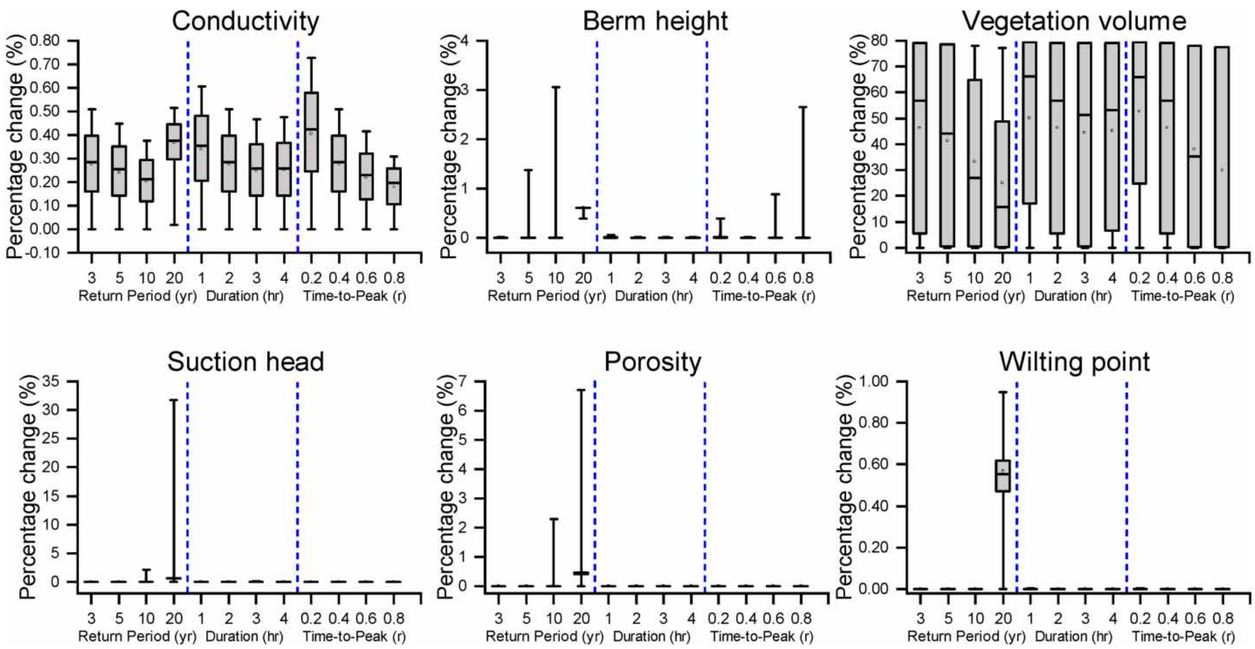


Figure 8 | Catchment-scale hydrological response of different BC design parameters on the peak runoff volume under return period, duration, and time-to-peak scenarios.

Taking vegetation volume as an example, comparatively, it demonstrated a larger rate of variation in storage volume for higher and longer storms compared to lower and shorter storms, as can be seen by the mean, median, and interquartile ranges of respective storms. No significant effect on the variation of storage volume was observed for time-to-peak storms for vegetation volume. Wilting point and soil thickness demonstrated nearly similar effects with better control on storage of stormwater for lower return periods and shorter storms compared to higher and longer storms. Interestingly, only storms having a short duration of 1 h and earlier peak storms with a time-to-peak ratio of 0.2*r* showed a significantly larger impact on storage volume compared to other storm scenarios. Approximately similar impacts are observed for other design parameters of the soil layer including conductivity, suction head, and porosity. The findings explain that both vegetation and soil have a strong influence on the storage efficiency of the BC, which significantly changes under different rainfall conditions and design configurations. Apart from the optimum selection of vegetation, the optimal selection of soil type and its thickness with better storage potential is crucial for improving the design objectives of the BC at the unit scale and amplifying its compound impacts to control stormwater runoff and peak flow and overflowing of urban drainage system at the catchment scale.

4.2.4. Outflow volume

Understanding the impacts of the design configuration of the BC on system outflow volume is evaluated by SA at the catchment scale, as shown in Figure 10. Based on the comparison of SA results, vegetation volume has a greater impact on controlling the system's outflow volume for lower return periods, shorter durations, and earlier peak storms compared to higher return periods, longer durations, and later peak storms. Overall, other design parameters including conductivity, berm height, suction head, porosity, and wilting point showed relatively lower sensitivities for all storm scenarios. Furthermore, these design parameters demonstrated comparatively better influence for higher return periods storms (i.e., 10-year and 20-year return periods) in comparison to others. It is inferred from the results that vegetation can play an important role in controlling stormwater flowing from catchment outlets to either wastewater treatment plants or other receiving water bodies. Particularly, the stormwater generated during peak rainfall period mostly synchronizes from different parts of the catchment and produces a higher peak runoff that mostly exceeds the intake capacity of wastewater treatment plants or conveyance capacity of the downstream drainage system, resulting in overflowing of the downstream drainage system. To reduce the hydraulic burden on the downstream drainage system during peak storm periods, the best possible

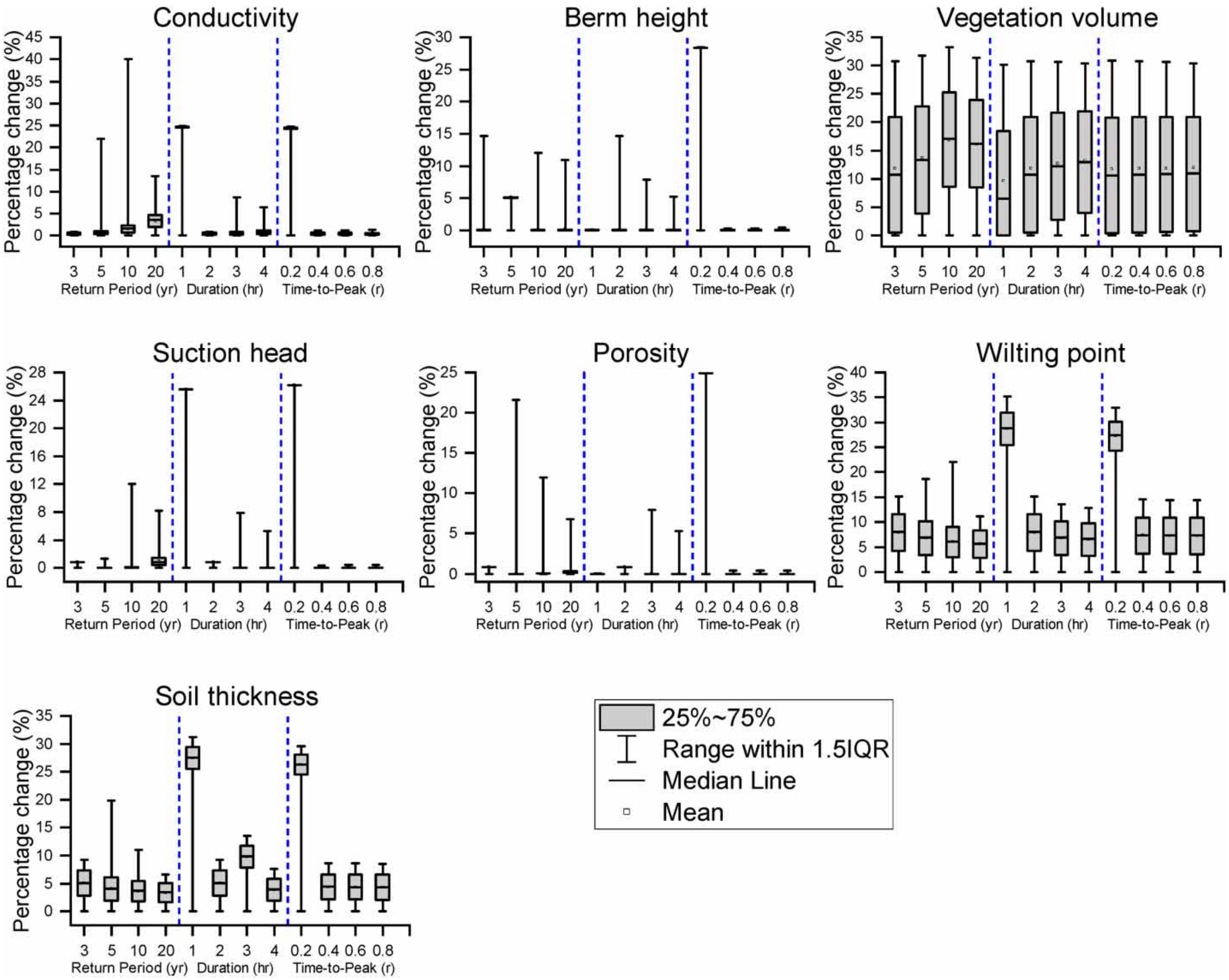


Figure 9 | Catchment-scale hydrological response of different BC design parameters on the storage volume under return period, duration, and time-to-peak scenarios.

design of the BC with optimally selected vegetation and soil parameters needs to spatially distribute in urban areas to reduce the probability of synchronization of peaks, which resultantly improves drainage efficiency of the downstream drainage system and reduce chances of overflow at the intake of wastewater treatment plants (Zeng *et al.* 2019).

Comparison of the hydrological performance of BC design parameters at the unit scale and catchment scale demonstrated their unique behaviors toward different rainfall conditions and model responses. The OAT SA results presented in this study are consistent with previous research studies where similar design parameters of green infrastructure are found to be the most influential compared to others (Wang *et al.* 2013; Meng *et al.* 2014; Chui *et al.* 2016; Korgaonkar *et al.* 2020; Tansar *et al.* 2023). Unit-scale SA improved understanding of dynamical behaviors of design parameters within their factor spaces in response to different storm scenarios and model outcomes, which explains how water balance in the BC (i.e., inflow volume, outflow volume, and storage volume) dynamically changes within the BC when design parameters vary, and which part of factor space of design parameter is more sensitive compared to others, and how its sensitivity changes with variation of intensity, duration, and location of peaks of storm (Madrazo-Uribeetxebarria *et al.* 2021; Tansar *et al.* 2023). These findings help stormwater modelers, drainage engineers, and nature-based practitioners to better understand the hydrological dynamics of each design parameter and their accurate selection to improve the design configurations of the BC for better planning, modeling, optimization, and implementation stages.

Catchment-scale SA results explain the potential, contributions, and impacts of BC design parameters to control stormwater. Vegetation volume, berm height, and other design parameters related to the soil layer represented significant

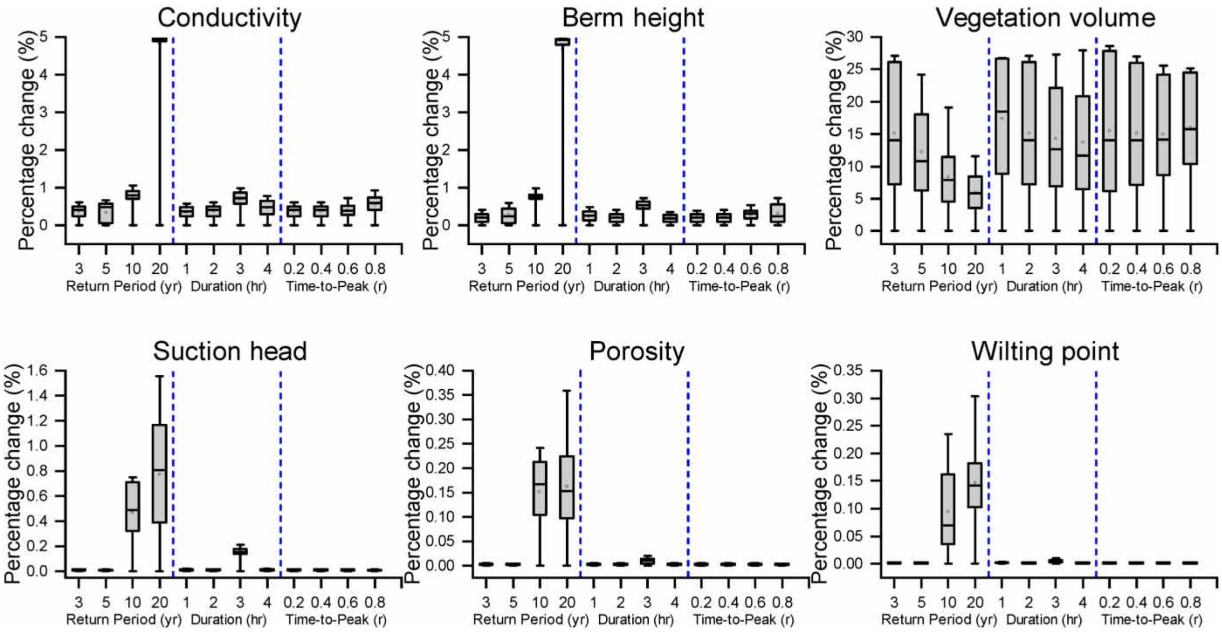


Figure 10 | Catchment-scale hydrological response of different BC design parameters on the outflow volume under return period, duration, and time-to-peak scenarios.

influence on the variation of different routing parameters including surface runoff, peak flow, storage volume, and system outflow. Our catchment-scale findings showed that the efficiency and effectiveness of the BC design significantly dependent on the careful selection of different parameters of vegetation (i.e., type, density, height, etc.), and soil (i.e., type, layer thickness, void ratio, etc.) and height of berm, which validate findings of past research studies that concluded conductivity, vegetation volume, and berm height are the most influential design parameters of the BC compared to others (Sun *et al.* 2011; Chui *et al.* 2016; Tansar *et al.* 2023). The studies also confirmed that accurate selection of soil type may not only contribute to enhancing the efficiency and effectiveness of the BC target design goals, but also significantly the improve collective performance of different design parameters related to soil layer (as different design parameters of soil have strong connections between them), and also boost the vegetation growth for achieving their design objectives. The long-term hydrological performance evaluation of the BC with consideration of different factors for improving BC design goals like surface infiltration rate, storage rate, and vegetation growth rate recommended loamy and sandy loam soils for achieving higher design goals (Meng *et al.* 2014; Leimgruber *et al.* 2018). Similarly, previous studies performed experiments and simulations for the optimization of design parameters of layers of bioretention tanks for improving quantitative and qualitative efficiencies (Li *et al.* 2018, 2020, 2021; Chen & Chui 2022). An optimally selected parameter of vegetation and soil improves BC's stormwater retained efficiency (i.e., infiltration and storage) at unit scale, and replicating such optimal BCs at catchment scale will ultimately have significant compound impacts on reducing surface runoff, peak flow, and probability of flooding. However, inaccurate design parameters lead to erroneous BC design units, and its replication at the catchment scale may significantly decrease performance.

5. CONCLUSIONS

Seven out of 18 BC design parameters including conductivity, berm height, vegetation volume, suction head, porosity, wilting point, and soil thickness are selected as sensitive during preliminary screening conducted by the OAT SA method. The comprehensive hydrological performance of selected bioretention cell design parameters is further evaluated at the unit scale and catchment scale.

Unit-scale SA concludes each BC design parameter has unique characteristics toward different model responses under various storm conditions which dynamically change with the variation of its design configurations in BCs, resultantly affecting its water balance (i.e., surface infiltration volume, surface outflow volume, and storage volume). Results provide evidence that the sensitivity of design parameters toward different model responses is dynamic within their factor spaces, with some portion of the design parameter being relatively most sensitive compared to others. These results guide the potential contribution of each design parameter toward total model response, especially their effective range of factor spaces producing higher impacts on model outputs, which should be carefully selected during the modeling, calibration, and optimization process.

Catchment-scale results clearly illustrate the significant impacts of vegetation and design parameters of soil layer on different routing parameters including surface runoff, peak flow, storage volume, and system outflow volume. Optimal selection of type and density of vegetation, and different design parameters of soil layer (i.e., type, layer thickness, void ratio, etc.) is critical for improving the effectiveness and maximizing the efficiency of BC design for better control of stormwater at the catchment scale. The improvement of the BC design unit and accurate design replication at the catchment scale may collectively produce substantial improvement in target design goals if the variation in the model outputs in response to change of design parameters is correctly understood.

The findings of this study recommend a precise selection of BC design parameters, especially berm height, vegetation volume, soil thickness in soil and storage layers, and other influential design parameters, during modeling and construction considering local climate dynamics and design guidelines for improving the BC design efficiency. Optimal design values of BC parameters effectively improved surface infiltration, storage, peak flow, and control surface outflow at the unit scale, resultantly, a significant increase in stormwater storage is observed at the catchment scale. Finally, the results of this study may be useful and helpful for urban stormwater system design and management. Considering the limitations of this study, future recommendations for research on design configurations of the BC are to find effective ranges of design parameters within their factor spaces for significant improvement in the BC design and reducing uncertainty linked with parameters, and its evaluation under short-term and long-term rainfall events.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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