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Comparing the hydrological performance of blue green infrastructure design strategies in urban/semi-urban catchments for stormwater management

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ABSTRACT

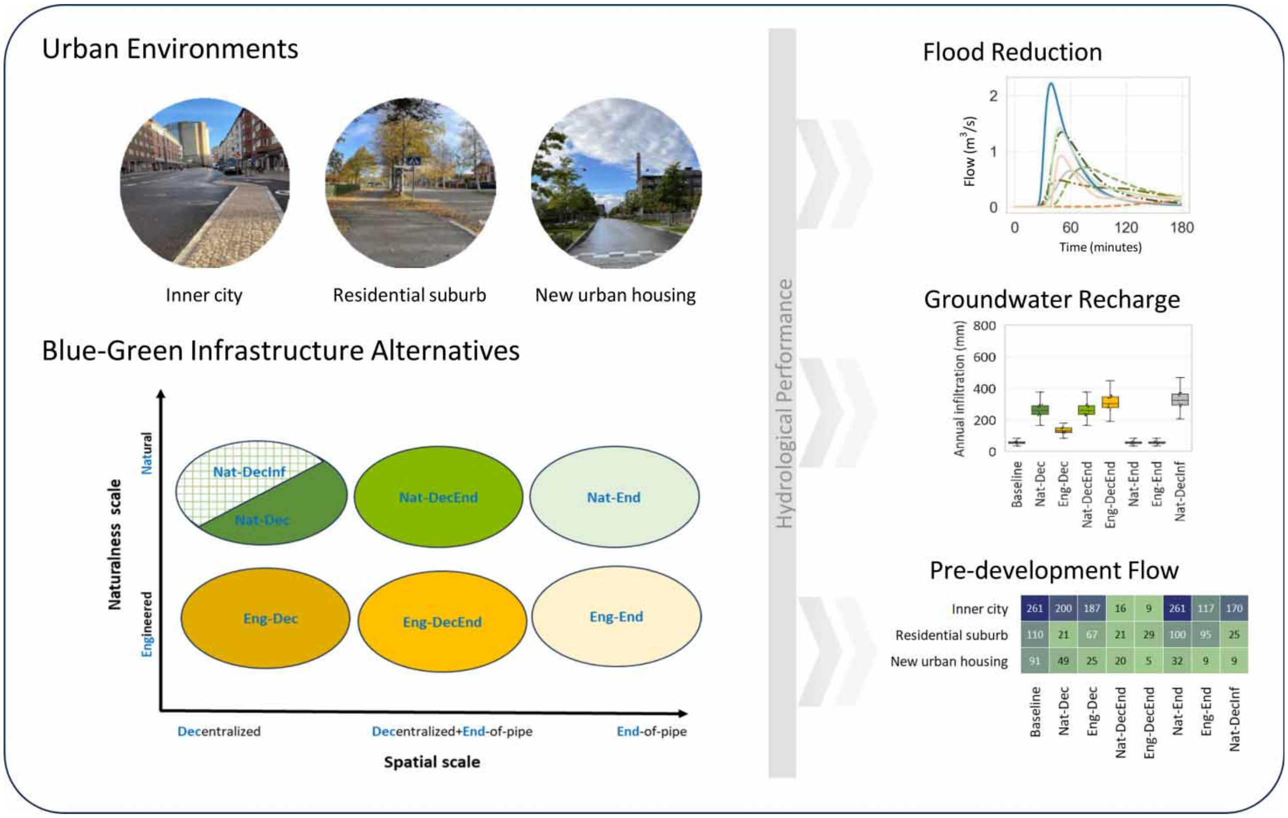
Blue green infrastructure (BGI), in recent decades, have been increasingly recognized as robust stormwater control measures to reduce urban flooding, promote infiltration, and restore a catchment's flow to its pre-development stage. However, studies comparing the hydrological benefits of BGI alternatives at catchment scale are often limited to single catchment or single/few BGI options scaled over a catchment. This study designed a set of BGI alternatives as a combination of different BGI facilities in terms of the following: (a) spatial distribution scale (end-of-pipe vs. decentralized) and (b) naturalness scale (less engineered vs. more engineered), in three different urban catchments representing an inner city, a residential suburb, and a new urban housing. In addition, their hydrological performances were compared. A 10-year return period design rain and a continuous rain series of 11 years were modelled for each BGI alternative using the computer model stormwater management model (SWMM). It was observed that in most catchments, decentralized alternatives (both engineered and natural) showed better potential to reduce the magnitude and frequency of flooding than centralized measures. Similarly, the tested decentralized natural, less engineered alternatives showed higher potential to increase infiltration than the decentralized engineered alternatives in all three catchments. Meanwhile, infiltration-based BGI alternatives showed similar potential to mimic pre-development flow as other decentralized BGI alternatives.

Key words: blue green infrastructure, flooding, infiltration, stormwater management, urban hydrology

HIGHLIGHTS

- The engineered BGI alternative reduced the magnitude and frequency of floods in urban areas.
- A combination of decentralized and centralized BGI alternatives applied specifically with more natural BGI facilities was the most effective BGI alternative to enhancing infiltration in urban environments.
- Opportunistic placement of BGI facilities is not sufficient in dense urban catchments; there is a need for a transformative strategy.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Urban stormwater management has become of increasing growing global concern over recent years as the combined effects of climate change and rapid urbanization have led to adverse hydrological effects in urban environments (IPCC 2023). Increased imperviousness in the urban environment has resulted in the disruption of the natural hydrological cycle by reducing the natural infiltration rates and depleting groundwater (Fletcher *et al.* 2013). Meanwhile, frequent extreme storm events amid climate change have attracted general concern among stormwater practitioners and urban planners, as a greater number of flooding events have been recorded in the recent past in many cities around the world (Damodaram *et al.* 2010; Loperfido *et al.* 2014; Jarden *et al.* 2016; IPCC 2023).

Solving these problems by using current practices such as larger stormwater pipes is costly and would only move the flooding problem downstream instead of solving it (Broekhuizen *et al.* 2019). At the same time, without substantial treatment, pipeline systems also transport the pollutants found in stormwater to receiving water bodies. Therefore, blue green infrastructure (BGI), also known as sustainable urban drainage systems (SuDS), low-impact development (LID), best management practices (BMP), or nature-based solutions (NBS) (Fletcher *et al.* 2013) have become an increasingly popular choice over recent decades for stormwater management. BGI mimic the natural hydrological process to manage the water at source by temporarily retaining it and by delaying flows during rain events, allowing the water to infiltrate the ground to enhance infiltration (Fletcher *et al.* 2013; Chen *et al.* 2019; Fiori & Volpi 2020).

Implementation of BGI in urban catchments is often challenging because there are many different options and design considerations for BGI and commonly a lack of space (Fletcher *et al.* 2013). Two important factors to consider are as follows: (a) the spatial distribution and (b) the use of more engineered (e.g., biofilters) vs. less engineered (e.g., swales). The first factor is considered by developing a spatial distribution scale that involves how the BGI facilities are distributed in the catchment – whether by taking either a decentralized approach (i.e., many smaller decentral facilities distributed in the catchment), or a centralized approach (one or few facilities, commonly implemented as end-of-pipe) or the combination of both approaches (e.g., retention facilities distributed within the catchment combined with an end-of-pipe treatment facility). The second scale is considered by developing a naturalness scale for the BGI facilities that focuses on the selection of BGI facilities either by using more natural, relatively simple, and robust BGI facilities such as swale for slow transport, open dry detention for storage, and/or sedimentation pond for treatment or by using more engineered BGI facilities, complex facilities incorporating more sophisticated design, processes, and/or structures, such as bioretention or constructed wetlands.

Only a few monitoring-based studies exist where different strategies for BGI have been compared (Li *et al.* 2017; Khan *et al.* 2022). Loperfido *et al.* (2014) monitored the runoff discharge of five different urban catchments applied with different distributed BGI alternatives from 2004 to 2012 and showed that distributed BGI caused higher baseflow, lower maximum discharge, and stream response than centralized BGI during rainfall events. Similarly, Wilson *et al.* (2015) observed more than 98% peak flow reduction in a catchment with the detention- and infiltration-based BGI facilities and noted a relatively wider range (56–100%) of peak flow reduction due to centralized BGI facilities while comparing inflow and outflow from these two sites. In general, on-site monitoring-based studies are rare and it is likely that the catchments have additional dissimilarities beyond just BGI, thus the results can be extrapolated only to catchments sharing similar characteristics. Furthermore, these field studies collected flow measurements from limited data points in the catchment, which limits the accuracy in capturing the interaction between a BGI facility and its catchment, as similar outflow measurements could be obtained from different ways of BGI implementation.

A more common approach is to use stormwater models to investigate effectiveness of different strategies for BGI implementation (Ahiablame & Shakya 2016; Jarden *et al.* 2016; Zhu & Chen 2017; Chen *et al.* 2019). Damodaram *et al.* (2010) carried out a continuous simulation using decentralized BGI designs for infiltration-based BGI facilities, such as permeable pavement, and storage-based BGI facilities such as detention ponds, and found that infiltration-based facilities were more effective in regular rain events (18, 45 mm) while storage-based BGI facilities were more effective for larger storm events (114, 279 mm) in reducing peak flows. Fiori & Volpi (2020) used a simple hydrological model, based on the instantaneous unit hydrograph, to model BGI effects on peak discharge quantiles (flow discharge characterized by a given return period) at the urban catchment, and found that centralized BGI facilities closer to the outlet showed increased peak discharge quantile compared to the baseline due to extended detention. The same study also showed that BGI effectiveness does not increase proportionally with the increase in the implemented BGI area. Results from these studies show that new knowledge is still emerging regarding the potential trade-offs and synergies associated with different BGI alternatives. In addition, catchment scale modelling studies are mostly either (i) focused on a single catchment, or (ii) limited to individual/few BGI facilities that have been scaled over catchments.

Limitations of these on-site and modelling studies indicate that the factors that drive variability in the hydrological responses among different BGI in urban catchments are not yet fully understood and require more research evidence. Therefore, this study applies a more structured approach to quantifying and comparing the hydrological performance of different BGI alternatives in urban catchments characterized by different land characteristics such as size, land use, development stage, and built-up density. Overall, the research aims to accomplish the following: (1) quantify how hydrological outcomes such as surface runoff, infiltration, and pre-development flow are affected by BGI design complexity and BGI spatial distribution, and (2) explain what factors drive variability in hydrological response among different BGI alternatives. Specifically, the research aims to provide answers to questions such as the following: (i) to what extent can the magnitude and frequency of flooding in a catchment be minimized by implementing different BGI alternatives across different urban catchments? (ii) How is the annual infiltration in the catchment affected when different BGI alternatives are used? (iii) And to what extent can the outflow from the catchment be restored to its pre-development stage by implementing different BGI alternatives?

It is hypothesized that differences between BGI alternatives will lead to different stormwater hydrological outcomes in different urban catchments. Likely, engineered BGI facilities will add more hydrological benefits in an inner city than residential suburbs during daily rain events because they allow effective use of space by facilitating both surface and filter media layer that may otherwise not be possible with retention-based natural BGI facilities. Similarly, the combination of the decentralized and end-of-pipe option is most likely to be beneficial, especially during intense rains, because the exceeding catchment flow otherwise not handled by the decentralized BGIs can be managed by using the end-of-pipe BGI facilities.

2. METHODS

2.1. BGI alternatives formulation

This study formulated a set of eight alternatives of BGI implementation along the (i) spatial and (ii) naturalness scales based on a comprehensive review of the existing literature and best practices in urban stormwater management. These alternatives are described and compared in Figure 1. The alternatives were chosen based on their demonstrated effectiveness in providing hydrological benefits in urban environments (Loperfido *et al.* 2014; Wilson *et al.* 2015; Li *et al.* 2017; Fiori & Volpi 2020) and their alignment with the environmental objectives of improving water quality, adding biodiversity, and other benefits. The number of BGI facilities in each alternative and their distribution in each catchment were determined based on stakeholder (municipal water companies and a researcher team with interdisciplinary expertise) discussion and field visits following common BGI implementation in Sweden and current Swedish design guidelines. They represent typical cases found in urban catchments. Spatial analysis using the catchments' land-use map was undertaken in geographical information system (GIS) software to find suitable locations for BGI. For instance, a permeable pavement was agreed as a viable choice in an open square of a highly impervious area of an inner city whereas a swale is more convenient to use in a less dense and relatively open residential area. In terms of alternatives, one baseline for each study area was formulated to depict the present stormwater network with the conventional piped system. Seven BGI alternatives, i.e., combination of various BGI facilities within the catchment, were formulated with the combination of (i) the spatial distribution scale and the (ii) naturalness scale. These alternatives were further categorized according to two scales, as follows:

- The spatial distribution scale: This was further sub-classified into three categories – decentralized (Dec), combination of decentralized and end-of-pipe (DecEnd), and end-of-pipe. In the study context, decentralized means a combination of several BGI facilities distributed throughout the catchment, whereas end-of-pipe alternatives include one or two centralized BGI facilities that receive flow from the catchment's outlet and are located close to the receiving water body.
- The naturalness scale: There is no measure of the naturalness of a BGI solution that can be perfectly objective. BGI facilities in this study are categorized as more natural facilities (Nat) or more engineered facilities (Eng) depending on the facilities' design complexity. Open dry detentions, floating curtain sedimentations, sub-surface detentions, swales, and stormwater ponds were classified as more natural BGI facilities since they rely on natural principles to retain or infiltrate stormwater and require relatively smaller maintenance and simpler, cheaper construction.

  Rain gardens, pre-cast stormwater treatment facilities (stormwater detention/treatment vault), bioretention facilities, stormwater tree pits, and constructed stormwater wetlands are included in the more engineered facilities category as these BGI facilities include more deign components, such as filter media and storage layer, involve more processes, and require more maintenance to function over time and commonly larger investments for construction. An additional BGI alternative Nat-DecInf was formulated in the natural decentralized alternative by considering BGI mainly targeting infiltration such as permeable pavement, infiltration trench, and infiltration basin.

2.2. BGI design

In total, 11 different BGI facilities were selected/modelled in the eight alternatives.

(i) Open dry detention facilities are dry spaces with grass or shrubs that can also be used to retain or attenuate flows during large storm events (Damodaram *et al.* 2010). They are designed to retain flows during extreme rain events and are usually located in available open spaces, such as building courtyards.

(ii) Sub-surface detention facilities are underground reservoirs filled with gravel and implemented in the sideways of streets in the study areas to provide stormwater volume retention.

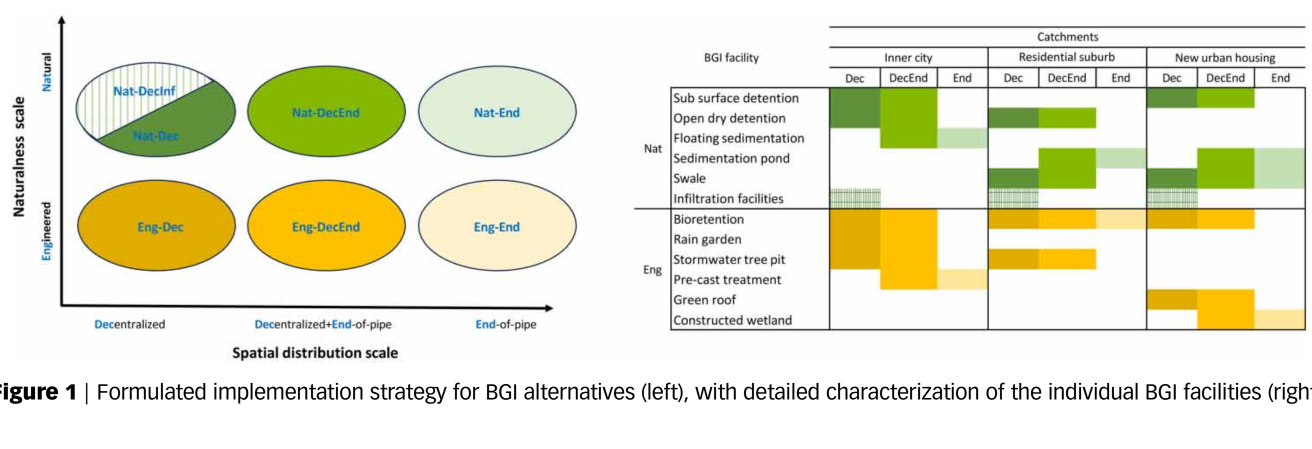


Figure 1 | Formulated implementation strategy for BGI alternatives (left), with detailed characterization of the individual BGI facilities (right).

(iii) Floating sedimentation curtain facilities are plastic curtains installed in the receiving water in front of the storm sewer outlet to facilitate sedimentation of coarse particles. Floating sedimentation curtains were dimensioned considering the settling velocity of coarse particles (>1 mm), but bypass intense extreme flows if they occur.
(iv) Sedimentation ponds are open ponds that have a similar design function to (iii), i.e., to settle particles in a pond, but they are constructed inland and allow infiltration over time.
(v) Swales are drainage channels with sloping sides that convey, attenuate, and treat stormwater runoff from roads and other surfaces. Swales in this study were designed to attenuate flow from sub-catchments during an intense rain event with a 10-year return period.
(vi) Bioretention facilities consist of 0.7–1 m of engineered soil media, a surface mulch layer, and various forms of vegetation that filter stormwater containing pollutants such as heavy metals and suspended particles, and provide water quantity benefits such as volume retention and peak flow delay. In this study, bioretention facilities were designed to retain daily rain events as well as delay the peak flows during intense rain events.
(vii) Rain gardens are pockets of land that have a similar design objective to bioretention facilities; however, in this study, the rain garden was designed with coarser filter media than bioretention facilities, to allow quicker infiltration, as is common in Sweden.
(viii) A stormwater tree pit has a tree surrounded by crushed stone of even size (4–8, 8–16, and 16–32 mm) to a certain depth. In this study it was designed with no surface storage, but with coarse filter media and a storage layer to the total depth of 1 m. It was designed to handle intense rain events.
(ix) Pre-cast treatment facilities are concrete structures used to retain water and facilitate sedimentation of particles. Since pre-cast treatment facilities are not commonly used compared to other BGI facilities, the design guidelines for them are not readily available, and thus, existing design practices for pre-cast facilities were used to design the facility in this study.
(x) Constructed wetlands were utilized as features with permanent pools of water that provide flow attenuation and allow sedimentation. In new urban housing, they are installed to provide detention time of 72 h. Water quality function such as total phosphorus removal of 65% was also considered in this study. The constructed wetland has an extended detention of 0.5 m and open water section 1 m below the permanent pool level. The bathymetry across the four marsh zones is to vary gradually ranging from 0.2 m above the permanent pool level to 0.5 m below the permanent pool level.
(xi) Infiltration facilities such as permeable pavements, infiltration trenches, and infiltration basins were implemented in suitable areas to allow infiltration during various design rain events.

The design rain events used to design the facilities, along with the BGI, facilities different design components, are presented in Table 1, which is based on CIRIA (2015), Larm & Blecken (2019) and Moreton Bay Waterways & Catchment Partnership

Table 1 | Overview of design procedure followed to design BGI facilities

	Design rain			BGI facility design components			
Name	**Return interval (years)**	**Duration (min)**	**Event size (mm)**	**Surface**	**Filter media**	**Storage**	**Drainage**
Sub-surface detention	10	30	20.8	✓	–	✓	–
Open dry detention	30	20	26	✓	–	✓	–
Floating sedimentation curtain	5	60	20.6	–	–	✓	–
Sedimentation pond	5	60	20.6	✓	–	–	–
Swale	10	30	20.8	✓	–	–	–
Biofilter	0.5	120	12.4	✓	✓	✓	✓
Rain garden	0.5	120	12.4	✓	✓	✓	✓
Stormwater tree pit	10	30	20.8	–	✓	✓	✓
Pre-cast treatment facility	5	60	20.6	–	–	✓	✓
Constructed wetland	0.5	120	12.4	✓	✓	✓	–
Infiltration facilities	5	60	20.6	✓	–	✓	–

(2006). While designing the BGI facility, runoff from each sub-catchment was taken into consideration. As a result, the same BGI facility has been implemented with different designs depending on the runoff volume received from the catchment. However, in some cases, the BGI facility was implemented with the maximum possible surface area when the available surface area in the sub-catchment was limited.

2.3. Study sites

Three distinct urban catchments were selected to represent different types of urban environments, namely an existing inner city, existing residential suburbs, and new development urban housing (Figure 2). The existing inner city environment was represented by Davidshall, located in south Sweden in Malmö (55° 35′ 58″N, 12° 59′ 54″ E). It consists of late 19th century multistorey buildings and has limited open space. It is 6.25 ha in area, where over 80% of its total surface area is impermeable. Ångbryggeriet, a residential catchment situated in the city of Östersund in central Sweden (63° 10′ 4″ N, 14° 39′ 12″E), represented residential suburbs. It is 55 ha in size with approximately 50% impermeable surfaces and consists of mainly single-family homes. New urban housing was represented by a planning phase residential area located in the city of Uppsala in southeast Sweden (59° 54′ 43″ N, 17° 29′ 42″ E). The area is 27.5 ha in size, and, after construction, the new urban housing area will be mainly covered by streets (38.0%), followed by roofs (28.8%), with the remaining area covered by private green land (30.4%) and parks (0.2%). Inner city and new urban housing have similar geographies with slopes ranging from 0.1 to 1%, while the residential suburb is steeper (0.1–5%).

2.4. Model implementation

2.4.1. Hydrological model set up

The eight BGI alternatives were set up using the Storm Water Management Model (SWMM), a dynamic rainfall-runoff simulation model developed by the United States Environmental Protection Agency (US-EPA) (Rossman & Simon 2022). SWMM is a commonly used modelling software in stormwater context and the outflow from different types of BGI facilities in SWMM have been documented to give satisfactory performance, such as green roof (e.g., Peng & Stovin 2017) and bioretention (Lisenbee *et al.* 2022), for both long-term and short-term simulations of different rain events. Similarly, in the context of catchment scale modelling, SWMM has been documented to analyse flow dynamics in a wide range of urban catchments (e.g., Palla & Gnecco 2015; Aryal *et al.* 2016). More specifically, it has been shown that 'uncalibrated models with sufficient land-use information reach performances comparable with those of calibrated models' (Petrucci & Bonhomme 2014). In this study, a standard SWMM modelling practice was used to set up the model, and the values for different catchments parameters were mostly referred from the SWMM manual (Rossman & Simon 2022). Each catchment was further sub-delineated into numerous sub-catchments in SWMM, depending on their receiving outlet junction and the land-use characteristics. Stormwater pipe network characteristics such as pipe elevation and size and size of junction were obtained from the respective municipalities. Terrain information such as slope of roof and road slope was obtained from the digital elevation model of the catchment available at 2 m resolution (Lantmäteriet 2024). Classification of land use for each sub-catchment was based on the property maps' database provided by the respective municipalities. A field visit was also organized to compare the land-use data, such as impermeable areas and slope of roof, with reality. The built-in LID module within SWMM was

Figure 2 | Street view and Google images showing the three urban catchments.

utilized to set up surface, soil, storage, and drainage components for BGI facilities – see Table S1 in supplementary material for more information on parameter values used to implement different BGI facilities. The properties of each LID module differ from the other depending upon the options to include different BGI layers such as surface zone, filter media, storage layer, and drainage layer. SWMM simulates hydrological processes in each layer with their respective governing equations (Rossman 2016). In this study, the dynamic wave method was used for flood routing. Infiltration was calculated using the Green-Ampt method, and Manning's equation was used to estimate the overland flow. The potential evapotranspiration process was calculated separately using the Food and Agriculture Organization (FAO) Penman–Monteith (FAO-PM) method and included in the simulation in SWMM. Environmental factors such as snow build-up/melt process were not included in this study because the occurrence of snow depends on climatic conditions, which is out of scope for this study, and processes such as snow removal activities and patterns of snow accumulation in snowdrifts have limited functionality in SWMM so far (Moghadas *et al.* 2016).

2.4.2. Rain selection for simulation

The BGI alternatives' hydrological performances were evaluated using both single design rain events and historical rain series. The hyetograph for the design rain was generated using the Chicago design storm method and for a 10-year 1-h return period, which is commonly applied for stormwater management in Swedish urban areas (Dahlström 2010). Total rain for the design rain was 25 mm, with a maximum intensity of 294 mm/h. For the historical rain, sensor data obtained from tipping bucket sensors for an 11-year period from 2013 to 2023 were utilized. Rain events were identified based on a minimum inter-event time of 6 h, and the analysis was limited to events greater than 2 mm with an average intensity greater than 0.1 mm/h to ensure that only rain events capable of generating significant flow would be used to obtain different parameters of hydrological metrics. A 2-year return period rain was used to calculate the pre-development flow from the catchment – see section 2.5 for more information on different hydrologic metrics used in this study. An overview of rain used for the simulation is presented in Table 2.

2.5. Hydrological metrics

Both in-catchment and the downstream flows were considered to calculate different hydrological metrics for the design rain simulation and long-term simulation (Table 3). For the design rain simulation, four different parameters were calculated to compare hydrological performances of various BGI alternatives. Flooding volume was calculated as the volume of stormwater overflowing from all junctions of the catchment normalized by the catchment area. The study focuses on the comparison to existing (conventional) stormwater practices followed in different urban areas; therefore, the existing baseline was used as the reference. For example, peak flow reduction was estimated to capture the effect of BGI alternatives to reduce the maximum flow and was calculated as the ratio of maximum flow of the BGI alternative to that of the maximum flow from the baseline condition (see Figure 3). Centroid delay, i.e., time difference between the centroids of the hyetograph and hydrograph, was calculated for each BGI alternative to obtain quantitative representation of timing of peak flow as well as shape of

Table 2 | Summary of rain data (2013–2023) used for simulation

Year	Number of events	Total rain (mm)	Max intensity (mm/h)
2013	43	330	55
2014	50	527	76
2015	57	426	67
2016	44	364	89
2017	57	470	56
2018	30	245	56
2019	57	398	52
2020	46	331	64
2021	32	383	180
2022	41	405	103
2023	71	702	103

Table 3 | Hydrologic metric used for design rain simulation and continuous rain simulation

Design rain simulation	Continuous rain simulation
Flooding volume	Number of rain events causing surcharges in node
Peak flow reduction	Potential infiltration
Centroid lag	Number of rain events where pre-development flow is exceeded
Peak flow delay	

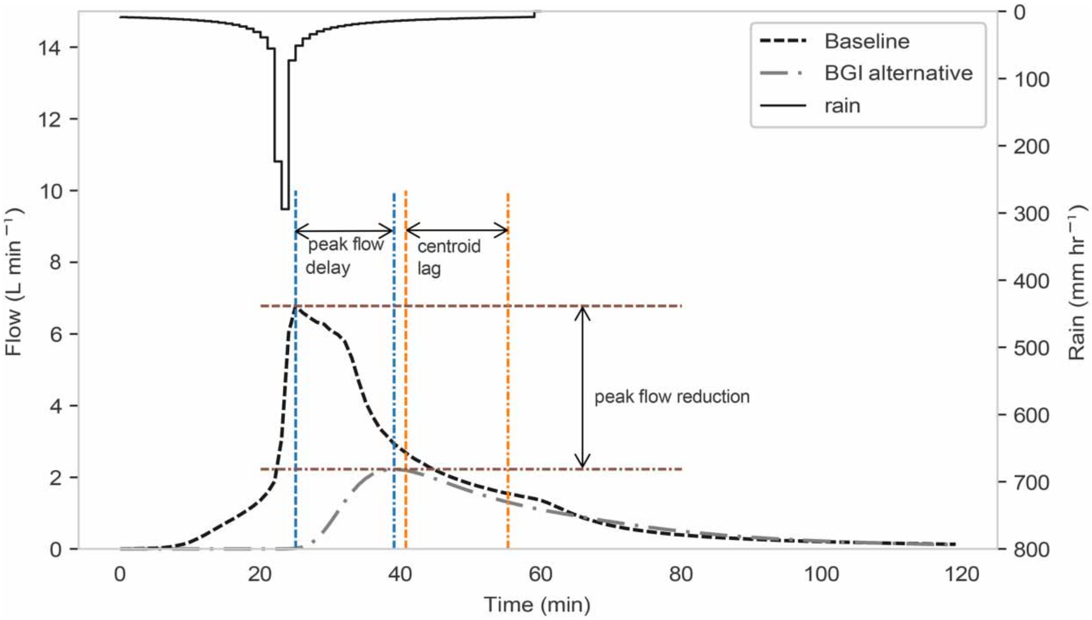


Figure 3 | Illustration of peak flow reduction, centroid lag, and peak flow delay used in this study. The blue line shows timing of peak flow and the orange line shows the time of centroid.

the hydrograph, see Jarden *et al.* (2016) for a detailed reference. To quantify the delay in maximum flow from the outlet, peak flow delay was calculated by subtracting the peak flow time for the baseline condition with time of peak flow in the BGI alternative.

A comparison of hydrologic performance during long-term rain was made with respect to the following: (i) number of rain events that exceeded pre-development estimated flow and (ii) the average number of rain events that caused flooding at the critical node. Pre-development flow for each catchment was estimated for a 2-year return period rain using the Swedish guidelines (Svenskt Vatten 2016) and based on Manning's equation. Similarly, critical node, i.e., the node where maximum flooding occurred, was identified after baseline simulation for each catchment, and the numbers of surcharges that occurred in the critical node every year during the long-term simulations were recorded. The potential infiltration to promote groundwater recharge was calculated for each year by adding the annual net infiltration during the 11-year simulation for the historical rain events.

3. RESULTS

3.1. BGI implementation in the study areas

Table 4 presents the summary of BGI implementation in the three study areas. In general, residential catchments (residential suburb and new urban housing) provide more opportunities to install BGI than the dense inner city catchment as shown by the higher percentage of BGI to catchment area. In some downstream sub-catchments of the inner city, BGI facilities could not be implemented due to lack of space. Dimensions for end-of-pipe facilities are 125 m^2 for floating sedimentation (Nat-End

Table 4 | Implementation of BGI alternatives in the three catchments

	Percentage of area with BGI			Total retention volume (mm)			BGI contributing to infiltration		
BGI alternative	**Inner city**	**Residential suburb**	**New urban housing**	**Inner city**	**Residential suburb**	**New urban housing**	**Inner city**	**Residential suburb**	**New urban housing**
Nat-Dec	3.3%	8.3%	22.2%	17.7	28.1	31.2	100%	100%	100%
Nat-DecEnd	3.5%	8.7%	22.3%	17.7	30.1	31.8	100%	100%	100%
Nat-End	0.2%	0.4%	0.1%	0	2.0	0.6	0%	100%	0%
Eng-Dec	0.6%	5.7%	20.5%	3.8	25.6	27.2	100%	100%	65%
Eng-DecEnd	2.3%	6.1%	22.3%	11.3	25.2	28.4	90%	57%	67%
Eng-End	0.1%	0.4%	2.0%	0.4	2.2	0.8	0%	100%	100%
Nat-DecInf	4.2%	5.7%	22.2%	18.1	27.7	28.3	100%	100%	100%

in the inner city), 60 m^2 for pre-cast treatment (Eng-End in the inner city), 2,000 m^2 for sedimentation pond (Nat-End in the residential suburb), 2,000 m^2 for bioretention (Eng-End in the residential suburb), 300 m^2 for sedimentation pond (Nat-End in the new urban housing), and 5,300 m^2 for constructed wetland (Eng-End in the new urban housing). The result shows that in general natural BGI alternatives result in relatively more retention volume than engineered BGI alternatives in all three catchments. For contribution to underlying soil infiltration, most BGI facilitate infiltration, except for some facilities such as floating sedimentation curtain and pre-cast treatment facility, which mainly delay the flows. Similarly, a large proportion of BGI (about 35%) consist of green roofs in the new urban housing catchment, which does not allow for infiltration to the native soil.

3.2. Flood reduction

3.2.1. Design rain simulation

The hydrographs of all the eight BGI alternatives in the three study areas are shown in Figure 4, and the details of the hydrologic metric for design rain simulation and continuous rain are shown in Figures 5 and 6, respectively. In general, all BGI alternatives generated peak flow less than that of the baseline conditions in the residential suburb and new urban housing compared to the inner city. The use of end-of-pipe BGI alternative show significant reduction in peak flow when installed close to the outlet like in Nat-End or Eng-End in residential suburb and new urban housing compared to the installation in the receiving water like in Nat-End in inner city. Similarly, the design of constructed wetlands to provide 72 h detention showed a significant effect of delaying the peak flow as well as reducing the maximum flow.

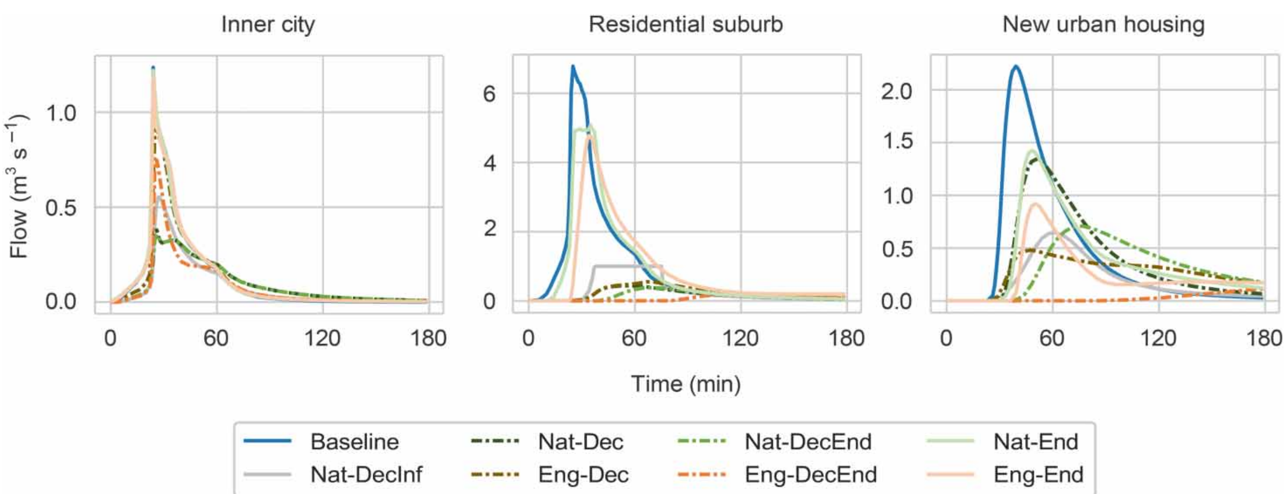


Figure 4 | Comparison of outflow runoff from baseline and BGI alternatives in the three study areas during design rain simulation.

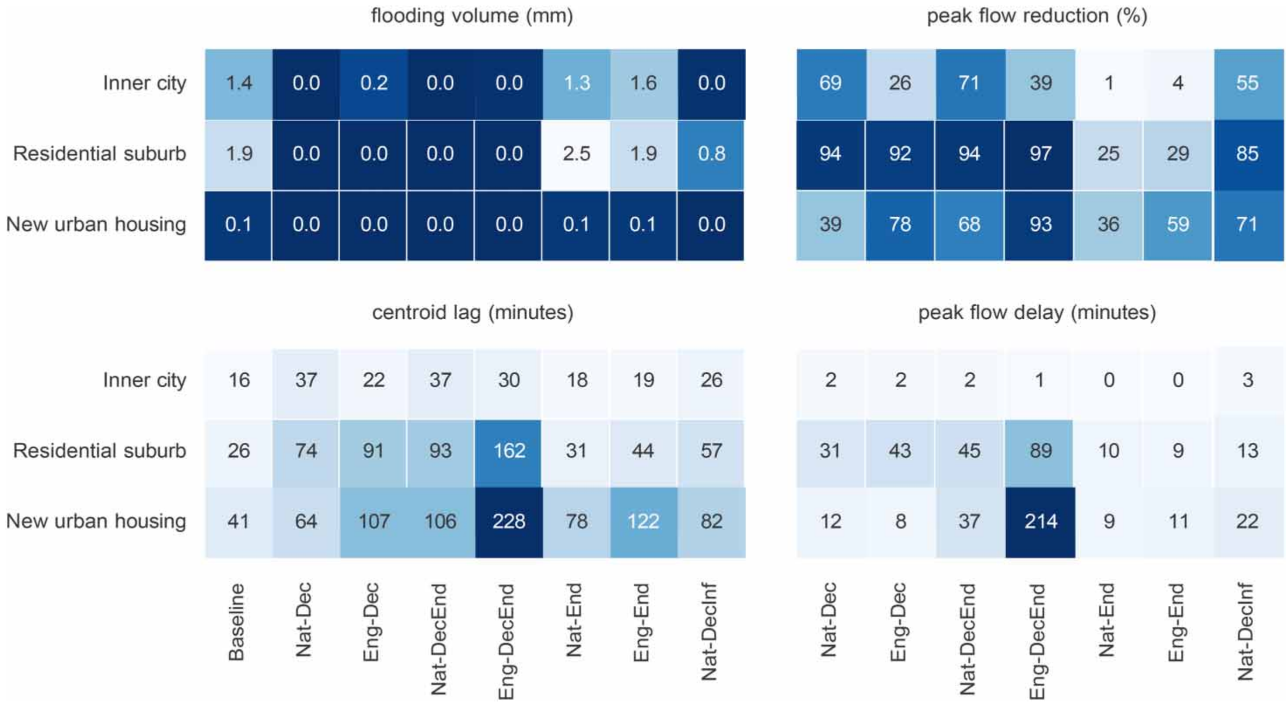


Figure 5 | Observed hydrological responses from design rain simulation for the three catchments.

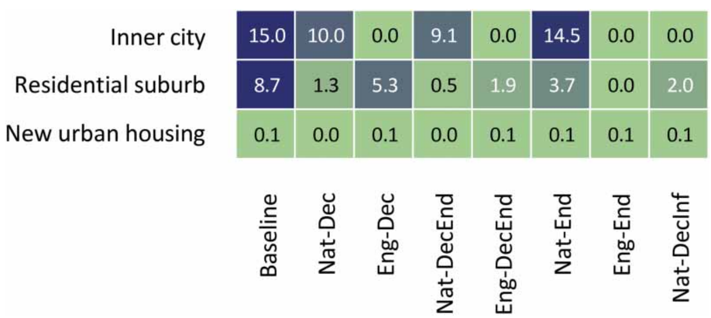


Figure 6 | Average number of rain events per year resulting in surcharge in the critical node across the three catchments.

Results from the design rain simulation described in section 2.4 showed that implementing decentralized (Dec) and a combination of decentralized and end-of-pipe (Dec-End) BGI alternatives mostly diminished flooding volume in all three catchments (Figure 5, top left). End-of-pipe BGI alternatives in some cases (Eng-End in the inner city and Nat-End in the residential suburb) showed about 15% more flooding volume than the baseline condition during the design rain simulation. No flooding was seen in any of the BGI alternatives in the case of new urban housing. However, the surface runoff from the BGI alternatives was (1–10 mm) in the new urban housing.

For peak flow reduction (Figure 5, top-right), the observed response after implementing different BGI alternatives was much more widespread compared to flooding volume. In general, peak flow reduction was significantly higher (about twice) with natural BGI alternatives in the inner city, but in contrast to this, it was noticeably higher (above 50%) for engineered BGI alternatives in new urban housing. Infiltration-based BGI alternatives showed somewhat lower peak flow reduction compared to the decentralized natural and engineered BGI alternatives in most cases. Similarly, the range for flow delays (centroid lag and peak flow; Figure 5 bottom-left and bottom-right) was from a few minutes up to 4 h for different BGI alternatives. Compared with results from peak flow reduction, both the delay responses also showed that adding end-of-pipe to decentralized measures produced better results by delaying flow up to few hours, especially with engineered end-of-pipe BGI facilities (Eng-Dec-End) in the two residential catchments.

3.2.2. Continuous simulation

For estimating in-catchment flooding potential, flow depth values that caused surcharges in the critical node (the node where maximum flooding was seen in the baseline simulation) were used as a reference (Figure 6). Compared with results of flooding volume in the design rain simulation, there were almost no surcharging events in the new urban housing for any of the BGI alternatives during the continuous simulation. Likewise, surcharging nodes were mostly diminished after implementing BGI alternatives in the residential suburb. In the inner city catchment, however, there were some rain events that caused node surcharge even after implementing BGI alternatives. More specifically, in the inner city the engineered BGI alternatives seemed to reduce surcharging events more than the natural BGI alternatives during continuous simulation.

3.3. Comparison to pre-development flow

The pre-development flow in the outfall of the catchments was calculated based on Swedish guidelines (Svenskt Vatten 2016) using the Manning equation for a 2-year return period rain. The values were 0.1 m^3/s for inner city, 0.4 m^3/s for the residential suburb, and 0.2 m^3/s for the new urban housing. In general, the catchment's pre-development flow was more frequently exceeded in the inner city compared to the two residential catchments (Figure 7). The effect of decentralized BGI alternatives (i.e., both engineered and natural) was lowest in the inner city, where such events were reduced by an average of 5.5 rain events per year in the natural and 6.4 rain events per year in the engineered BGI alternatives with reference to the baseline. However, more significant reductions were seen by adding an end-of-pipe BGI alternative to the decentralized alternatives, where the number of events exceeding pre-development flow was reduced from 261 rain events in the baseline to a minimum of 16 rain events for the natural and 9 rain events for the engineered BGI alternatives in the inner city. By contrast, the decentralized alternatives (Nat-Dec and Eng-Dec) in the new urban housing showed noticeable reduction (about half) in such events for both engineered and natural BGI alternatives.

3.4. Infiltration

Infiltration was calculated as the average of net infiltration during each year (Figure 8). Annual mean infiltration for the new urban housing (152 mm) was much higher than the residential suburb (88 mm) and the inner city (57 mm). With BGI implementation, an expected increase in infiltration was observed, although it was much higher for natural BGI alternatives in general compared with engineered BGI alternatives. For instance, the increment in infiltration for the natural BGI alternatives (Nat-Dec) in the three study catchments exceeded the respective baseline by 5.5 times in the residential suburb, 4.6 times in the inner city, and 1.6 times in the new urban housing. Likewise, the potential infiltration amount was similar in the infiltration-based BGI alternative (Nat-DecInf), although in the new urban housing, the annual mean infiltration amount with the infiltration BGI alternative (317 mm) was significantly higher than the natural (Nat-Dec-244 mm) and the engineered (Eng-Dec- 157 mm) BGI alternatives. Results from end-of-pipe BGI alternative, where the BGI facilities were implemented in the receiving water, showed less effect on infiltration.

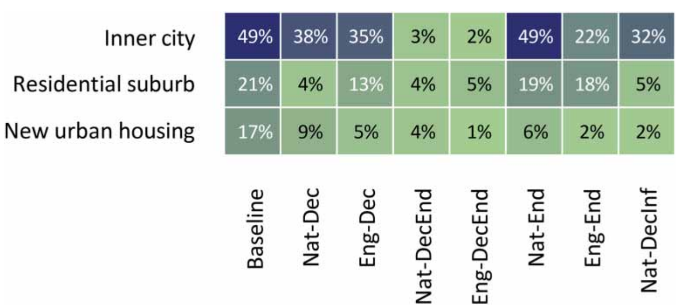


Figure 7 | Percentage of rain events resulting in exceedance of pre-development flow across the three catchments during continuous simulation.

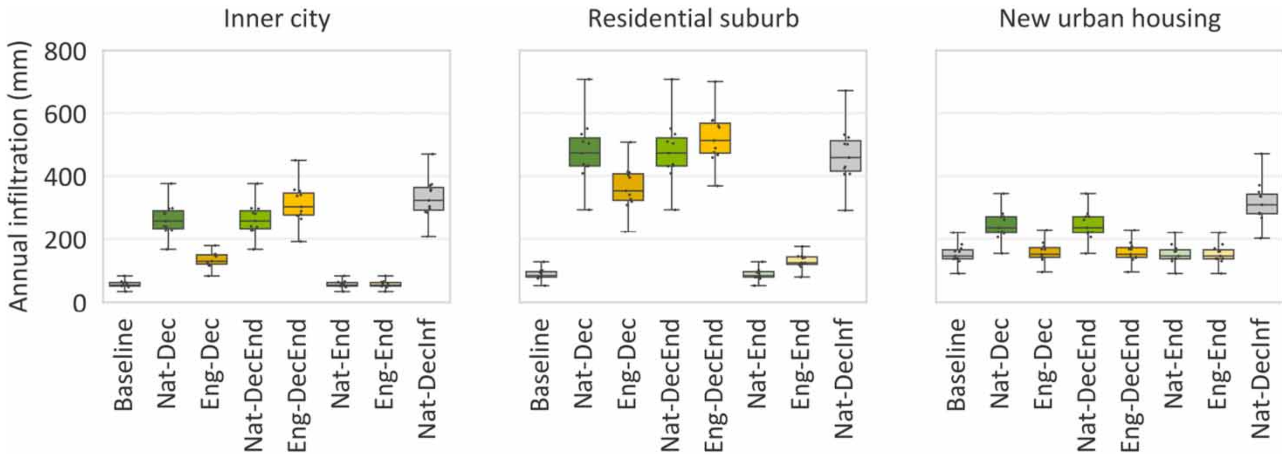


Figure 8 | Observed annual infiltration from the three catchments during continuous simulation of 11 years.

4. DISCUSSION

4.1. Flood reduction

4.1.1. Design rain

There was no overflowing water from the junctions in the new urban housing, but there was some surface runoff even after implementing the BGI alternatives. There were no overflowing junctions because the stormwater pipe networks were designed using a similar rain event with a 10-year return period. This study showed surface runoff ranging from 4 to 40%, which corroborates the findings from Xiao *et al.* (2022) who showed surface runoff of about 20% after testing performance of a BGI alternative in a 10-year design rain.

There was more peak flow reduction with natural BGI alternatives in the inner city, and with engineered BGI alternatives in the new urban housing, during design rain simulation (Figure 4). The inner city is characterized as having high impermeability, thus leading to higher discharge rates during high flow rain events. Furthermore, as the amount of available space is also a key constraint in the inner city, not all sub-catchments were retrofitted with BGI facilities. As the precipitation increases, the underlying soil in BGI facilities becomes more saturated as shown by Khan *et al.* (2022). When the underlying soil saturates, the capacity of a BGI facility to store water in the storage layer/surface layer then becomes the limiting factor for volume retention and delay in flow. Engineered BGI facilities such as bioretention have limited surface retention capacity compared to open dry detention facilities or sedimentation ponds. Residential suburbs, however, are typically more permeable and provide more freedom to carefully plan and distribute engineered facilities compared to inner city areas. As a result, there is less chance of soil saturation in an engineered facility, and thus better peak flow reduction. The results for peak flow reduction in the residential catchments were different from that of Giacomoni *et al.* (2014), which showed a BGI alternative implementing open dry detention was more effective than BGI alternatives with other facilities such as rain barrel, green roof, and permeable pavement in urban catchment for a 10-year return period design rain.

In addition to the influence of filter media, the design of drainage layer also contributed to the higher flow delay seen in engineered BGI alternatives than natural BGI alternatives. The drainage layers for bioretentions, rain gardens, and stormwater tree pits were designed with a specific hydraulic residence time of 20 min to ensure flow delay, and for water quality purposes. Similarly, the low time to peak as seen in the hydrograph in the Eng-DecEnd alternative in new urban housing was because the stormwater wetland was designed with 6 h residence time to allow sedimentation of finer particles and provide water quality function.

Results from the inner city and the residential suburb show that implementing just end-of-pipe BGI alternatives leads to more flooding volume during the design rain simulation (10-year return period) in some cases. This could be because BGI facilities such as bioretention (used as Eng-End in the inner city) or a stormwater pond (used as Nat-End in the inner city) are designed such that the water has a specified residence time as mentioned earlier within the facility before it is discharged. During high flow events, where the volume of the facility is expected to be exceeded, this exceeding water could overflow from the end-of-pipe facility resulting in more flooding volume. One possible way to bypass the exceeding flow would be by using flow routing devices such as a weir. Alternatively, a larger retention-based facility could be implemented at a centralized location although it is usually difficult to obtain enough sufficient space within dense urban spaces. Damodaram *et al.* (2010) found higher peak flow reduction with a significantly large detention pond (maximum depth of 5.4 m and surface area of 46,888 m^2) compared to a decentralized measure for design rains with a greater than 10-year return period.

4.1.2. Continuous rain

Compared with results from Ahiablame & Shakya (2016) and Damodaram *et al.* (2010), infiltration-based BGI alternatives (Nat-DecInf) were observed to be somewhat effective methods compared with others during continuous simulation. This is because infiltration measures could be implemented in urban spaces otherwise not suitable for other BGI facilities, for example, in footpath or car parking areas. Chen *et al.* (2019) developed criteria to implement different BGI facilities in the urban area and observed that infiltration facilities (at 4.3%) could be implemented in roughly 1% more area than bioretention (3.6%), and as a result, noted higher annual volume reduction with the infiltration alternative (3.4%) than with bioretention (0.2%). However, results from intense design rain simulation for the infiltration-based BGI alternative (Nat-DecInf) show lower peak flow reduction and flooding volume. This difference in performance caused due to varying rain intensity shows that infiltration facilities are suitable just for storm events with less intensity.

4.2. Comparison to pre-development flow

It was expected to obtain larger flows in the inner city compared to the residential catchments due to high imperviousness; however, contrary to this assumption, it was observed that both the decentralized BGI alternatives (Nat-Dec and Eng-Dec) in the inner city had very little effect on reducing the number of rain events where the pre-development flow would be exceeded (Figure 7). This could be due to the difficulty in uniformly distributing BGI facilities in inner city environments, which then changes flow dynamics in the catchment. It was also interesting to observe that both Nat-DecEnd and Eng-DecEnd had relatively similar and significantly better performance in all three catchments. This indicates that the end-of-pipe option is useful in handling excess flows otherwise not managed by decentralized BGI alternatives, and it is especially true in dense urban areas such as the inner city.

4.3. Infiltration

It is seen that the area of BGI implementation is not the only factor to influence the amount of net infiltration, although it is one of the major factors. In the inner city, on average, an expected higher infiltration in natural decentralized BGI with infiltration (Nat-DecInf) was seen compared to natural decentralized (Nat-Dec) because of the larger surface area of about 0.9% (Table 4). But when the area of implementation was equal as in the case of the new urban housing, the net average infiltration in Nat-DecInf was noticeably higher than Nat-Dec although both BGI alternatives had 100% of BGI facilities contributing to infiltration. Nat-DecInf also achieved similar amount of net infiltration than Nat-Dec in the residential suburb, although with an overall lower area of implementation (about 2.6%). This shows that contribution to infiltration is more nuanced than increasing surface area to give more infiltration and the other factors like selection of BGI facilities, their design, and distribution also play a major role.

A higher infiltration was hypothesized in the residential suburb because it is less built-up than the inner city areas and has relatively larger open spaces compared to the new urban housing area. The results regarding infiltration (Figure 8) show that the mean infiltration amount compared to the baseline is proportionally higher in the residential suburb (up to 5.4 times) than the new urban housing (up to 2.1 times) with different BGI alternatives. This is influenced by the design of the BGI facilities and the percentage of BGI facilities that contribute to groundwater infiltration in the different catchments (Table 4). In the new urban housing, for instance, swales were designed to provide conveyance for stormwater runoff and therefore have higher surface slope than other BGI facilities. Swales also occupy more surface area compared to other BGI facilities in new urban housing, which facilitates more flow conveyance than storage. By contrast, infiltration facilities were designed to delay flow and encourage infiltration, which results in higher infiltration as seen in the infiltration-based BGI alternative (Nat-DecInf) in the new urban housing. However, when the retention-based BGI alternatives are used, there is little to separate between the infiltration amount from the natural decentralized (Nat-Dec) and natural decentralized with infiltration (Nat-DecInf) BGI alternative as seen in the inner city and residential suburb.

Furthermore, in all three catchments in general, infiltration amount in natural BGI alternatives (Nat-DecEnd and Eng-DecEnd) is much higher than in the engineered BGI alternatives (Eng-Dec and Eng-DecEnd). BGI facilities with drainage pipes, such as the bioretention facilities or rain gardens used in this study, limit the ability of the BGI facility to enhance the exfiltration into the surrounding soil, thereby reducing the potential to increase infiltration. Infiltration BGI alternatives (Nat-DecInf), conversely, infiltrate water directly into the native soil leading to more infiltration. However, it is sometimes important to consider the effect of groundwater table, as the infiltration is limited by groundwater drainage (Locatelli *et al.* 2015). This effect of groundwater table was not considered in this study.

4.4. Study limitations

There are many sources of uncertainty in urban drainage models that influences the output from the model substantially, and different models set up with the goal of representing identical simple synthetic catchments may give strongly varying results (Broekhuizen *et al.* 2019). Although calibration can to some extent compensate for measurement errors as shown by Dotto *et al.* (2014), in cases where measured data are absent, accurately capturing parameter uncertainty and its impact on various hydrological outcomes becomes challenging and may be perceived as relatively less significant. It is considered that it is more important to acknowledge other sources of uncertainties such as how the results change when the BGI facilities are maintained differently, receive different rain intensities, or how the individual BGI facilities are designed.

4.4.1. Role of maintenance

Like all infrastructure, BGI must be regularly maintained to fulfil its intended function over time. However, different BGI facilities have different maintenance needs (Blecken *et al.* 2017), e.g., different frequency, scale, complexity, knowledge, and cost of maintenance. The results from this study showed that the more engineered BGI alternatives promise higher potential for flooding reduction than the more natural BGI alternatives in the residential areas. However, achieving this higher potential is a long-term perspective and in relation to natural BGI alternatives requires more efforts for maintenance and, thus, the more natural facilities could still be a preferred solution. Natural BGI facilities, such as swales and detention ponds, involve more natural processes and less engineered components and are, thus, relatively robust facilities over time (Blecken *et al.* 2017). In turn, they require less maintenance compared to more engineered facilities such as bioretention and rain gardens where regular maintenance is required, e.g., to prevent diminishing effective porosity in filter media due to continued clogging (Khan *et al.* 2022). Therefore, if maintenance is insufficient or even neglected (as is often the case in practice) (Blecken *et al.* 2017), a similar function can be achieved in the long term with natural BGI facilities, despite their lower maximum potential. Overall, the cost–benefit ratio for these less engineered facilities might, thus, be better. More engineered facilities may even fail completely in case of no maintenance. In cases where both alternatives have similar maximum potential, as during continuous simulation in the inner city in this study, there is a larger risk that engineered BGI alternatives end up being less efficient in the long run than natural BGI facilities. Finally, maintenance is of specific concern when the BGI facilities are implemented (at least partly) on private ground, where implementation of maintenance is often doubtful as long as no efficient control exists. In summary, beyond the general potential of the alternatives, the actual performance, potential risk of failure, and the long-term functionality and effectiveness, particularly of natural BGI facilities alongside the engineered ones, must be regarded in the decision-making process (Sun *et al.* 2024). This time scale has not been included in this study but should be of concern to forthcoming research.

4.4.2. Effect of varying rain patterns

Past studies have shown reduced peak flow, shorter time to peak, and lower volume reduction for BGI for increasing rainfall peak coefficient, intensity, and duration (Zhu & Chen 2017; Chen *et al.* 2021). Regarding timing of peak intensity, few studies have evaluated BGI performance for various rain events. For instance, while studying the effect of rainfall patterns on the runoff control performance of permeable pavements, Chen *et al.* (2021) showed that a rainfall event with a peak intensity coefficient (higher values indicate delayed time to peak intensity) of 0.8 led to more flooding volume than a similar size rain event but with a peak intensity coefficient of 0.2. Alternatively, Zhu & Chen (2017) showed that during higher rain intensities the impact of rainfall duration and the rainfall peak coefficient on the BGI performance was small. Higher intensity leads to quicker soil saturation, and the storage function of the BGI becomes the limiting factor as described in section 4.1. In this study, BGI alternatives (Nat-Dec and Nat-DecEnd) showed better performance than infiltration based facilites (Nat-DecInf) during intense rain due to their relatively large retention function but when the total storage function of BGI facilities are less utilized such as in regular rain events it is Nat-DecInf that has better performance due to relatively more surface area of implementation as shown in section 3.1. However, more retention without drainage also means the soil remains saturated for longer, so there could be higher risk of surface runoff, which ultimately leads to lower infiltration.

Therefore, a faster drop in infiltration in relation to rain can be expected in BGI facilities with retention and no drainage, such as open dry detention in Nat-Dec compared to Eng-Dec BGI facilities.

4.4.3. Design of BGI facilities

BGI facilities can be constructed using different design options with respect to filter media properties, ponding depth, and drainage layer options, all of which then affect the potential of the facilities to reduce and delay peak flow timing and the capacity to handle the total rain volume. In this study, one representation of each BGI facility was considered, based on common design recommendations (CIRIA 2015; Larm & Blecken 2019). Alternative designs would most likely result in different results. For instance, a stormwater tree pit in our case was designed with a drainage pipe and sealed bottom, and the drainage layer was designed so that water spends a specified time in the storage layer to utilize it more effectively. Implementing a faster drainage system might help in peak flow reduction as the soil has less chance to saturate due to continuous drainage, but this also means the surface and storage layers are not utilized to the full extent, which affects flooding volume. Similarly, a drainage layer with a longer residence time and filter media with low porosity will mean that the stormwater tree pit behaves as a ponding zone (Khan *et al.* 2022), which may reduce flooding volume but does not fully achieve the intended function of the stormwater tree pit. Similarly, soil conductivity was set to 40 mm/h, but for soils with lower conductivity, there would be a slowdown in infiltration from the ponding layer to the storage layer, and thus the accumulated water in the surface layer would become overland flow as mentioned by Khan *et al.* (2022). In case of less engineered and more natural BGI facilities like a swale, Abida & Sabourin (2006) for instance achieved total runoff retention of over 92% of rainfall events with less than 6 mm using an underdrain. Several other studies have shown variations in the hydrological performance of grass swales, due to variation in design configuration soil characteristics, infiltration rate channel roughness, grass height, and density (Ahmed *et al.* 2014). Similarly, in case of infiltration, past research has shown that infiltration capacity decreases with shallow groundwater as mentioned in section 4.3.

5. CONCLUSIONS

To quantify the hydrological performance of the various strategies for BGI implementation to manage stormwater in an urban environment, a hydrological model was used. The performance of eight BGI implementation alternatives that varied in terms of (a) how natural or engineered the facilities were and (b) how they were distributed or centralized in the catchment were estimated. Simulations were carried out for three typical urban topologies: inner city, residential suburb, and new urban housing.

In terms of flooding reduction, the following conclusions were drawn:

- Decentralized and centralized BGI alternatives: In most cases, decentralized alternatives (both engineered and natural) showed better potential to reduce magnitude and frequency of flooding than centralized measures. However, the potential appeared similar for centralized measures with larger surface areas. In residential catchments in some cases, using some centralized BGI alternatives showed higher flooding volume than the existing baseline condition with conventional stormwater pipes. Adding BGI measures to the decentralized alternatives (both engineered and natural) at the downstream end significantly improved the potential to reduce flooding in all three catchments.
- Engineered and natural BGI alternatives: In residential areas, engineered BGI alternatives showed the highest potential to reduce flooding, while in inner city catchments, the more natural BGIs showed higher potential. Infiltration-based BGI alternative was a somewhat more effective practice than others during continuous simulation for reducing flooding. However, for intense design rains, this alternative showed lower peak flow reduction and higher flooding volume, which indicates that storm events with high intensity are too large for infiltration-based BGI facilities to handle.

In terms of annual infiltration:

- Decentralized and centralized BGI alternatives: In all three catchments, the decentralized BGI alternatives showed better potential to increase infiltration than centralized BGI alternatives.
- Engineered and natural BGI alternatives: The tested decentralized natural alternatives showed higher potential to increase infiltration in all three catchments than the decentralized engineered alternatives. The infiltration-based BGI alternative showed similar infiltration potential as other decentralized BGI alternatives.

In terms of comparison to pre-development flow:

- The effect on the runoff from the outflow varied with different urban catchments, although adding BGI measures close to the downstream end of the catchment to the decentralized alternative (both engineered and natural) significantly reduced the number of rain events exceeding the catchments pre-developed flow.

Results from this study provide valuable insights for stormwater management practitioners and municipal planners on the better understanding and effective implementation of BGI alternatives across different urban catchment types. However, site-specific conditions should always be considered. More specifically, we show that if the space available for BGI is limited due to the typology of catchment, the effect of different strategies will remain limited. It is argued that opportunistic placement may not suffice in densely developed urban catchment areas: there is a need for a transformative adaptation strategy. Additionally, practical considerations such as maintenance requirements and performance variations due to varying rain intensities should be explored.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories https://dx.doi.org/10.5281/zenodo.13990223.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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