Not all SuDS are created equal: Impact of different approaches on Combined Sewer Overflows

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Highlights

- We analysed the performance and cost-effectiveness of SUDS in reducing CSOs.
- We investigate effectiveness of specific spatial deployment strategies for SUDS.
- Bioretention and permeable pavements as most effective and cost-effective option
- Catchment-wide SUDS implementation fared better than deployment in priority areas.
- SUDS effective for CSO mitigation but differ due to mechanisms and spatial deployment

Abstract

Sustainable urban drainage systems (SuDS) help in stormwater management by reducing runoff volume, increasing runoff concentration time and thereby improving the drainage system capacity. This study investigated the potential and cost-effectiveness of SuDS in reducing combined sewer overflows (CSOs). We simulated the performance of four SuDS techniques (bioretention cell, permeable pavement, rain barrel and green roof) at incremental levels of spatial coverage for a small urban catchment with a combined sewer system. We also used an Analytic Hierarchy Process (AHP) considering end-point CSO, land use, imperviousness, slope and elevation criteria to identify priority areas for SuDS deployment. Results show that CSO volume attenuation ranged a maximum of 50-99% for the catchment, depending on the deployment strategy and underlying mechanisms of each technology. We

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also found that deployment of SuDS in AHP-selected sub-catchments improved CSO reduction only for rain barrels and green roofs, but not for bioretention cells and permeable pavements. SuDS were also a cost-effective retrofit option: for a 40% volume reduction, the SuDS cost, at most, 25% of the equivalent cost required for a large CSO tank. Outcomes of this study demonstrate the efficacy of SuDS in controlling CSOs, adding yet another tangible benefit to their increasingly recognised multi-functionality.

Keywords

Analytic Hierarchy Process (AHP), Combined Sewer System, Life Cycle Costing (LCC), Storm Water Management Model (SWMM), Urban Drainage Modelling

1 Introduction

Combined sewer systems capture and convey both stormwater and municipal sewage through a single sewer line towards a central treatment facility. Typically, only a limited amount of stormwater is processed in the treatment plant. Anything that exceeds this capacity is directly released to the receiving water body through designated storage and overflow structures, a process referred to as combined sewer overflows (CSOs). CSOs have garnered much interest around the world since many cities have combined sewer systems in place (Komínková et al., 2016; Llopart-Mascaró et al., 2015; Xu et al., 2018). CSOs adversely impact water quality and are considered one of the leading causes of urban surface water pollution (Copetti et al., 2018; Passerat et al., 2011; Riechel et al., 2016; Weyrauch et al., 2010; Xu et al., 2018).

Exceeded drainage capacity can also lead to urban floods, which might cause traffic disruption, economic damage, and jeopardise human health (Qin et al., 2013). Both issues, CSOs and exceeded drainage capacity, are proliferated in expanding urban areas in which the increase in impervious coverage puts a strain on existing drainage infrastructure and shortens catchment response time, thereby bringing reduced infiltration, higher flood magnitudes and shorter flood duration (Martin-Mikle et al., 2015).

Traditionally, CSO and urban flood reduction measures have a strong focus on the expansion of buffer volume or conveyance capacities of existing sewer systems (Tavakol-Davani et al., 2016; Wan and Lemmon, 2007). Integrated approaches have also assessed the combined control of sewer and wastewater treatment plant to maximise in-sewer storage, thereby prolonging the need for additional new infrastructure (Erbe and Schütze, 2005; Langeveld et al., 2013). However, many of these highly engineered, 'grey' approaches are costly and largely focus on collecting and removing waters from urban areas (Montalto et al., 2007; Tavakol-Davani et al., 2016).

Over decades, the application of distributed runoff management strategies has also gained traction in which stormwater runoff volume and peak time are controlled by reducing surface imperviousness, increasing infiltration and retention as well as reusing stormwater on or near the site of runoff generation (Lund et al., 2019; Qin et al., 2013). These measures are collectively known using different terminologies such as Sustainable Drainage System (SuDS), Water Sensitive Urban Design (WSUD), Low Impact Development (LID), Best Management Practices (BMPs), Green Infrastructure (GI) or Stormwater Control Measures (SCMs), among other terms, the use of which depends upon the context, region and the primary focus of these measures (Fletcher et al., 2015).

Irrespective of the terminology, these measures comprise structural (i.e. physical infrastructure) and non-structural (i.e. policy, planning controls, education and operational) measures to manage drainage systems while also providing additional benefits such as alternative water supply and improvements in amenity, biodiversity, water quality, and urban micro-climate (Fletcher et al., 2015; Riechel et al., 2016) among other ecosystem services (Kuller et al., 2017). Selected examples of such SuDS (the term we henceforth use to refer to these interventions) include permeable pavements, green roofs, bioretention cells and rain barrels.

Literature can be found assessing, on the one hand, the efficacy of SuDS – under different rainfall characteristics and at different spatial extents – in reducing CSOs and, on the other hand, the impact of their spatial arrangement on CSO reduction outcomes. For example, Qin et al. (2013) presented the application of SuDS in a district in Shenzhen, China in which swales, permeable pavement and green roofs were able to reduce local urban flooding under rainfall storms of different return periods, duration and peak ratios. Tao et al. (2017) concluded that SuDS were effective in reducing peak urban runoff and CSO volume for low intensity and short duration rainfall events but not for high-intensity events. Freni et al. (2010) have compared the performance of infiltration-based SuDS (termed 'Distributed BMP solution' in their study) with a centralised storage 'grey' option and a mixed option (distributed BMP combined with centralised storage), concluding that centralised storage was more robust and effective. This is in contrast to the conclusions of a comprehensive study by Lucas and Sample (2015) that compared CSO reduction performance of grey infrastructure (storage) against SuDS (termed 'GI' in their paper) with and without outlet control for a high-intensity rainfall event. They concluded that while grey infrastructure was better able to reduce CSO frequency, CSO volume was better attenuated with outlet-controlled SuDS.

Many of these studies are useful yet, at times, provide conflicting insights into SuDS performance in reducing CSOs, warranting further research into their efficacy, system configuration and the key underlying mechanism affecting their performance. This knowledge gap constitutes the fundamental basis of this paper. Furthermore, many of these studies, which use modelling as their primary methodology, adopt event-based simulations to make inferences about CSO reduction processes (Tao et al., 2017; Tavakol-Davani et al., 2016). Simulating with a continuous, long-term rainfall data, however, would allow for a clearer, more comprehensive analysis as it better captures the variations in the rainfall patterns and the subsequent hydrological changes, yielding more accurate approximations of the hydrographs (Grimaldi et al., 2012) and, in turn, the interaction of SuDS and CSO outfalls (Lucas and Sample, 2015).

The second thematic in the literature focusses on the deployment strategy (i.e. the spatial arrangement) of SuDS, which is typically based upon design manuals and guidelines (for example, Connecticut Department of Environmental Protection (DEP) (2011)) and spatial planning tools (for examples, UWOT by Makropoulos et al. (2008) and UrbanBEATS by Bach et al. (2020)) that leverage appropriate land use type, slope, soil properties and elevation. Most of these tools, however, often aim for a broader perspective of stormwater management (usually reducing urban runoff and/or increasing the time of runoff concentration) and do not explicitly focus on the requirements for CSO reduction (Kuller et al., 2017; Makropoulos et al., 2008). The design, planning and deployment of SuDS, thus, rely upon tools that offer only an implicit guideline for CSO reduction. An exception to this is the spatial planning approach by Fu et al. (2019), which considers CSO location as one of its design criteria, but suffers drawbacks when defining its role for CSO reduction. This raises questions as to whether existing design criteria and guidelines for SuDS deployment are also effective and applicable for CSO reduction. The lack of attention to this objective in existing approaches is a key knowledge worth understanding as it would allow better quantification of a potential functionality of SuDS that appears to be overlooked among its many other benefits and further contribute its business case.

This paper aims to investigate the impact of SuDS implementation on CSOs. In particular, we address the aforementioned knowledge gaps through three specific objectives:

i. Elicit the long-term efficacy (35 years) of SuDS in reducing CSOs encompassing events with varying rainfall patterns,

ii. Assess the impact of spatial deployment strategies for SuDS (i.e. targeting selective sub-catchments as opposed to uniform catchment-wide implementation), and

iii. Understand the cost-effectiveness of SuDS from a life-cycle costing perspective, in particular, we adapt the methodology of Montalto et al. (2007), Tavakol-Davani et al. (2016) and Johnson and Geisendorf (2019), to compare different types of SuDS.

Our study is limited to four common SuDS technologies: bioretention systems, rain barrels, porous pavements and green roofs. These represent the most relevant SuDS processes (retention/storage, infiltration and their combination) and therefore the methodology is transferable to other measures.

2 Material & Methods

2.1 Overview

An overview of this study is illustrated in Fig. 1. All spatial analyses (e.g. terrain processing for selecting sites for SuDS implementation or calculating roof areas) was performed in ArcGIS Desktop v10.6 (hereafter referred to as GIS) adapting the methodology proposed by Jack (2012) and Ahiablame & Shakya (2016). Hydrologic-hydraulic simulation was performed using US EPA’s Storm Water Management Model (EPA SWMM) v5.1 (hereafter referred to as SWMM) (Rossman, 2010, 2015).

The first part of the study involved the setup and calibration of an urban drainage model of the Fehraltorf sewer catchment as our case study (described in Section 2.2). Using topographical data and the pre-existing sewer network, originally developed in SWMM by Keller (2016), we calibrated and validated the model against available data on flow conditions therein (Blumensaat et al., 2019; used as our reference scenario, which we compare to scenarios of SuDS implementation) – more details in Section 2.3. Then, we simulated the model using a continuous 35-year rainfall time series (Section 2.4) in which different SuDS interventions were included (Section 2.5.1) and their performance evaluated against reference flows, firstly for different rainfall events (of varying intensity, duration and volume as identified within the time series), and, subsequently, over a long-term period (Section 2.5.2).

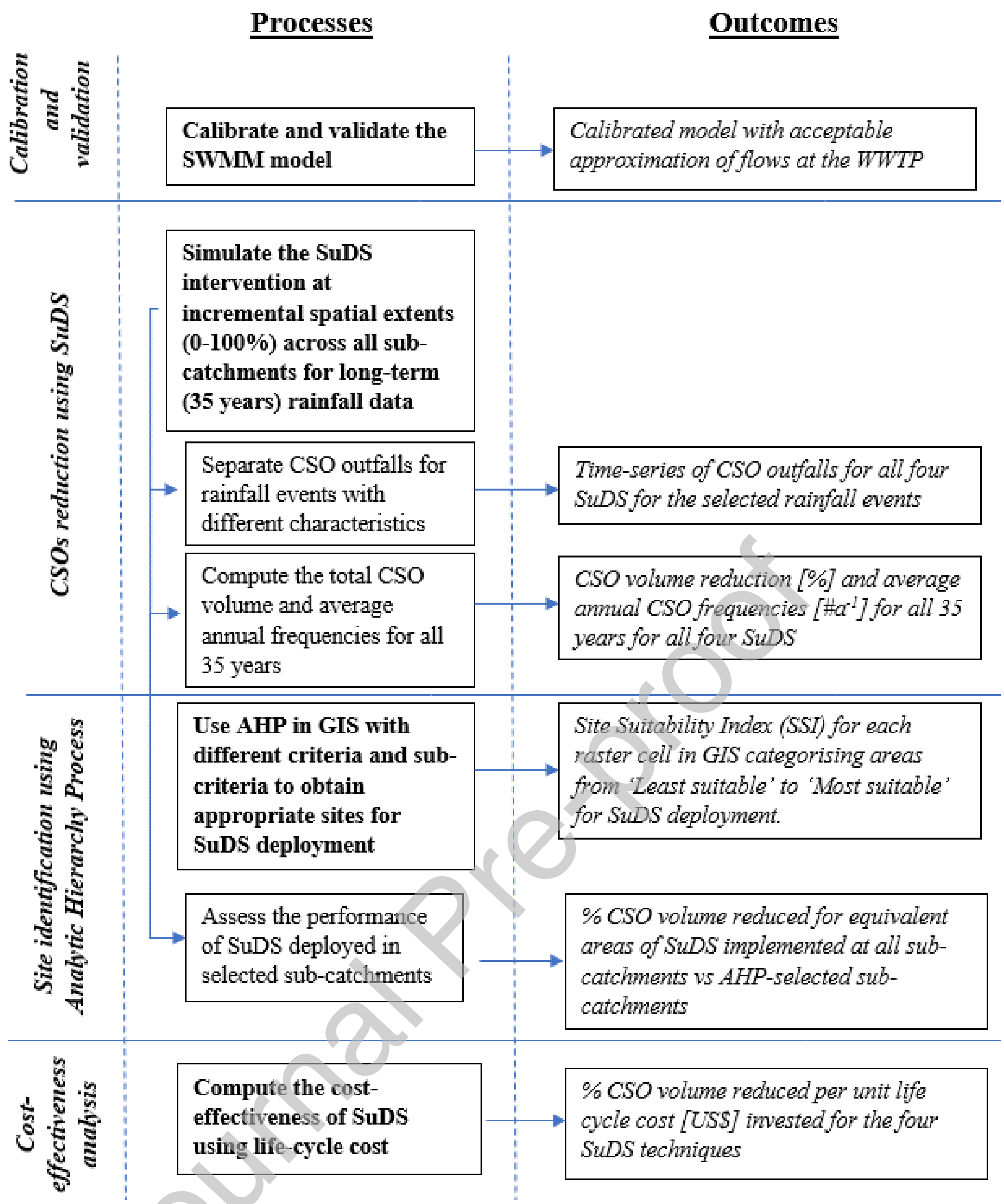


***Fig. 1**. Overview of the methodology and expected outcomes of this study*

In determining if implementing SuDS in selected sub-catchments was more beneficial than distributing them uniformly throughout the entire catchment, we used the Analytic Hierarchy Process (AHP) in which different locational criteria were considered, to identify a ranking of specific sites to deploy SuDS (described in Section 2.5.3). Finally, a cost-effectiveness analysis of SuDS techniques was conducted to compare the life cycle cost (LCC) incurred for CSO reduction (described in Section 2.6).

2.2 Case study description

The Fehraltorf catchment is located 15 km east of Zurich, Switzerland. About 82 ha of the municipality is connected to a combined sewer system (shown in Fig. 2). Domestic sewage generated from Fehraltorf and two neighbouring municipalities Rumlikon and Russikon (not

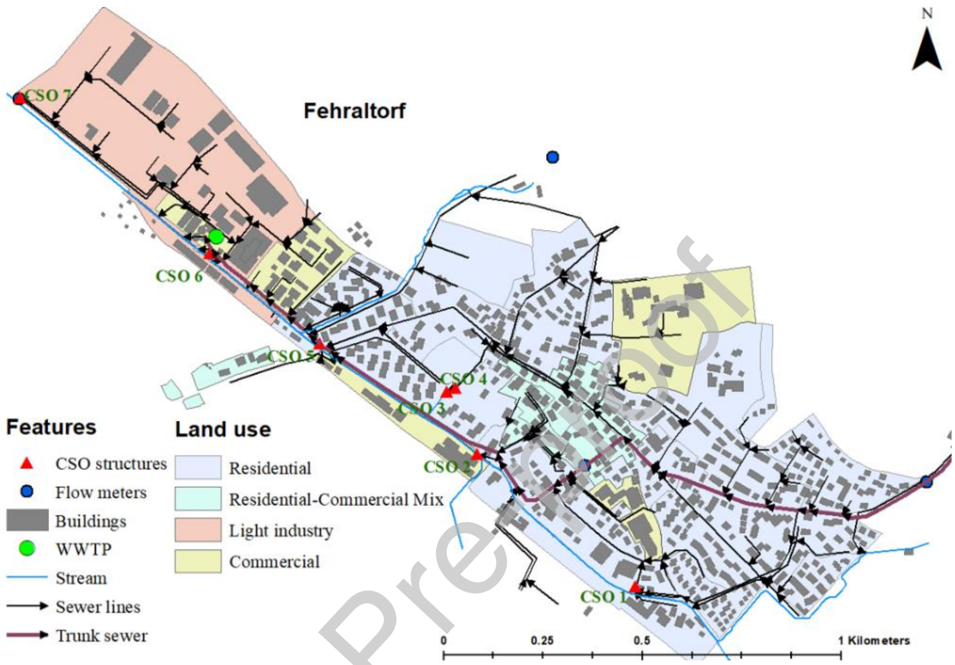


***Fig. 2**. Overview of the sewer network in the study area of Fehraltorf municipality in Zürich, Switzerland, including locations of the treatment plant, trunk sewer (sewer main), flow meters and overflows structures.*

shown in Fig. 2) are collected and conveyed together with stormwater runoff to a treatment plant with a maximum treatment capacity of 180 Ls^{-1}. During large storm events, when the conveyance and the treatment capacities are exceeded, sewage overflow is directly released from the CSO structures (triangles in Fig. 2) to Rohrbach and Luppmen creeks that flow through the catchment.

We selected the Fehraltorf catchment as our case study as it is of a reasonable size to conduct an exploratory analysis using long-term simulation. The catchment also has a rich existing data set with which we can set up and calibrate our urban drainage model

(Blumensaat et al., 2019; Keller, 2016) including a well-documented spatial database of sewer assets.

2.3 Urban drainage model

All hydrodynamic analyses in the study were performed using a sewer network model implemented in SWMM by Keller et al. (2016). The model includes 246 sub-catchments that drain into 427 junction nodes (manholes) connected by 431 links (conduits) and seven CSO structures (as shown in Fig. 2). The infiltration process was simulated using the Hortonian model which implies the generation of an overland flow when precipitation exceeds the infiltration rate. Routing was simulated using the dynamic wave method. Groundwater infiltration into the drainage system was included in terms of monthly values (Keller, 2016). For dry weather flows (municipal sewage), hourly variations for different days of a week were included (Keller, 2016).

The SWMM model was calibrated by changing the Manning's coefficient, infiltration rates and depression storage for both permeable and impermeable fractions of all the sub-catchments (Table S1 in the Supplementary Material). For the calibration and validation processes, rainfall and flow observation data of 1-minute temporal resolution between February 10, 2016, and June 28, 2018, were used (Blumensaat et al., 2019). We compared the observed and simulated flows at the inlet of the treatment plant for which the flows from two areas located upstream (Russikon and Rumlikon) were also included as separate, direct inflows in SWMM since the measured flow included inflows from all three municipalities. Model performance was evaluated using the Nash–Sutcliffe Efficiency (NSE) coefficient (Nash & Sutcliffe, 1970) presented in Section S1 in the Supplementary Material.

The model calibration and validation results depicted in Fig. S1 shows a good approximation of low flows, but the peaks were under-represented, hence the relatively low NSE coefficients (NSE=0.74 for calibration; and NSE=0.44 and 0.24 for validation). However, considering that we are making relative assessments of the changes in the CSO events due to SuDS implementation, we believe the calibrated model serves as an adequate baseline for benchmarking the SuDS scenarios since the flow dynamics are well replicated by the model.

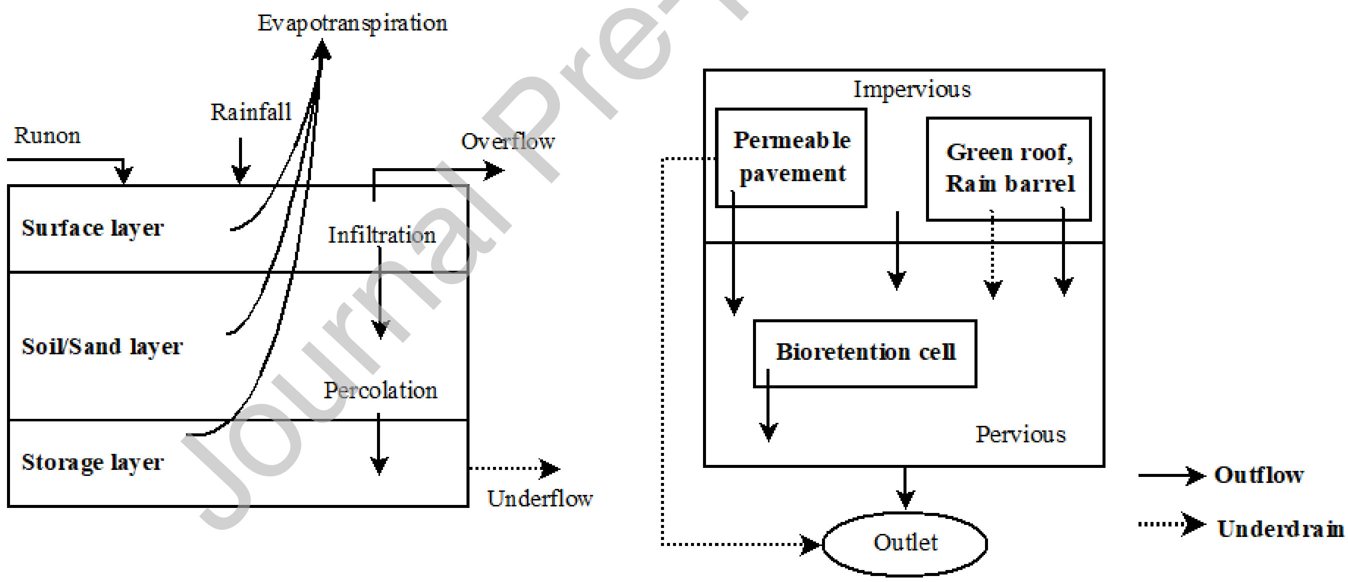
2.4 Rainfall data

For long-term simulation, a 35-year long rainfall time series between January 1st, 1981, to December 31st, 2016 at a 10-minute temporal resolution was used from the station in Kloten (20 km away from the study site), downloaded from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) repository. We assumed an intra-arrival time of four hours for event-based simulation (Gaál et al., 2014; Staufer et al., 2012) and that the rainfall events had a minimum sum of 12 mm, a minimum duration of three hours, and a threshold 10-minute peak intensity of 0.7 mm to limit the number of rainfall events. This results in 600 rain events over the 35 years. From the long-term simulation, we filtered out the performance of SuDS for three contrasting rainfall events to analyse their performance in reducing CSOs: (1) 41.1 mm, 2.83 day rain event in January 2001 that had the highest rainfall duration, (2) 31.7 mm, 7.33 hr rain event of May 1988 that had the highest intensity (109.7 mm/h), and (3) 107.9 mm, 1.6 day rain event of September 1987 that had the highest volume.

2.5 SuDS deployment and simulation scenarios

2.5.1 A general impression of SuDS in SWMM

In this study, four SuDS techniques were considered: bioretention cells, green roofs, permeable pavements and rain barrels. We chose these systems because of their scalability, allowing for local scale implementation and their contrasting underlying functionality for stormwater management (Rossman, 2015, 2010) allowing for a broader understanding of how their different mechanisms of SuDS can support CSO reduction, if at all. For instance, bioretention cells primarily offer infiltration and evapotranspiration whereas rain barrels only store stormwater from rooftops before releasing to the pervious fraction of the sub-catchments. Permeable pavements detain water temporarily before releasing slowly from the underdrain into the sub-catchment outlet, whereas green roofs behave similar to bioretention cells, except that they capture only direct rainfall (but no runon from roofs) from which water infiltrates into the underlying soil and drainage mat.



(a) Conceptual representation of SuDS and hydrologic response in SWMM (Rossman, 2015)

(b) SuDS deployment used in this study

Fig. 3. *Conceptual representation of SuDS and its deployment in SWMM*

In SWMM, these SuDS techniques are represented using a combination of vertical layers of surface, soil and storage (Fig. 3a) (Rossman, 2015). The surface receives run-on and direct rainfall as inflows. Water is lost through runoff, evapotranspiration (ET) and infiltration into the soil layer. The latter constitutes an amended soil mix from which water may be lost through ET and can percolate into the underlying storage layer (Rossman, 2015). This layer comprises coarse stone or gravel from which water is lost either by infiltration into natural soil layer or by outflow through an underdrain (commonly a perforated pipe). Table 1 shows the characteristics of the SuDS considered in the study using typical values found in the literature such as Rossman (2015) and Chui et al. (2016). Further details on the SuDS techniques are provided in Section S2.

Table 1 *Summary of SuDS characteristics. Typical values were used for all the parameters based on Rossman (2015) and Chui et al. (2016). The uncertainty of SuDS performance was analysed by simulating using the minimum and maximum values of the two most sensitive parameters of the SuDS options shown in the brackets, based on Leimgruber et al. (2018) for green roof and bioretention cell and Randall et al. (2020) for permeable pavement. For rain barrels, the height of the barrels was doubled and halved.*

Layer	**Parameter**	**Bioretention cell**	**Permeable pavement**	**Green roof**	**Rain barrel**
Surface	Berm height [mm]	75	-	25	-
	Vegetation volume fraction	0.05	-	0.4	-
	Roughness (Manning's n) [-]	0.2	0.012	0.1	-
	Surface slope [%]	1	1	1	-
Soil/Sand	Thickness [mm]	(300-2000) 600	250	(40-200) 100	-
	Porosity (volume fraction)	0.52	0.437	(0.36-0.65) 0.52	-
	Field capacity (volume fraction)	0.15	(0.05-0.2) 0.062	0.15	-
	Wilting point (volume fraction)	0.08	(0.01-0.08) 0.024	0.08	-
	Conductivity [mm/h]	(50-140) 119.4	118	119.4	-
	Conductivity slope	45.05	120.4	45.05	-
	Suction head [mm]	48.26	49.02	48.26	-
Pavement	Thickness [mm]	-	200	-	-
	Void ratio (Voids/Solids)	-	0.2	-	-
	Impervious surface fraction	-	0.1	-	-
	Permeability [mm/h]	-	400	-	-
Drainage mat	Thickness [mm]	-	-	50	-
	Void fraction	-	-	0.55	-
	Roughness (Manning's n)	-	-	0.3	-
Storage	Thickness [mm]	300	300	-	(600-1800) 1220
	Void ratio (Voids/Solids)	0.3	0.3	-	1
	Seepage factor [mm/h]	4	0.5	-	-
Underdrain	Flow coefficient [mm/h]	-	4.24	-	36.62

Offset height [mm]	-	100	-	100

2.5.2 Scenario 1: Deployment across all sub-catchments

The first deployment strategy was to target the runoff generated from the impervious fraction of the sub-catchment as illustrated in Fig. 3b which shows that the runoff from impervious fraction surfaces was specified to be diverted to the SuDS. The outlet of the SuDS (as overflow or underdrain) was set differently for each SuDS based on its working mechanism.

The performance of SuDS techniques was assessed in terms of CSO volume and frequency at varying incremental spatial coverage that ranged from 0 to 100% (with non-linear increment) for each of the SuDS. The values of coverage can be understood as following: all sub-catchments contain different amounts of pervious and impervious fractions and a different number of buildings and roof areas. Therefore, a 5% coverage of permeable pavement would mean replacing 5% of impervious areas (not counting the building or roof area) of all sub-catchments by the pavements. Similarly, a 10% coverage of rain barrels would imply installing rain barrels at 10% of the households in all the sub-catchments. A 100% implementation represents the best possible case for the four SuDS at the given configuration which can be argued to be unlikely to be met in the municipality, especially for bioretention cells and permeable pavements. However, it is expected that its outcome will serve as a benchmark to compare the CSO reduction for all other scenarios. Further details on calculations of SuDS' spatial coverage is provided in Section S3.

In this first implementation scenario, our analysis entailed simulating using a 35 year-long rainfall data, from which we reported the CSO outfalls, first for selected rainfall events with different key characteristics (see Section 2.4), and then for the entire 35-year period to compute total CSO volume and average annual frequency. A CSO event was assumed when the flow rate in the system exceeded 180 Ls^{-1}, the maximum capacity of the treatment plant. To distinguish one CSO event from another, an intra-event time of four hours was further assumed (Gaál et al., 2014; Staufer et al., 2012). The total CSO volume was computed by adding the volume of overflow water from the CSO structures for all the 35 years; the average annual CSO frequency by dividing the total number of CSO events by 35 years.

For the uncertainty analysis of CSO reduction, the performance was recorded for the four SuDS options when the two most sensitive parameters for each SuDS option were changed to their maximum and minimum values (Table 1) and the results compared with those obtained using typical parameter values at the inflexion point of the CSO reduction curve for the four SuDS techniques.

2.5.3 Scenario 2: Deployment in selected sub-catchments

The second implementation scenario aimed at mimicking an engineering approach to identify the most suitable areas for SuDS implementation. The sub-catchments for priority deployment are chosen using different criteria such as, but not limited to, the topography of the area, land use, land availability and soil properties. The influence of these factors differs from one geographical location to another, which calls for an analytic tool to systematically rank these variables based on their relative importance. Analytic Hierarchy Process (AHP) is one such tool that has been used extensively to rank multiple criteria and their sub-criteria (of same or different units) to create a relative importance hierarchy to establish coefficients using a set of eigenvectors (Section S4) and identify appropriate locations where SuDS can be most effective (Ahammed et al., 2012; Jack, 2012).

We performed two sets of AHP study. First, only four major criteria (land use, imperviousness, slope, and elevation) were considered, with a set of sub-criteria for each of these (Fig. 4). Of the four primary criteria used, land use was assigned the highest importance followed by imperviousness, slope and elevation, respectively, thereby prioritising source runoff control at residential areas at relatively higher elevations. These criteria, and sub-

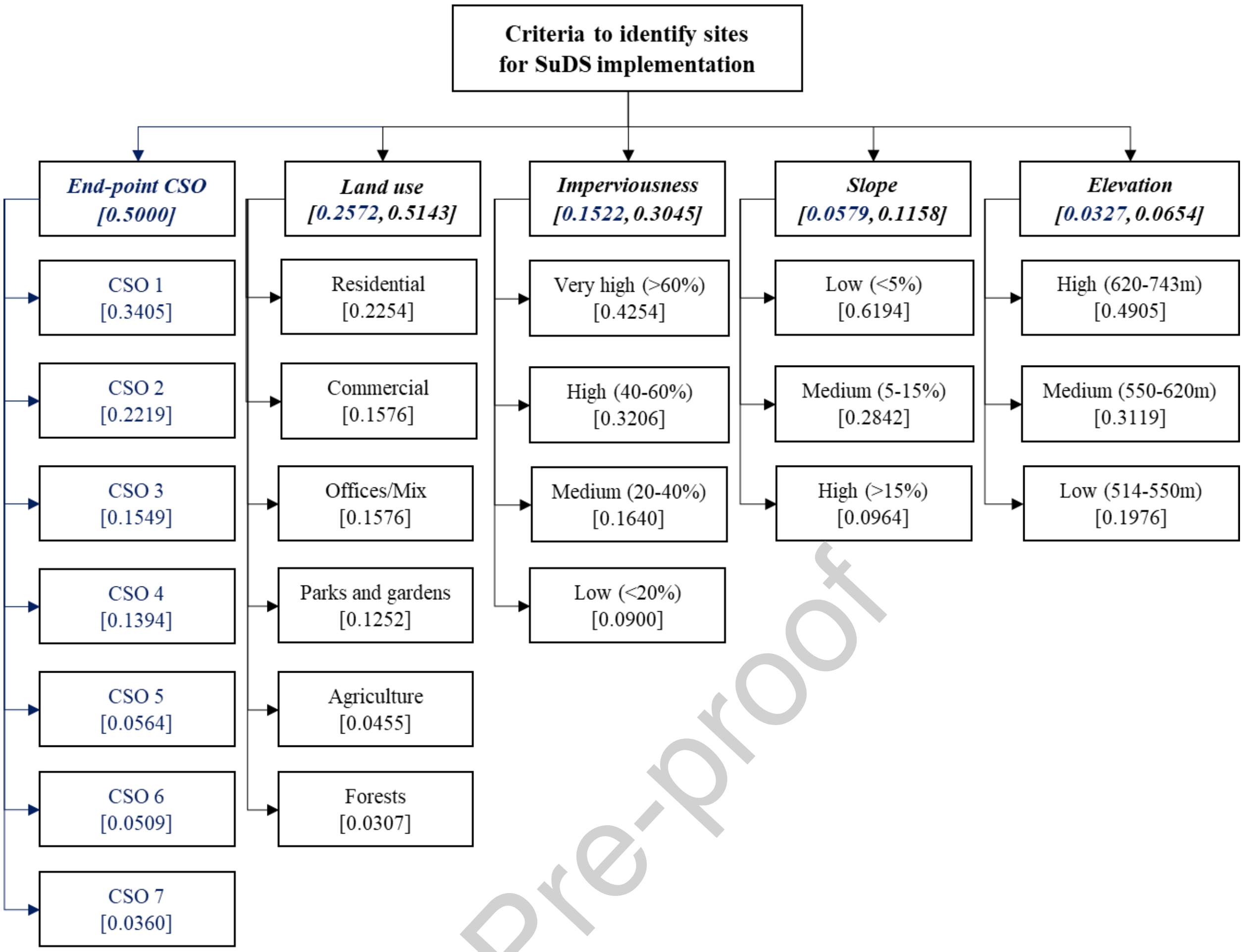


Fig. 4. *Criteria and sub-criteria used in AHP to identify appropriate sites for SuDS implementation with corresponding variable coefficients (eigenvectors) and product values shown in square brackets. Two sets of analyses were performed: first considering only land use, imperviousness, slope, and elevation as criteria with all eigenvectors shown in black, and second, with the inclusion of end-point CSO criterion shown in blue.*

criteria and their relative importance (their ranks and relative weights) were assigned based on available GIS data, literature recommendations (Connecticut Department of Environmental Protection (DEP), 2011; Eckart et al., 2017), and prior knowledge and experience of the co-authors of this study. Note that we only used this approach of selecting the criteria and assigning the weights to implement the SuDS systematically in spatially appropriate locations and not to make the SuDS selection. Second, we also included the end-point CSO criterion, which considers the CSO structures that each of the sub-catchment ultimately drains into. The objective of this assignment was to determine if the location of CSO structures played a role in CSO mitigation.

Each of the criteria and their relative importance were first ranked using a numeric scale of 1 (least important) to 5 (highly important), followed by constructing a pair-wise chart and then computing eigenvectors to assign coefficients to the primary criteria. The eigenvectors were used to transform the relative weights into normalised coefficients based on a 0 to 1 scale (Jack, 2012). The construction of the pair-wise matrix and the computation of eigenvectors were repeated for every criterion and sub-criterion (Fig. 4).

We determined suitable sites for SuDS deployment using Raster Overlay analysis of the weighted criteria (from previous steps) in GIS to calculate the site suitability index (SSI) using the additive approach in Eqn. 1:

$$SSI = \sum\left(\beta_c(V_c)\right) \quad (1)$$

where,

SSI = Site Suitability Index for SuDS [-],

c = {end-point CSO, land use, imperviousness, slope, elevation},

β_c = Variable coefficients (eigenvectors) of the criteria [-],

V_c = Product of the sub-criteria weights and their variable coefficients [-].

In the equation, the β values are the variable coefficients (eigenvectors) whereas the *V* values are the product of the sub-criteria weights and their coefficients. For example, high imperviousness (>60%) criterion has a coefficient of 0.4254 (Fig. 4). Thus, an individual raster cell of imperviousness rating of 70% has a *V* value of 0.70(0.4254) = 0.2978. For imperviousness, the β value is 0.3045 and so the compound variable $(\beta\ (V))$ is (0.3045(0.2978)). This was done for all criteria and sub-criteria and added to obtain a suitability index for each raster cell. Finally, the raster cells were classified using ‘natural breaks' into five relative categories in GIS ranging from 'Least suitable' to 'Most suitable' for SuDS implementation based on their SSI values (Jack, 2012).

For the second AHP study, the 'end-point CSO' criterion was assigned a weight of 0.5 and the other criteria the half the values assigned to the first AHP study. In this case, the corresponding sub-criteria to the seven CSO structures were assigned proportional weights based on the volume of outfalls from each of these.

To determine if incorporation of SuDS in selected sub-catchments was more effective than distributing them uniformly throughout all sub-catchments, a comparison was made between the CSO volume reduction when equivalent areas of each of the four SuDS techniques were incorporated in the two sets of AHP-identified sub-catchments versus when they were incorporated uniformly in all sub-catchments. This means that the CSO reduction after implementing, for example, permeable pavements (covering 2.5 ha) in the 35 AHP-identified sub-catchments were compared against when an equivalent area was implemented in all sub-catchments.

2.6 Cost-effectiveness analysis

Although technical assessment of the SuDS in CSO reduction may explain the physical processes, their implementation in practice is bound to be determined by the financial investments as well. To this end, we analysed the cost-effectiveness of the SuDS by calculating the life cycle cost (LCC) required for each of the SuDS. The LCC analysis included the installation and operation and management (O&M) of the SuDS over different life spans as shown in Table 2. Decommissioning costs of SuDS were not included assuming that they will be rehabilitated during or beyond their functional life span, which either occurs beyond the planning horizon of the economic analysis or becomes a negligible amount after discounting. The horizon was taken to be 40 years, the lowest common multiple of the life span of the SuDS techniques (Park, 2013). All SuDS implementation were assumed to occur at year zero (taken as 2019) and the O&M costs were assumed to be 1.5 % of the installation costs (Montalto et al., 2007). The life cycle costs incurred were evaluated and compared for analysis of cost-effectiveness using the net present value (NPV) (Eqn. 2) with a discount rate of 2%, a typical value used for Swiss urban water infrastructure (Logar et al., 2014).

$$NPV = \sum_{i=0}^{n} FV_i (1+r)^{-i} \quad (2)$$

where,

FV_i = Future value of the cost at year i [US$],

r = discount rate [%],

n = planning horizon [years]

***Table 2** Construction and O&M cost and expected life span data for SuDS based on Montalto et al. (2007) and Chui et al. (2016). Typical values were used for cost calculation whereas the range of costs was calculated using the minimum and maximum values shown in the brackets.*

	Description [Unit cost]	**Bioretention cell**	**Permeable pavement**	**Green roof**	**Rain barrel**
Construction cost [US$]	Plant [US$/m^2]	(7-60) 60	-	(7-60) 7	-
	Gravel [US$/m^2]	(88-92) 88	(59-92) 88	-	-
	Soil/Sand [US$/m^3]	(63-94) 63	63	63	-
	Excavation [US$/m^3]	(5-28) 28	28	-	-
	Filter fabric [US$/m^2]	-	(2-7) 7	-	-
	Pavement [US$/m^3]	-	200	-	-
	Waterproof layer [US$/m^2]	-	-	133	-
	Roof barrier [US$/m^2]	-	-	27	-
	Drainage mat	-	-	(30-35) 35	-
	Rainwater barrel	-	-	-	(700-800) 750
	Pipe [US$/m]	-	200	-	12
	Disposal	(7-17) 7	(7-17) 7	-	-
O&M [US$]	Share of net construction cost [%]	1.5	1.5	1.5	1.5
Life span [a]	Expected life span in years	40	40	40	20

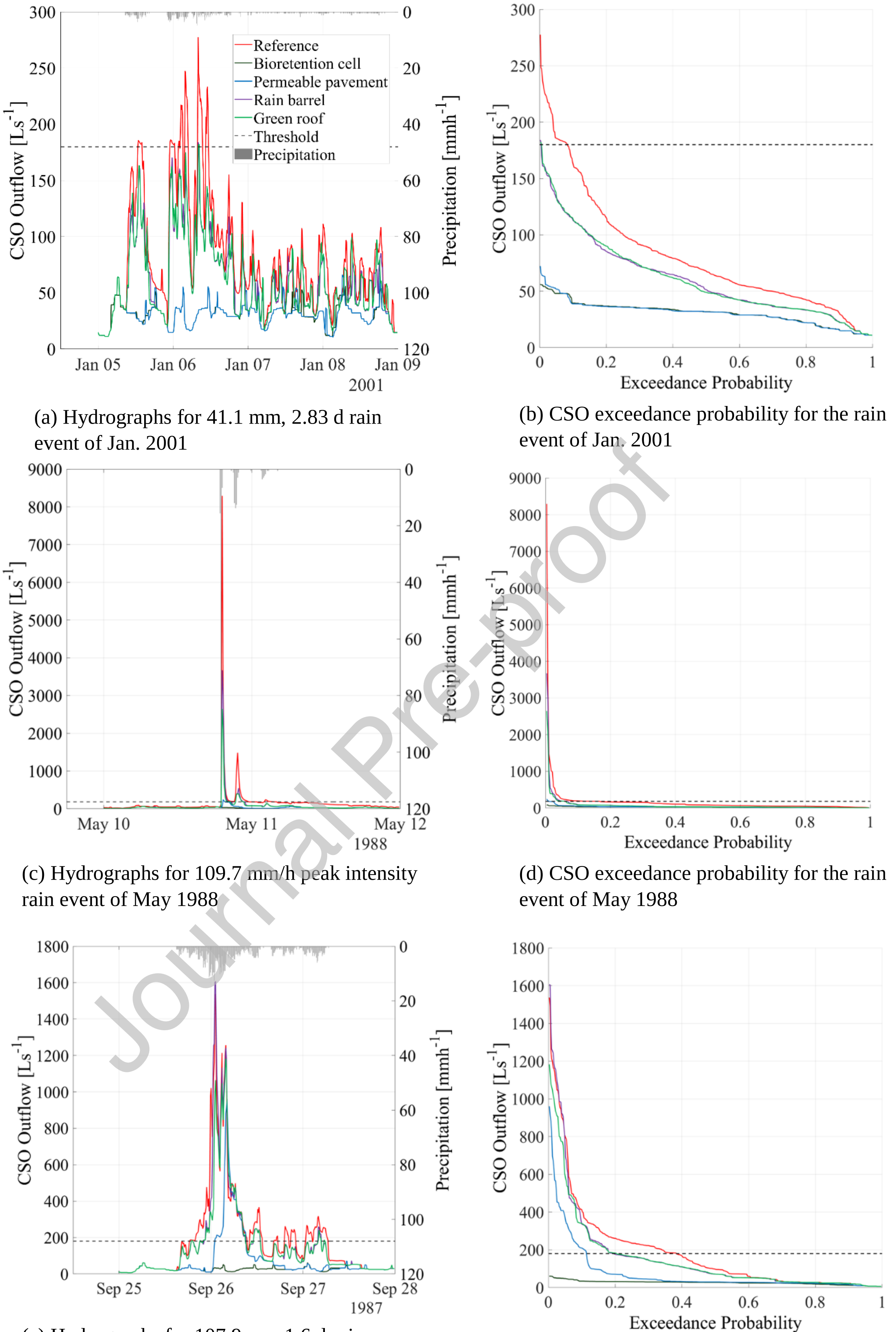
To determine the cost-effectiveness of SuDS against a typical ‘grey’ option, we also compared the NPVs of different sizes of CSO tanks (small, medium and large) yielding 25, 35 and 40% CSO volume reduction as described by Montalto et al. (2007). Here, the comparison is simply based on the costs incurred for the respective CSO volume reduced from a single CSO tank, as if all flows from the municipality is drained to it. This is a simplistic comparison -- since the number, size and spatial distribution, and also the different costs for construction of tanks, is disregarded -- that nevertheless predisposes a tentative idea of the cost-effectiveness of the SuDS techniques in comparison to the grey option.

3 Results and discussion

3.1 Performance of SuDS during selected rainfall events

The performance of SuDS during the three selected rainfall events described in Section 2.4 were compared in terms of the changes in the hydrographs (representing CSO outflows) as illustrated in Fig. 5.

The hydrographs and the CSO exceedance probability curves for the high-duration rainfall event in January 2001 (Fig. 5a and 5b) depict a clear reduction in CSO outflow for bioretention cells and permeable pavements throughout the rainfall event, including the peak rainfall of 6 mm/h in which the peak flow rates were shaved off by 80% and 74%, respectively, and reduced below the threshold value of 180 Ls^{-1}.



(a) Hydrographs for 41.1 mm, 2.83 d rain event of Jan. 2001

(b) CSO exceedance probability for the rain event of Jan. 2001

(c) Hydrographs for 109.7 mm/h peak intensity rain event of May 1988

(d) CSO exceedance probability for the rain event of May 1988

(e) Hydrographs for 107.9mm, 1.6 d rain event of Sep. 1987

(f) CSO exceedance probability for the rain event of Sep. 1987

Fig. 5. *Changes in hydrologic response to rainfall events of January 2001 (highest duration), May 1988 (highest intensity), and September 1987 (highest volume) for SuDS implementation at maximum possible spatial extent*

The high-duration rainfall event was steady but not intense: at no point in time during this storm event did the precipitation rate exceed the infiltration rate in bioretention cells that precluded the generation of an infiltration excess runoff. As for permeable pavements, the attenuation was largely from infiltration of water into the storage bottom and the bypass of infiltration excess runoff into the pervious fraction. Although rain barrels and green roofs showed considerable reductions in the peak outflows as well (nearly 34%), the outflows still exceeded the threshold: the persistent, intense rainfall may likely have filled the barrels and fully saturated the roofs.

Hydrographs for the high-intensity rainfall event, which had a spell of intense rain and a dry spell before and after the peak, showed a peak outflow over 8200 Ls^{-1} for the reference condition (Fig. 5c). The peak was reduced when bioretention cells were implemented, during which dry antecedent soil moisture conditions allowed for water to infiltrate at a maximum rate. Although permeable pavements reduced peak outflow by nearly 97% to 241 Ls^{-1} (Fig. 5d), the rainfall event was too intense to attenuate the outflow below the threshold value. Likewise, green roofs and rain barrels also showed limited impact: peak outflow was reduced by 68% and 55% to 2645 Ls^{-1} and 3670 Ls^{-1}, respectively.

For the high-volume rainfall event of September 1987 (Fig. 5e and 5f), the reference case showed a peak flow of 1537 Ls^{-1}. In this case, as well, only bioretention cells were able to reduce peak flow and this reduction was largely due to runoff attenuation brought about by surface infiltration for the first few hours followed by percolation and exfiltration into the natural soil. For permeable pavements, there was an outflow due to both infiltration excess runoff as well as a delayed-release from the storage layer. For green roofs, the intense, sustained rainfall allowed only a marginal reduction in CSOs. Interestingly, peak CSO outflow for rain barrels exceeded the reference case, possibly because the barrels were filled by persistent (steady) rainfall before the peak occurred, causing the overflow to spill over the pervious fraction. This, alongside the runoff from the impervious fraction for the sustained rainfall as well as flows from the underdrain of the barrels, may have caused the peak CSO flow rate to even exceed the reference value.

These results highlight that CSO attenuation is limited during high rainfall duration and intensity, echoing the conclusions drawn by Tao et al. (2017). Antecedent conditions (of soil and composite SuDS layers) also seem to play a significant role in determining the occurrence of CSOs, thereby highlighting the importance of using long-term rainfall data for event-based analyses.

3.2 Effectiveness of SuDS in reducing CSOs

The responses of the four SuDS to the selected rainfall events (Section 3.1) also help explain their overall effectiveness in reducing CSO volume and frequency for all precipitation data between 1981 and 2016 (see Fig. 6). The figure elucidates that each of the SuDS technologies, with their different dimensions, dissimilar working mechanism and unique deployment requirements, exhibited contrasting efficiencies in CSO reduction. The performance also depended on the volume of water (direct rainfall, runoff or runon) routed to the SuDS.

Bioretention cells deployed in the permeable fractions of the sub-catchments received direct rainfall and runoff from the entire impervious fraction of the sub-catchments. Infiltration and ET of water from the composite layers, as well as the exfiltration of water into natural soil, resulted in a notable CSOs reduction: despite a mere 2% spatial coverage of the bioretention cells, CSO volume reduction exceeded 71% (Fig. 6a). Further increasing the spatial coverages of the bioretention cells exceeded that of the impervious areas in the sub-catchments, resulting in a diminishing return of CSO volume reduction. When spatial coverage was increased to 30% (equivalent to roughly 14 ha), CSO volume reduction

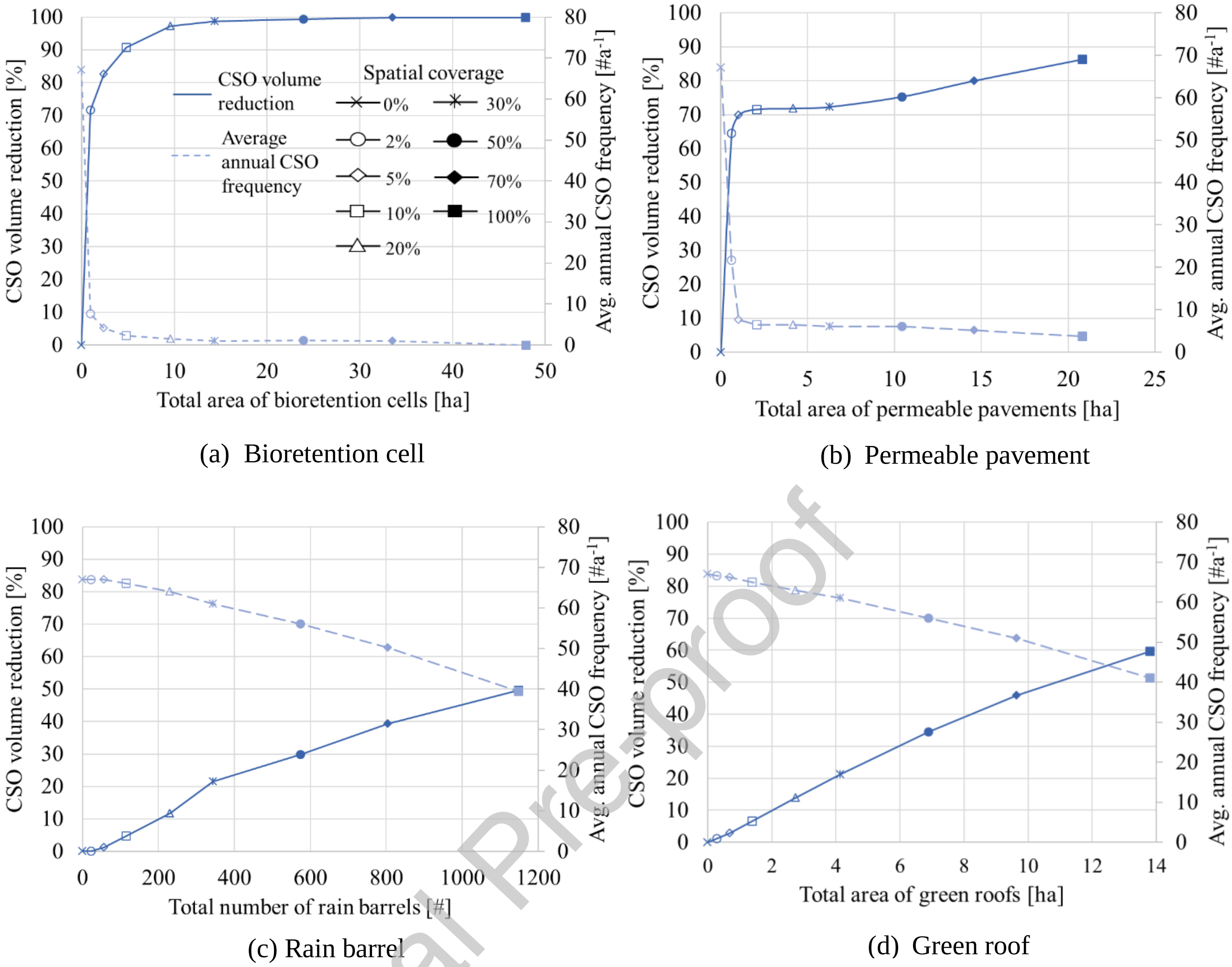


Fig. 6. *Comparison of CSO volume and average annual frequency reduction due to SuDS for continuous precipitation data between 1981 and 2016. The dashed line represents average annual CSO frequency whereas the solid line represents CSO volume reduction.*

increased logarithmically to nearly 99%, and the number of annual CSO events was reduced to one, which can be argued, based on Fig. 5, to have occurred during an intense rainfall event.

Permeable pavements were implemented in the impervious fractions of the sub-catchments, thereby reducing the surface runoff generation, in all rainfall events excluding those of high intensity and long duration (Fig. 5). As such, total CSO volume reduction was only about 86% even at 100% coverage (Fig. 6b). The trend for CSO reduction was also somewhat different: there was logarithmic growth in CSO volume reduction up to a 30%

coverage (6 ha), followed by a linear increase in which we anticipate that CSO events arising from all but highly intense rainfall events were attenuated.

Rain barrels and green roofs both showed incremental improvement in CSO reduction with an increase in spatial extents (Fig. 6c and d respectively). It is also interesting to note that although green roofs were better able to reduce CSO volume, rain barrels fared better in reducing CSO frequency (41 annual events for green roofs against 39 events for rain barrels at 100% coverage). Green roofs, like bioretention cells, offer evapotranspiration and infiltration, except that they receive only direct rainfall: the evaporation of waters from the roofs may have led to a higher reduction in CSO volumes. On the other hand, rain barrels only offered temporary storage of stored water: the delayed-release may have led to a higher reduction in CSO frequencies and since they did not have ET, the volume reduction was relatively lower.

The uncertainty analysis using the range of minimum and maximum parameter values presented in Table 3 show that bioretention cells exhibited the highest deviation due to a wide range of design depth configurations available for the soil layer that greatly affects the infiltration and evapotranspiration processes.

Table 3 *CSO reduction using minimum and maximum values of the most sensitive parameters for the four SuDS techniques in comparison with that obtained using typical parameter values. The comparison was done at the inflexion point of the CSO reduction curve for different spatial extents.*

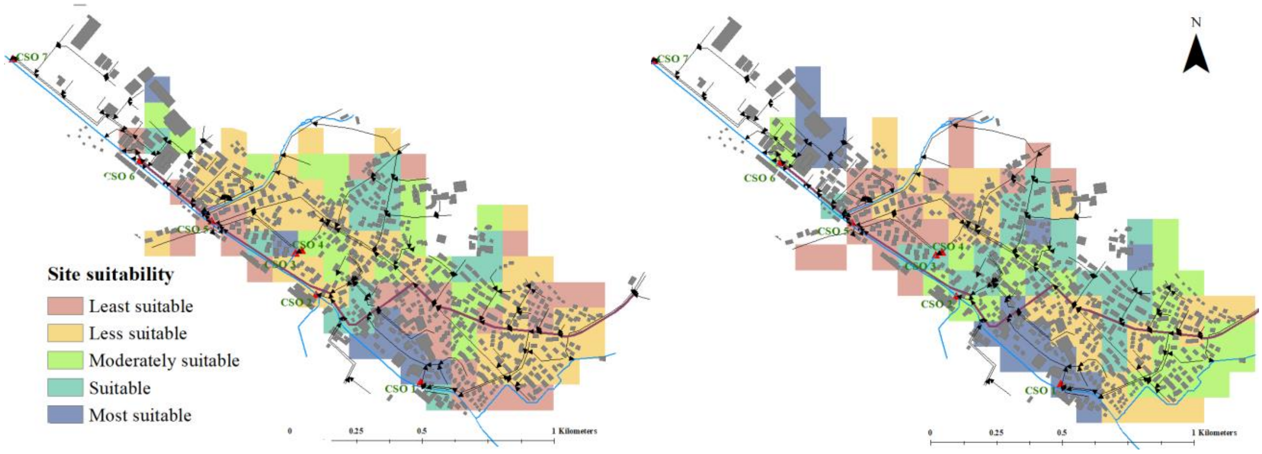
	Minimum	**Typical**	**Maximum**
Bioretention cell			
CSO frequency [$\#a^{-1}$]	5	2	2
CSO volume reduction [%]	61.22	90.71	92.3
Permeable pavement			
CSO frequency [$\#a^{-1}$]	8	8	8
CSO volume reduction [%]	69.87	69.89	69.89
Green roof			
CSO frequency [$\#a^{-1}$]	62	62	62
CSO volume reduction [%]	18.1	21.28	22.39

Rain barrel			
CSO frequency [$\#a^{-1}$]	66	66	66
CSO volume reduction [%]	4.52	4.67	4.78

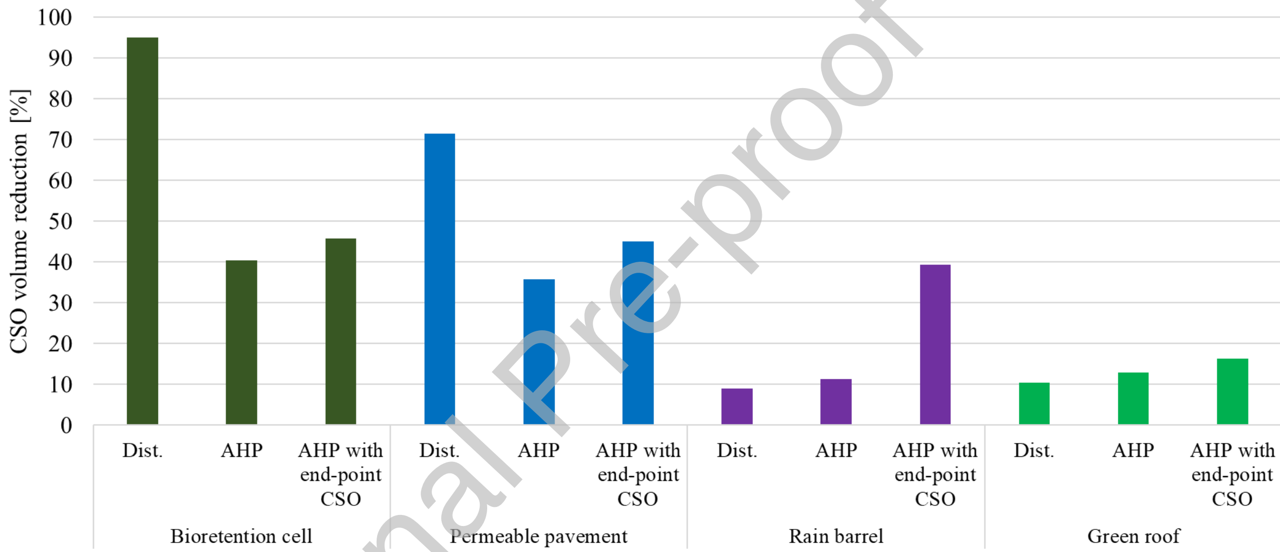
Interestingly, increasing the height of rain barrels inversely affected the CSO volume reduction process. The comparison at different rainfall events for large and small tank sizes (shown in Section S5) show that large tanks fared well during short bursts of intense rainfall and relatively poorly when the rainfall was steady but not intense. In fact, the times at which the flows from larger tanks exceeded the smaller tanks were *not* when the rain subsided; they occured *during* the rainfall. This could possibly be because the tank might have been filled when the rainfall occurred: as the tanks were emptying gradually, when large tanks were "more filled" than smaller tanks, any occurrence of rainfall could have resulted in more storage of water in small tanks than in large tanks, and hence, more spills for the latter.

3.3 Effectiveness of implementing SuDS in AHP-identified sub-catchments

The criteria and sub-criteria used in the two AHP cases to calculate the SSI identified nearly 14% of the total area to be either 'Most suitable' or 'Suitable' for the placement of SuDS (Fig. 7a). In the first case, the hierarchy of the criteria and sub-criteria (as well as the weights assigned to each of these) suggested prioritising interventions geared towards source control in urbanised residential areas (Fig. 7a, left). However, given the relatively homogeneous distribution of residential areas (Fig. 2), other criteria (elevation and slope) may have taken precedence. The identified areas were largely concentrated at higher elevations, away from the trunk line (Fig. 2). The average imperviousness was about 37%, with a mean runoff coefficient of 0.35. In the second case, areas contributing to CSO 7 (sub-catchments in the north-west) were identified as suitable for SuDS deployment (Fig. 7a, right), in addition to the sub-catchments in the south were identified from the previous AHP case.



(a) Result of AHP showing different levels of suitability to implement SUDS in Fehraltorf municipality: without end-point CSO criterion (left) vs with end-point CSO criterion (right)



(b) Comparison of CSO volume reduced when equivalent coverages of SuDS were implemented across the study site ('Dist.') vs when implemented in the two sets of AHP-identified sub-catchments with ('AHP with end-point criterion') and without end-point CSO criterion ('AHP')

***Fig. 7.** Results of Analytic Hierarchy Process (AHP)*

The comparison of CSO volume reduction from the distributed implementation versus that in AHP-identified sub-catchments is depicted in Fig. 7b. Implementing SuDS in AHP-identified sub-catchments, without considering the end-point CSO locations, was not effective for bioretention cells and permeable pavements; the CSO reduction for the two SuDS techniques were 40% and 36%, respectively, which is considerably lower than in the distributed case: 95% and 71%, respectively. For rain barrels and green roofs, the targeted

AHP approach showed marginal improvement in CSO volume reduction, but on a very low level.

The evolution of outflows from the CSO structures for an equivalent spatial coverage for the two AHP and distributed cases (Fig. 8) helps explain the results of Fig. 7b. The location of CSO structures played an important role: those located downstream of the catchment (CSOs 6 and 7) had the two largest outflows (nearly 67% for reference case) and, thus, a greater influence on the occurrence of CSO events (and consequently in the efforts to reduce them). The total reduction in CSO volume from distributed implementation was caused by a decrease in the outflows from all seven CSO structures for all four SuDS; for the AHP case, the reduction was largely from CSO structures 1, 2 and 6, and hardly had any effect on CSO 7, resulting in a lower CSO reduction in comparison with the distributed case. This effect was not as prominent in the case of rain barrels and green roofs because of the relatively sparse distribution of buildings in the areas contributing to CSOs 6 and 7.

The criteria set in the AHP, based on design manuals, led to the selection of areas where

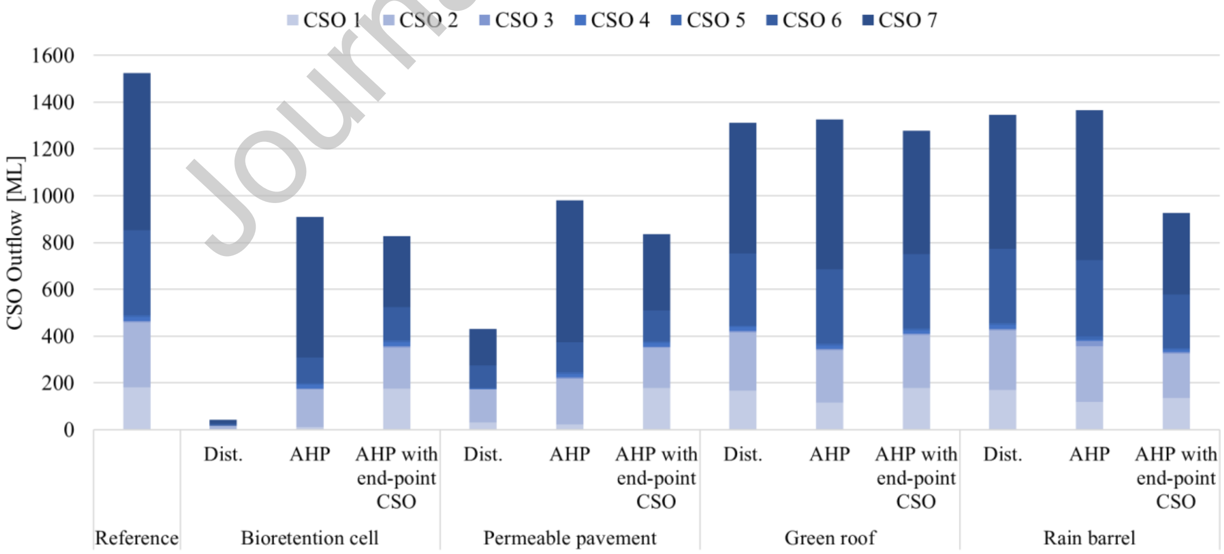


Fig. 8. *Distribution of CSO outflows from the seven CSO structures when implementing the four SuDS in distributed and the two sets of AHP-identified sub-catchments (with and without 'end-point CSO' criterion.*

surface runoff was high. However, by including the end-point criterion in the second AHP study, the location and distribution of CSO structures were given due emphasis, leading to SuDS deployment in several sub-catchments that largely drain to CSOs 6 and 7. This improved the CSO volume reduction for all four SuDS techniques, more so for the rain barrels than for other SuDS, which remarkably showed nearly 39% CSO reduction. In this case, targeted deployment disconnects the flows from rooftops, preventing or at least delaying flows draining into the CSO structures.

The analysis also shows that the effect of targeted SuDS deployment for CSO reduction cannot be generalised. While targeted deployment favour rain barrels and green roofs, it is rather beneficial to have bioretention cells and permeable pavements distributed throughout the catchment. In other words, the deployment can be based on other benefits for SuDS (for example, runoff reduction or improvement in amenity), and can still yield significant of CSO reduction.

3.4 Cost-effectiveness analysis of SuDS

The result of the cost-effectiveness analysis is shown in Fig. 9 in which the curves for each of the four SuDS show the NPVs of the cost incurred for the CSO volume reduced for different spatial extents. The NPVs of the costs of CSO tanks of three different sizes (Montalto et al., 2007) are also provided for comparison as described in Section 2.6.

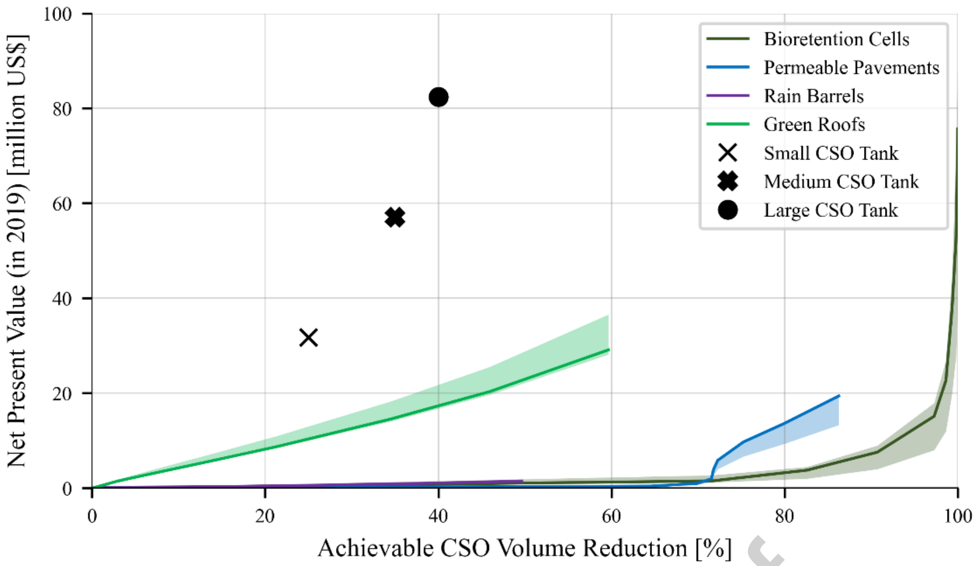


Fig. 9. *Achievable CSO volume reduced per unit life cycle cost invested for the four SuDS techniques. The solid line represents the sum using typical unit costs whereas the shaded region depicts the sum for a range of unit costs. The NPV of the CSO tanks are also presented for comparison based on Montalto et al. (2007).*

At first glance, NPVs of the SuDS are considerably lower than those for CSO tanks for 25, 35 and 40% CSO volume reduction. For example, reducing the CSO volume by 40% using green roofs (for which the NPV is the highest among the four SuDS) costs only 25% of that required using a large CSO tank; other SuDS cost much lower for this level of CSO volume reduction. Although simplistic in the calculation, the high disparity in costs between the CSO tanks and SuDS implies that the latter may be considered a cost-effective retrofitting option to attenuate outflows.

Among the four SuDS, bioretention cells had the highest total unit cost due to incremental conversion of the pervious areas resulting in higher spatial coverage and considerable investments required for the plants, soil/sand layer, gravel, and the excavation works. Considering that costs required for operation and maintenance were assumed to be proportional to the capital investment, bioretention cells also had the highest O&M cost, nearly three times higher than that of the green roof, the second-highest in the list. However, the CSO volume reduction for bioretention cells was so high even at low spatial coverage, and the difference in performance so large over that of other SuDS, that they emerge as high-cost, high-reward option. Interestingly, the curve for bioretention cells showed a clear diminishing return of CSO volume reduction for any investment made above US$ 15 million. This represented the upper limit of the cost required to effectively reduce CSOs in the studied system.

The analysis also positioned permeable pavements as a cost-effective option: they delivered high CSO reduction for less than half the land area required for bioretention cells. They also required lesser excavation (depth) to accommodate the soil, pavement and storage layers (750 mm deep) than bioretention cells (900 mm deep), which had a much deeper soil layer (Table 1). This had direct implications in terms of the costs required for excavation, gravel or soil/sand as shown in Table 2.

These results are in line with conclusions of Liu et al. (2015) and Liu et al. (2016) but contradict that of Chui et al. (2016) in which permeable pavements were more cost-effective than bioretention cells. This is because of the differences in the composite layers and design configurations (for example, the presence (or lack thereof) of soil/sand layer in permeable pavements) and in the unit costs of the components in the two papers (for example, excavation costs), thereby emphasising the significance of an uncertainty analysis which we have shown in Fig. 9 in shaded colours for each of the four SuDS techniques.

At the other extreme, green roofs were the least cost-effective option because of the high investments required for drainage mat and waterproofing, in addition to those required for roof protection, the soil layer, and the operation and maintenance. The low cost-effectiveness of green roofs for CSO reduction also conforms to the conclusions by Montalto et al. (2007), Liu et al. (2015) and Chui et al. (2016). On the other hand, rain barrels had the lowest unit cost of the four SuDS techniques as there were no expenses for waterproofing, the soil/sand layer or excavation (Table 2). Due to the low capital investment, the O&M cost was also quite low. Thus, rain barrels, despite having the lowest CSO attenuation (for distributed case), were effective for the investments required.

The cost-effectiveness analysis, thus, facilitated a direct comparison of the four SuDS techniques which, in turn, allowed for a new perspective in addition to the technical analysis of CSO volume and frequency reduction (as observed in the case of rain barrels). This corroborates the need for an integrated technical-economic assessment for a comprehensive assessment of SuDS in reducing CSOs.

4 Further discussion

Although our study has established the effectiveness of different SuDS techniques in reducing CSOs, we acknowledge that the SWMM model might profit from further calibration (for example, different runoff coefficients for different types of surface covers) for a better approximation of the peak flows that could, in turn, yield a more accurate representation of CSO events. As the measured (observed) inflows at WWTP were computed indirectly from water level values using Manning-Strickler equation, this may also have led to errors in estimating the flows and hence contributed to the relatively low NSE values. However, considering that we are conducting relative assessments of the changes in the CSO events due to SuDS implementation, the calibrated model serves as a reasonable baseline for benchmarking the SuDS scenarios as the flow dynamics are well replicated by the model. This is especially relevant since our model comprises various complex hydrological and hydraulic processes.

The presented simple sensitivity analysis (Table 3) showed consistent results over the different SuDS considered in this study. The influence of the model parameters that characterise the SuDS (i.e. the composite layers of the four SuDS) could, however, warrant further sensitivity analysis.

The use of threshold criteria (of 180 L s^{-1}) to define a CSO event is also simplistic as CSO structures typically detain excess water before discharge into the receiving water body. Incorporating this feature of CSO structures into the study could result in a more accurate estimation of CSO volume and frequency.

5 Conclusion

Our study to investigate the performance of SuDS techniques in reducing CSOs using a 35-year long rainfall data allowed for a comprehensive understanding of the SuDS performance for rainfall events of different key characteristics. We also investigated if targeting selected few sub-catchments for SuDS implementation was more effective than distributing them uniformly all over the study site. Finally, to determine the cost-effectiveness of the SuDS, we used the NPV of the life-cycle cost to compare the performance of the SuDS techniques against CSO tanks of different sizes.

All four SuDS techniques showed considerable reduction in CSOs, although this largely depended upon underlying mechanism and deployment. Specifically, we found that:

1. Performance under different rainfall events could also be considered robust, especially for bioretention cells, which significantly attenuated CSOs, including those originating from high-intensity and high-duration rainfall events. Other SuDS techniques showed limited CSO reduction during high-intensity rainfall events.
2. Location and distribution of CSO structures were crucial in regulating CSO outflows for rain barrels and green roofs but the criteria from current design guidelines used in our AHP analysis were valid and significant but were poor guidance for reducing CSOs.

3. Cost-effectiveness analysis showed that bioretention cells may have the highest return of investment among the four SuDS despite their high unit cost. At the other extreme, green roofs emerged as the least cost-effective option. The cost-effectiveness analysis also showed a rather high return of investment for rain barrels that could yield a significant CSO volume reduction with strategic placement at a considerably low cost.

Nevertheless, this study has shown that the potential of SuDS in controlling CSOs is undoubtedly significant. Findings support yet another benefit of such multi-functional decentralised measures in integrated urban drainage management and deserve more attention in future research and practice.

Conflict of interest

None.

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6 Appendix

Supplementary material

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Graphical abstracts