


Sensitivity of sustainable urban drainage systems to precipitation events and malfunctions

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ABSTRACT

In recent years, sustainable urban drainage systems (SUDSs) have become increasingly popular, sometimes taking over large parts of conventional stormwater management. SUDSs are usually designed using simple design procedures based on statistical rainfall data, without long-term simulations or real rainfall events. In addition, there is little experience of how SUDS respond to potential failures and malfunctions, often caused by ageing infrastructure and lack of asset management. Based on these two factors influencing the hydrological performance of SUDS, this study investigates the sensitivity of seven different SUDSs to rainfall events and malfunctions. The study was conducted using the SWMM 5.2 modeling software and the low impact development (LID) module was implemented for a period of 60 years. The SUDS are studied as individual infrastructure and as part of a small urban catchment. The results show that only the green roofs and rainwater cisterns have a statistically significant correlation between the length and return period of rain events and runoff values, with higher correlations for longer rain events. In contrast, the failures and malfunctions investigated can have a significant impact on the hydrological performance of SUDS. In particular, the design return period of SUDS was occasionally significantly exceeded for the strong malfunction scenarios studied.

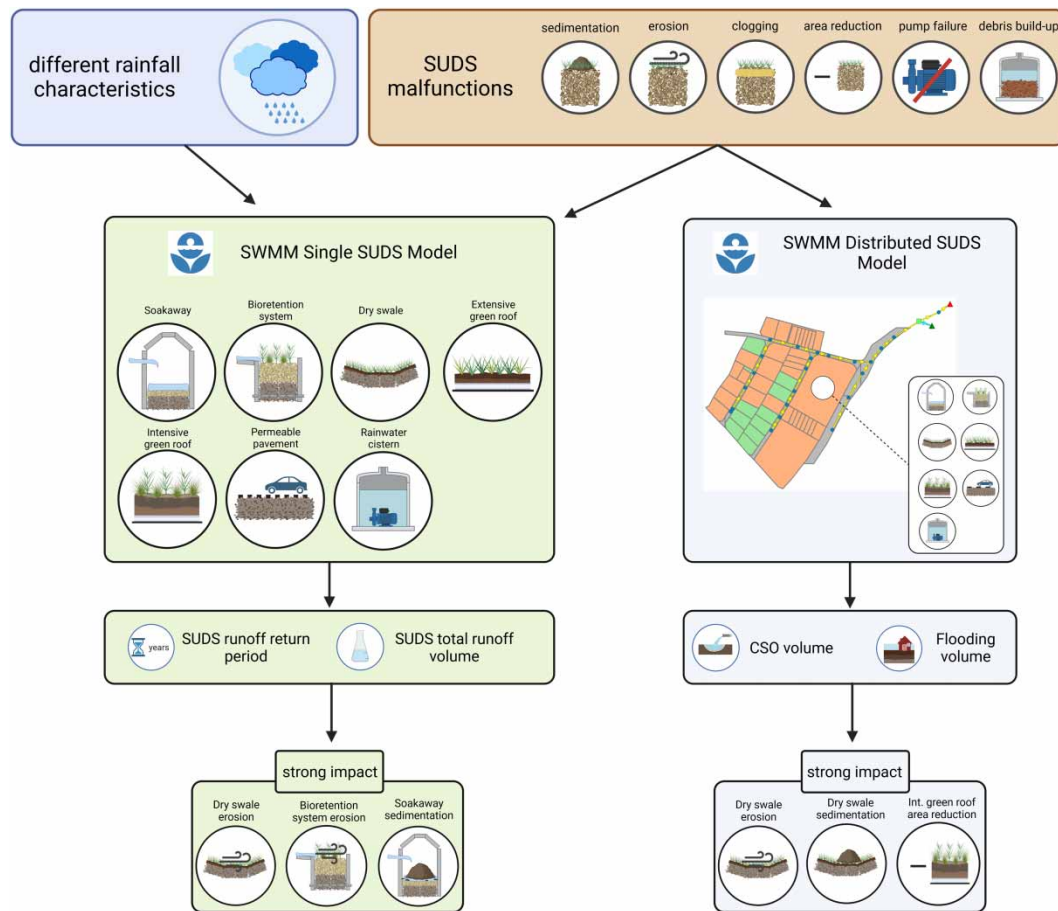
Key words: long-term modeling, malfunctions, rainfall events, SUDS design, sustainable urban drainage systems

HIGHLIGHTS

- Modeling common malfunctions in SUDS with SWMM 5.2.
- 60-year long-term continuous rainfall–runoff modeling with high-resolution rainfall data.
- Comparing SUDS performance of real rainfall events to design events.
- Analysis of malfunctions in SUDS for single infrastructures and in a small Austrian community.
- Recommendations to adapt the design of SUDS to malfunctions.

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GRAPHICAL ABSTRACT



INTRODUCTION

In response to the diverse ecological and hydrological problems caused by the traditional management of urban drainage (Wong & Brown 2009), a paradigm shift has been taking place for several years. Contrary to the concept of conveying water away as fast as possible in piped networks (grey infrastructure), the goal today is to manage rainwater on-site (store, infiltrate, and evaporate) to approach the natural water balance (Pochodyla *et al.* 2021). For this purpose, sustainable urban drainage systems (SUDSs), low-impact development (LID) (Fletcher *et al.* 2015), sponge city concepts (Jiang *et al.* 2018), or Blue Green Systems (Almaaitah *et al.* 2021) are used in a variety of different design approaches, from green roofs to vegetated swales and rainwater tanks. Despite the small differences in approach, this paper uses the term SUDS to refer to decentralized urban drainage. Current and near future challenges, such as increasing urbanization, surface sealing, stricter regulations, climate change impacts, and budget limitations are accelerating their development and implementation worldwide (Cohen-Shacham *et al.* 2016).

In contrast to their original design to protect adjacent water bodies and address stormwater quality issues, SUDSs are increasingly being used for urban flood protection. This trend is increasing as conventional sewer systems are additionally stressed by climate change-induced heavy rainfall events and urbanization. SUDS can reduce the hydraulic stress on a conventional sewer system and are therefore an important solution for climate change adaptation (Almaaitah *et al.* 2021). This brings the hydraulic properties of SUDS into focus and makes them particularly important for urban flood protection.

However, the proper operation, maintenance, and rehabilitation of SUDSs are crucial to ensure their performance (Blecken *et al.* 2017). Asset management is common for grey infrastructure, with widely used inspection and rehabilitation techniques and years of experience (Tscheikner-Gratl *et al.* 2020). However, asset management for SUDS is often less professional, less frequent, and less regulated due to of the diversity of infrastructure types,

spatial scales, levels of multifunctionality, and individuality (Langeveld *et al.* 2022). Maintenance is often unregulated or unimplemented, and action is taken only when a malfunction occurs, also because responsibilities or ownership are often not clearly defined, or the facility is located on private land. In addition, there is little experience among practitioners and the administration of the distribution, condition, and performance of SUDSs. There is little long-term experience of the performance of SUDS, as most have not reached their expected lifespan of 40–100 years. In conclusion, there is a need to shift from just the development and construction of new SUDSs to also the management and maintenance of SUDSs (Vollaers *et al.* 2021).

The novelty and lack of management and maintenance of SUDSs make them susceptible to malfunction and failure (Marlow *et al.* 2013). Vollaers *et al.* 2021 found three main issues that contribute to SUDS malfunction: (i) new technology requiring different knowledge and skills with which practitioners are unfamiliar, (ii) crossing system boundaries (above ground) and at the interface of different subsystems, and (iii) increased complexity compared to conventional urban drainage, with less straightforward decision-making, complicated communication, and misunderstandings.

The ageing and malfunctioning of SUDSs have been reported and tested in the field for a variety of different infrastructures like permeable pavements (Al-Rubaei *et al.* 2015; Boogaard *et al.* 2023), green roofs (De-Ville *et al.* 2017; Bouzouidja *et al.* 2018), rainwater tanks (Magyar *et al.* 2011; Moglia *et al.* 2016), vegetated swales (Kluge *et al.* 2018; Sañudo-Fontaneda *et al.* 2020; Zaqout & Andradóttir 2021; Boogaard 2022; Boogaard *et al.* 2023), and stormwater infiltration systems (Warnaars *et al.* 1999; Siriwardene *et al.* 2007; Bergman *et al.* 2011; Virahsawmy *et al.* 2014; Conley *et al.* 2020; Jeon *et al.* 2022). However, more research is needed on the long-term performance of SUDSs, the types and severity of malfunctions, and appropriate monitoring (Cotterill & Bracken 2020).

Hydrologic rainfall–runoff models can be used to evaluate the long-term performance of SUDSs, particularly in response to rare and extreme rainfall events, and the effects of different failure modes. A commonly used software for SUDS modeling is SWMM 5.2 (Rossman 2010). Although it is regularly used to model SUDS such as green roofs (Liu & Chui 2019), permeable pavement (Abdalla *et al.* 2021), rain gardens (Li *et al.* 2016), and bioretention systems (Lisenbee *et al.* 2022), this is usually done under the assumption that SUDS work at their initial performance for the entire period. The degradation of hydrological performance due to ageing and malfunction is usually not considered. This can lead to unrealistic expectations of the long-term performance of SUDS, which often require regular maintenance to function properly (Conley *et al.* 2020).

Although there are some exceptions, modeling malfunctions that affect the hydrological performance of SUDS (Siriwardene *et al.* 2007; Boogaard 2022) is rare. More commonly, malfunctions that affect the water quality characteristics of SUDS are modeled, but usually only for single events and not for longer periods of time. Based on these research gaps, in this work we investigated the runoff behavior of SUDS for precipitation events with different return periods and durations, and their behavior during different possible malfunctions. The results aim to improve the understanding of (i) the long-term performance of SUDS designed for single events, (ii) how different precipitation events affect their runoff behavior, (iii) how malfunctions affect the hydrological performance of SUDS, and (iv) how the design of SUDS can be improved to account for different rainfall events and malfunctions.

METHODOLOGY

The sensitivity of SUDS with respect to different rainfall events and characteristics, as well as to malfunctions, is investigated using two models, the single SUDS model and the distributed SUDS model (Figure 1).

Single SUDS model

To investigate the sensitivity of SUDS to precipitation events and malfunctions, we modeled individual SUDS using the EPA SWMM 5.2 software (Gironás *et al.* 2010). SWMM is a rainfall–runoff model commonly used to model sewer networks; however, with the LID Control Editor (Rossman 2010), it can also simulate SUDS. A total of seven different decentralized systems were investigated as individual systems (Figure 2) (Table 1). All systems, with the exception of the permeable pavement, manage rainwater from a roof area of 1,000 m² and were dimensioned according to the valid design standards in Austria ÖNORM B 2506-1 (ÖN 2000) and ÖWAV-guideline 45 (ÖWAV 2015). The sizing is based on a simple design procedure that uses statistical precipitation data rather than long-term simulations. For infiltration systems, a return period of 5 years was assumed in the design, while for the other systems, the common implementation approaches of FLL (2018a) for green roofs

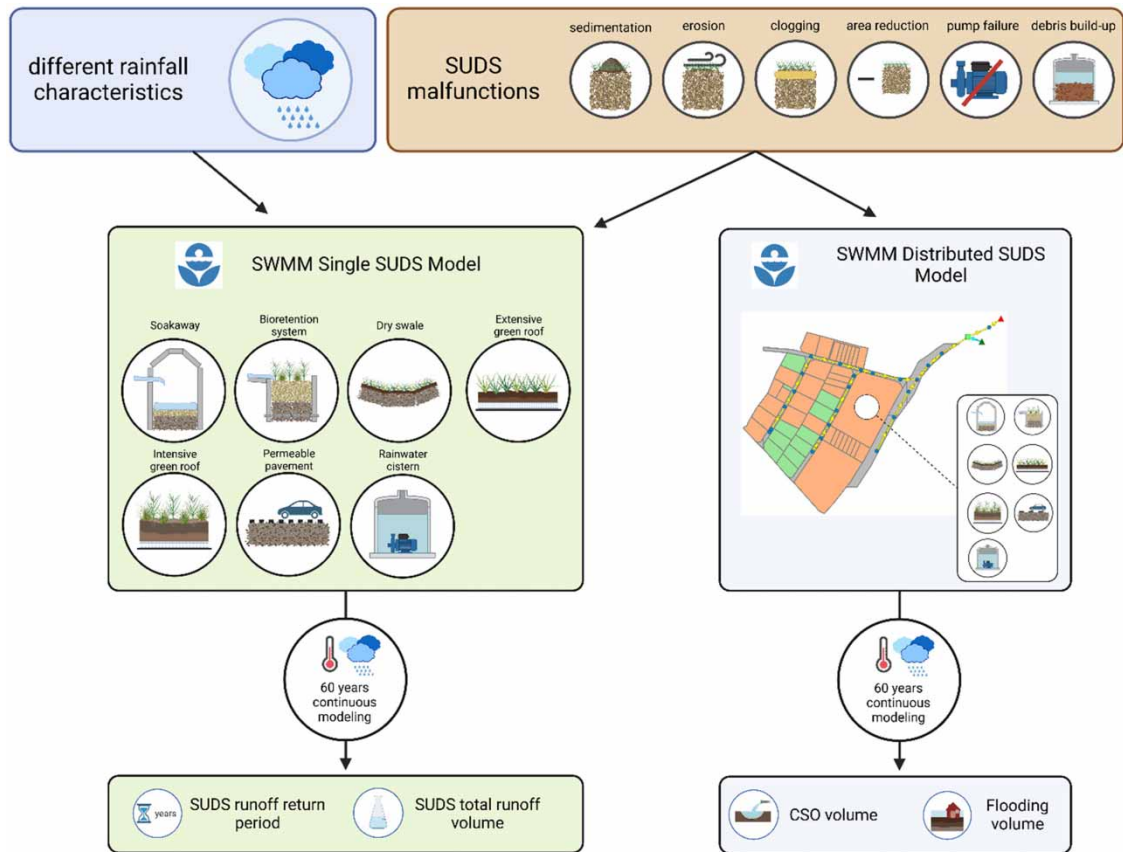


Figure 1 | Flowchart of the methodology used in this paper. The sensitivity of SUDS is analyzed with respect to different rainfall characteristics and possible malfunctions. These conditions are modeled for seven different SUDS, either as a single SUDS in the single SUDS model or distributed over a neighborhood by the distributed SUDS model. Both models are run for all scenarios over a continuous time series of 60 years and analyzed for four different criteria.

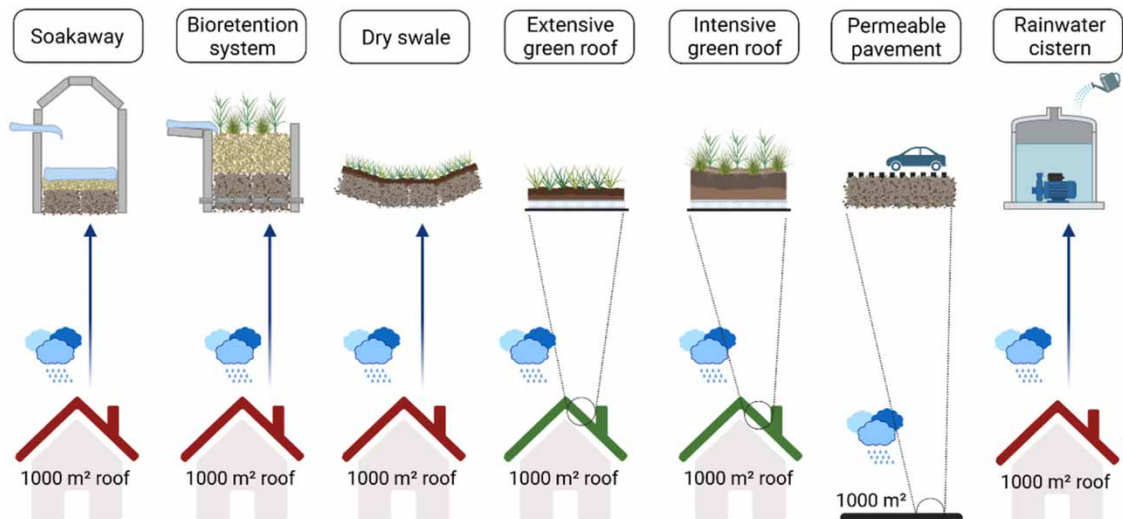


Figure 2 | Representation of the single SUDS model in the SWMM with the seven investigated SUDS: Soakaway, bioretention system, dry swale and the rainwater cistern treat the rainwater of a 1,000 m² roof, extensive and intensive green roof and permeable pavement are 1,000 m² in size.

and DIN (DIN 2002) for rainwater tanks were used. For infiltration infrastructure, the design guidelines include additional safety factors to account for clogging of filter materials and a reduction in storage volume. Green roofs and permeable pavement are not designed for specific return periods, and rainwater tanks are designed to achieve

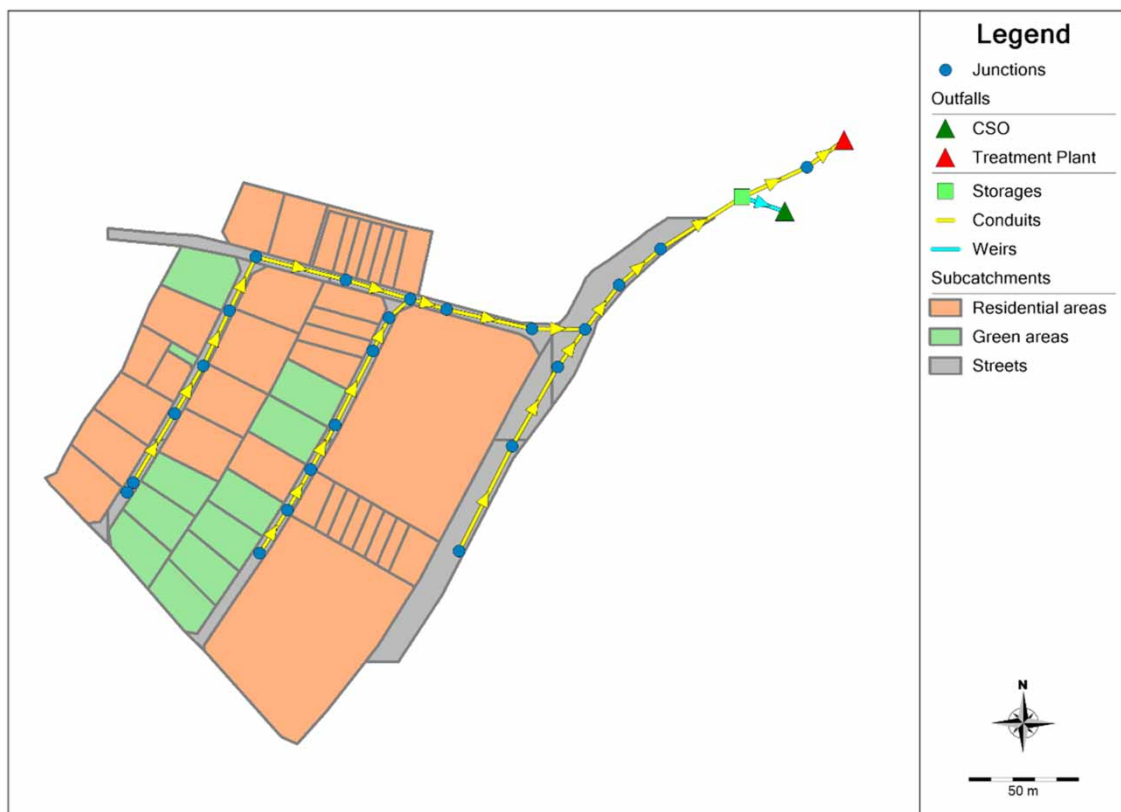
Table 1 | Overview of modeled SUDS and their design return periods and design guidelines

SUDS	Size (m ²)	Design return period (years)	Design guideline
Soakaway	12.6 (31 m ³)	5	ÖNORM B 2506-1 (ÖN 2000)
Bioretention system	44	5	ÖNORM B 2506-1 (ÖN 2000)
Dry swale	93	5	ÖNORM B 2506-1 (ÖN 2000)
Extensive green roof	1,000	/	FLL (2018a)
Intensive green roof	1,000	/	FLL (2018a)
Permeable pavement	1,000	/	FLL (2018b)
Rainwater cistern	30 m ³	/	DIN 1989-1 (DIN 2002)

a specific rainwater yield. The SWMM LID parameters of the SUDS reflect the physical properties of the soils and substrates used in Berlin (Germany) for infiltration systems, and in Neubrandenburg (Germany) for green roofs. The parameters of the infiltration systems were calibrated and validated using the water balance model Abimo 3.2 (Glugla *et al.* 1999), and the green roofs were calibrated based on a measurement series of the University of Neubrandenburg (Schubert *et al.* 2015). The single SUDS model is used to investigate the influence of different precipitation events and SUDS malfunctions using two criteria: (i) the number of runoff events within the modeled period (60 years), also referred to as the modeled return period and (ii) the total runoff for each individual SUDS for the modeled period.

Distributed SUDS model

To analyze the performance of the SUDS within a system, a part of a small Austrian community was investigated as a second case study (Oberascher *et al.* 2021). The total area is 3.7 ha, out of which 1.4 ha (37%) are sealed and connected to the sewer system (Figure 3). The connected properties are all residential, which would potentially

**Figure 3** | Map of the distributed SUDS model.

allow for decentralized stormwater management. The combined sewer system carries rainwater and wastewater to a municipal wastewater treatment plant to the northeast and is relieved by a combined sewer overflow during heavy rainfall. Similar to the single SUDS Model, 7 different scenarios for decentralized stormwater management were created, in addition to the current state (Table 2). In each scenario, each connected property is completely managed by SUDS. A cascade of SUDS in series was not considered in this study. For each property, the decentralized systems were dimensioned according to the design standards applicable in Austria (Table 1). With the exception of the permeable pavement, all measures have an emergency overflow to the combined sewer system, which could potentially lead to additional stress on the drainage system. The Distributed SUDS Model is used to investigate the influence of SUDS malfunctions using two criteria: (i) total combined sewer overflows (CSOs) for the modeled period and (ii) total sewer flooding for the modeled period.

Rainfall data and analysis

Both models were simulated using a continuous 60-year (1951–2010) rainfall series from the Berlin-Dahlem weather station. The time series has a temporal resolution of 5 min and was used in a previous study (Funke *et al.* 2019). The time series was chosen because it covers a very long period with a high temporal resolution. Several heavy rainfall events occurred within the time series, and their return periods were calculated using the Gumbel distribution according to DWA-A 531 (DWA 2012). A total of 9,709 events occurred during this period, the majority of which had low rainfall amounts and intensities. Only 141 events had an intensity of more than 10 mm/h. An overview of the return period and the intensity of the heaviest rainfall events for different durations is presented in Table 3. In addition, daily maximum and minimum temperatures from the same weather station were used to calculate evaporation using the Hargreaves method (Hargreaves & Allen 2003).

Table 2 | Overview of the modeled SUDS scenarios without malfunctions in the distributed SUDS model

Scenarios	LID area (m ²)
Base	0
Soakaway	125 (312.5 m ³)
Bioretention system	687
Dry swale	1,390 (417 m ³)
Extensive green roof	9,999
Intensive green roof	9,999
Permeable pavement	3,739
Rainwater cistern	286 m ³ (11.6 m ³ /d water usage)

Table 3 | Ten highest rainfall intensities for different duration intervals with the corresponding return periods (T) in years

	15 min		30 min		1 h		6 h		24 h	
	mm	T (years)	mm	T (years)	mm	T (years)	mm	T (years)	mm	T (years)
1	28.4	68.5	41.8	91.0	52.0	82.9	56.0	38.7	113.2	306.4
2	23.7	22.5	36.6	40.5	47.5	48.3	55.0	34.5	98.1	104.4
3	23.3	20.4	32.7	22.0	40.7	21.3	53.6	29.5	73.1	17.6
4	23.0	18.9	29.8	14.0	38.7	16.8	53.5	29.2	69.5	13.6
5	20.9	11.6	27.8	10.3	36.0	12.1	51.6	23.6	68.9	13.0
6	20.4	10.2	27.4	9.6	35.2	11.0	47.0	14.1	63.7	9.0
7	19.1	7.6	27.4	9.6	34.1	9.7	46.4	13.2	58.6	6.3
8	18.9	7.2	26.8	8.8	33.3	8.8	44.6	10.8	58.3	6.1
9	18.6	6.7	25.4	7.1	31.6	7.2	44.5	10.6	57.4	5.7
10	18.3	6.2	24.4	6.0	30.5	6.3	42.0	8.0	56.3	5.3

The 60-year time series consists of over 9,000 precipitation events, for which the intensity–duration–frequency (IDF) curves have been evaluated. In addition to runoff, information on seasonality and antecedent conditions (e.g. soil moisture) is available for each event. Each of the single SUDS was tested for a linear correlation between the total event runoff and the return period of different IDF curves. The correlation was calculated using Pearson's correlation coefficient. In addition, the results of the natural rainfall events were compared to those of two synthetic design rainfall events with the same interval length and return period. Both synthetic rainfall types are commonly used as design events in Germany and Austria and consist of (a) a uniform rainfall distribution, i.e. a constant rainfall intensity (block rain), or (b) a Euler II-shaped distribution. For the Euler II design rainfall events, different initial saturations of the SUDS from 0 to 100% were tested to account for different pre-moisture conditions.

Malfunction scenarios

The influence of malfunctions and incidents on SUDSs is investigated for both the single SUDS model and the Distributed SUDS Model. For this purpose, 1–3 possible malfunctions were defined for each system type and calculated as light and strong scenarios (Table 4). A light malfunction reflects a slight but frequent impairment of the infrastructure, while a strong malfunction reflects a comparatively strong but infrequent impairment of the infrastructure. The scenarios studied are only rough guidelines for the extent to which infrastructure can be affected by incidents; other manifestations are also possible. For each malfunction, the corresponding SWMM LID parameters have been adjusted according to Table 4.

RESULTS AND DISCUSSION

The results are presented in the following three sections. First, the runoff in the base scenario without malfunctions is analyzed. Subsequently, the sensitivity of the single SUDS model to precipitation events of different durations and return period is examined and finally the effects of malfunctions in the single SUDS model and the distributed SUDS model are analyzed.

Runoff in base scenarios (no malfunctions)

Single SUDS model

For the single SUDS model, the runoff frequency in the base scenario (no malfunctions) was first examined. Over the modeled 60-year period, all infiltration infrastructure exceeded the design return period of 5 years, with excess runoff occurring less frequently. The soakaway and bioretention system experience runoff five times within the 60-year period (modeled return period of 12 years) and the dry swale experiences runoff three times (modeled return period of 20 years) (Table 5). However, it is important to note that this is based on the assumption that the characteristics of the infrastructure (infiltration rate, storage volume, and void ratio) remain constant over the entire period. The modeled structures exceeded the return period due to the required freeboard and an additional safety factor in the design, necessary to simulate potential clogging of the filter media.

The various SUDS significantly reduce the total runoff volume over 60 years compared to a steep roof of the same size, as shown in Table 5. Extensive and intensive green roofs reduce runoff by 65.6 and 82.8%, respectively, while the cistern reduces runoff by 81.8%. SUDS designed to treat stormwater through infiltration achieve even greater reductions in total runoff, with the soakaway achieving a reduction of 99.63%, the bioretention system reducing runoff by 99.75%, and the dry swale achieving a reduction of 99.93%. The permeable pavement produced no runoff for the entire modeled time series, resulting in a 100% reduction.

Figures 4 and 5 show the runoff from all SUDS for two very heavy rain events. The first event is a short and intense rain event with 52 mm/h ($T = 82.9$ years), resulting in runoff from the bioretention system, the extensive green roof and rainwater cistern. However, all the other SUDS have sufficient storage volumes to prevent runoff. The second event is a longer event of moderate intensity with a rainfall intensity of 113.2 mm/24 h ($T = 306.4$ years), resulting in runoff from all SUDS except for the permeable pavement. The cistern shows the highest runoff values, which correlate directly with the rainfall intensity after the cistern's storage volume is filled. The extensive green roof shows runoff much earlier, shortly after the start of the rainfall event, and attenuates the runoff considerably. Soakaway and bioretention systems, due to their relatively large storage volumes or high infiltration capacities, begin to produce runoff much later. Dry swale and

Table 4 | Overview of modeled SUDS malfunctions and their corresponding SWMM LID parameters

SUDS	Malfunction	SWMM LID parameter	Initial value	Light malfunction scenario (%)	Strong malfunction scenario (%)	Reference
Soakaway	Sedimentation	Surface berm height	2,500 mm	-25	-50	Conley <i>et al.</i> (2020), Siriwardene <i>et al.</i> (2007)
		Soil conductivity	360 mm/h	-50	-75	
Bioretention system	Swale erosion	LID control area	78 m ²	-25	-75	Kluge <i>et al.</i> (2016)
		Surface berm height	340 mm	-25	-75	
	Swale sedimentation	Surface berm height	340 mm	-10	-50	Conley <i>et al.</i> (2020), Zaqout & Andradóttir (2021)
		Soil conductivity	16.7 mm/h	-10	-25	
Dry swale	Storage clogging	Storage void ratio	25	-25	-50	Bergman <i>et al.</i> (2011)
		erosion	LID control area	152 m ²	-25	
	sedimentation	Surface berm height	340 mm	-25	-75	Kluge <i>et al.</i> (2016)
		Soil conductivity	16.7 mm/h	-10	-25	
Extensive green roof	Substrate erosion	Soil thickness	108 mm	-25	-50	Cascone (2019), Liao <i>et al.</i> (2022)
	Erosion of fine particles	Soil field capacity	35%	-25	-50	Bouzouidja <i>et al.</i> (2018)
	Area reduction	LID control area	894 m ²	-10	-25	-
Intensive green roof	Substrate erosion	Soil thickness	250 mm	-25	-50	Cascone (2019), Liao <i>et al.</i> (2022)
	Erosion of fine particles	Soil field capacity	35	-25	-50	Bouzouidja <i>et al.</i> (2018)
	Area reduction	LID control area	1,000 m ²	-10	-25	-
Permeable pavement	clogging	Soil conductivity	360 mm/h	-50	-75	Al-Rubaei <i>et al.</i> (2015), Boogaard <i>et al.</i> (2023)
Cistern	pump failure	Pump curve	0.013 l/s	-10	-25	Moglia <i>et al.</i> (2016)
	debris build-up	Storage depth	1,500 mm	-25	-50	Magyar <i>et al.</i> (2011)

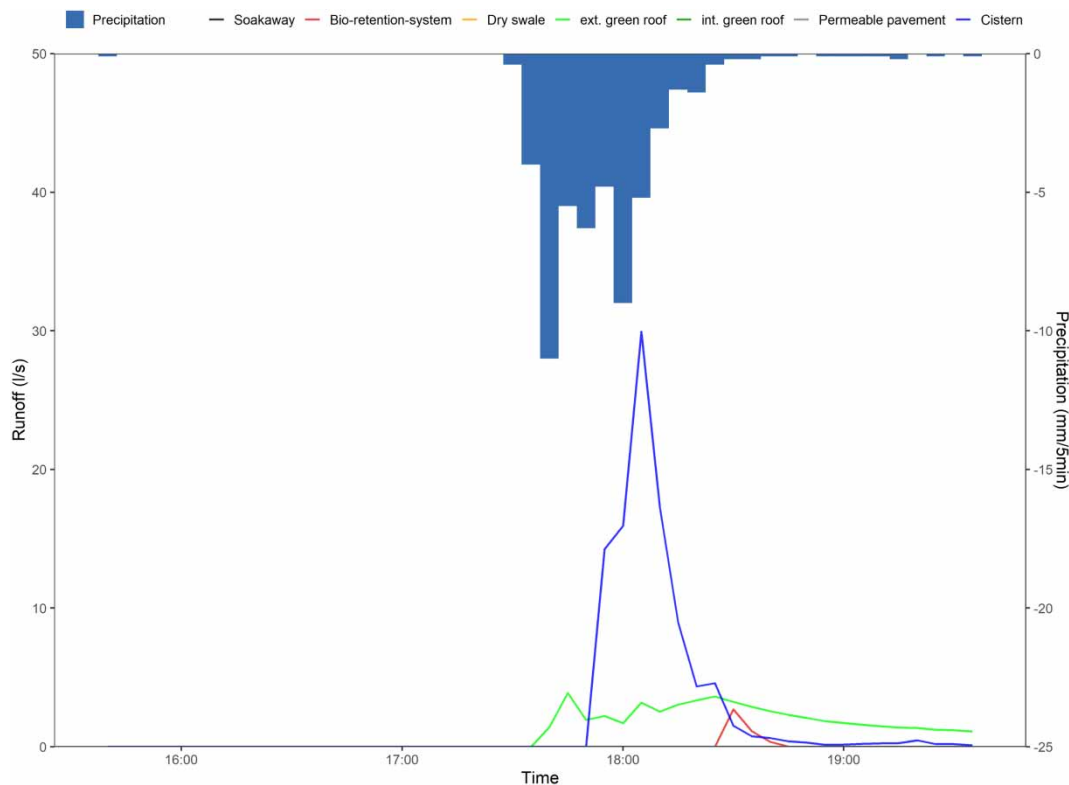
Table 5 | Results of the single SUDS model for the base and SUDS scenarios without malfunctions**Single SUDS model**

SUDS	Runoff events (60 years)	Total runoff volume (m ³)	Runoff coefficient (%)
Base (without SUDS)	7,583	29,562.8	100
Soakaway	5	110.1	0.37
Bioretention system	5	45.8	0.15
Dry swale	3	21.6	0.07
Extensive green roof	7,009	10,179.7	34.4
Intensive green roof	3,737	5,080	17.2
Permeable pavement	0	0	0
Rainwater cistern	933	5,382.8	18.2

intensive green roof show the least amount of runoff, which also starts later than all other SUDS. The dry swale shows a small attenuation of the runoff curve, while the intensive green roof shows a large attenuation with an almost constant runoff unaffected by rainfall intensities.

Distributed SUDS model

For the distributed SUDS model, the SUDS were designed based on the same Austrian design guidelines used in the single SUDS model. However, in contrast to the single SUDS model, other impervious and pervious areas such as streets, pavements, and parking lots, which are not treated by SUDS, also contribute to the catchment runoff. When interpreting the results, it is important to note that all roof areas in the catchment area are treated by a specific SUDS. Therefore, the impact on the criteria of CSO and sewer flooding may be much higher than that in real catchments where only a few houses are treated by SUDS.

**Figure 4** | Runoff from the single SUDS model for a short intense rainfall event (52 mm/1 h). Only the bioretention system, extensive green roof, and cistern show runoff.

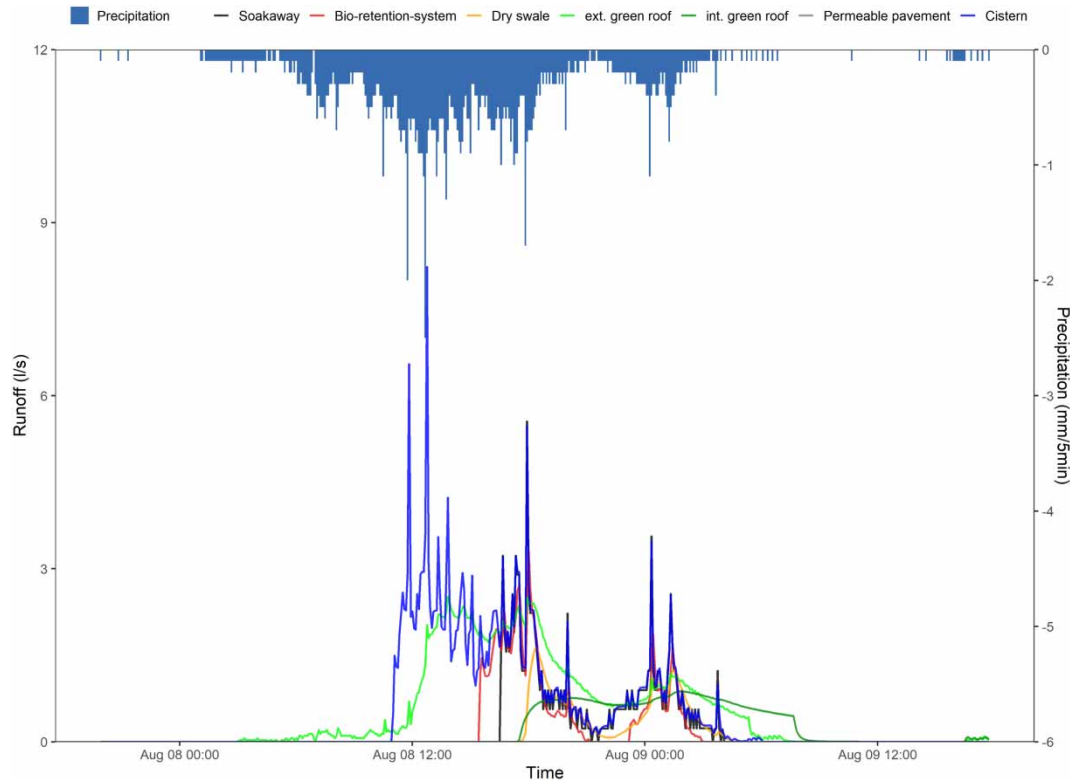


Figure 5 | Runoff from the single SUDS model for a long rainfall event (113 mm/24 h). All SUDS investigated except permeable pavement show runoff.

All investigated SUDS scenarios in the distributed SUDS model considerably reduce the number of CSO events over 60 years (Table 6). The highest reduction is achieved by infrastructure that infiltrates rainwater, with soakaways (80.5%), dry swales (83.7%), and bioretention systems (83.6%). Green roofs showed a slightly smaller reduction, with extensive (64.1%) and intensive (79.7%) green roofs. The permeable pavement (29%) and rainwater cistern (27.7%) had the lowest reductions. The permeable pavement performed worse than in the single SUDS model because it was the only infrastructure that did not treat runoff from roofs, but was applied to sidewalks and parking lots. Therefore, the potential reduction is much lower. The ranking of the scenarios for the CSO Volume criteria was similar to that of the CSO events, with the highest reduction achieved by infiltration infrastructure and the intensive green roof, followed by the extensive green roof. Permeable pavement and rainwater cisterns had the lowest reduction.

Table 6 | Results of the distributed SUDS model for the base and SUDS scenarios without malfunctions

Distributed SUDS model			
SUDS	CSO events (60 years)	CSO volume (m ³)	Flooding volume (m ³)
Base (without SUDS)	1,035	55,600	945
Soakaway	202	12,300	290
Bioretention system	169	9,630	166
Dry swale	170	9,430	60
Extensive green roof	372	15,100	103
Intensive green roof	210	10,200	66
Permeable pavement	735	34,300	458
Rainwater cistern	748	43,900	565

Green roofs and dry swales were particularly effective for the criteria of flood volume. The extensive green roof reduced the flood volume by 89%, the intensive green roof by 93%, and the dry swale by 93.7%. Green roofs have a high potential to reduce flooding due to their good detention performance, even during heavy rainfall events (Stovin *et al.* 2017; Johannessen *et al.* 2018). The bioretention systems and the soakaways also showed significant reductions in the flood volume by 82.4 and 69%, respectively. However, the detention performance of the dry swales, bioretention systems, and soakaways may be limited during heavy rain events due to their overflow into the sewer system, which may reduce their ability to reduce flooding during such events, even though they have an exceptionally low long-term runoff coefficient. The permeable pavement and rainwater cistern scenarios showed only a moderate reduction in flooding compared with the other scenarios, with reductions of 51.5 and 40%, respectively. This observation aligns with the findings for the CSO criteria, where the performance of the permeable pavement was limited by its small relative area, and the performance of rainwater cistern was limited by its weak performance during larger events when the storage volume was exceeded.

Sensitivity to precipitation events

Each of the single SUDS was tested for a linear correlation between the total event runoff and the return period of 6 rainfall interval lengths (15, 30 min, 1, 3, 6 and 24 h) (Figure 6). The black dots show individual rainfall events that resulted in runoff with the corresponding total runoff on the y-axis and the rainfall return period of the event on the x-axis. The lines show the total runoff for single synthetic rain events for block rain (red) and Euler 2 rain (black) with the same interval length and return period as the natural rain events. For the Euler 2 synthetic rain events, pre-moisture conditions between 0% (black) and 100% (light grey) were tested.

The soakaway had only five runoff events during the study period, and there was no significant correlation between the rainfall return period for different interval lengths and runoff ($p > 0.05$) (Figure 6). Only the 24-h design rainfall events with a return period greater than 10 years result in runoff; there is no difference between the design rainfall types and a small difference between the pre-moisture conditions.

The bioretention system has five runoff events over 60 years, and no significant correlation between the rainfall return period and runoff was observed ($p > 0.05$). The longer the design rainfall event, the higher the runoff values, with the initial saturation strongly influencing runoff. The Euler-2 shape design rain results in a higher runoff than the block rain.

The dry swale has only three runoff events during the study period, two of which are very small ($< 0.02 \text{ m}^3$). The results show no significant correlation between the rainfall return period and runoff ($p > 0.05$). For the design rainfall events, only the Euler-2 design rainfall longer than 3 h generates runoff. The assumed initial saturation significantly changes the results.

The extensive and intensive green roofs experienced 7,009 and 3,737 runoff events, respectively, over 60 years. The extensive green roof has a highly significant correlation between total runoff and the return periods for the 24-h rainfall sum ($r = 0.66$) and a moderately significant correlation for the 6-h rainfall sum ($r = 0.55$) and 3-h rainfall sum ($r = 0.48$). Similarly, the intensive green roof had comparably significant correlations for return periods of the same duration. For the extensive green roof, natural events show a higher runoff volume than Euler 2 and block rainfall for all rainfall lengths and return periods. Higher pre-moisture conditions better represent runoff than no initial saturation. For the intensive green roof design, rainfall events with no pre-moisture conditions show runoff only for a 24-h rainfall duration and return periods greater than 30 years. Higher pre-moisture conditions significantly increase the runoff and better represent natural rainfall for all time periods.

The permeable pavement has no runoff events over 60 years because its infiltration capacity is high enough to handle all events. For design rainfall events with very high pre-moisture conditions ($\geq 75\%$) and high return periods (≥ 10), the model shows small runoff.

The rainwater cistern has 933 runoff events over 60 years, and there is at least a moderately significant correlation between the total runoff and rainfall return periods for all event lengths. The highest correlations were observed for 24-h rainfall duration ($r = 0.81$), 6-h rainfall duration ($r = 0.7$), and 3-h rainfall durations ($r = 0.61$). Design rainfall events without initial saturation show much lower runoff values than real rainfall events. As expected, the cistern runoff is strongly influenced by the rainwater tank prefill.

In conclusion, soakaway, bioretention system, dry swale, and permeable pavement have very few runoff events in 60 years, and there is no correlation between runoff and rainfall return period. The results show that the runoff characteristics of the SUDS are only partially explained by the characteristics of the rainfall events, and that other

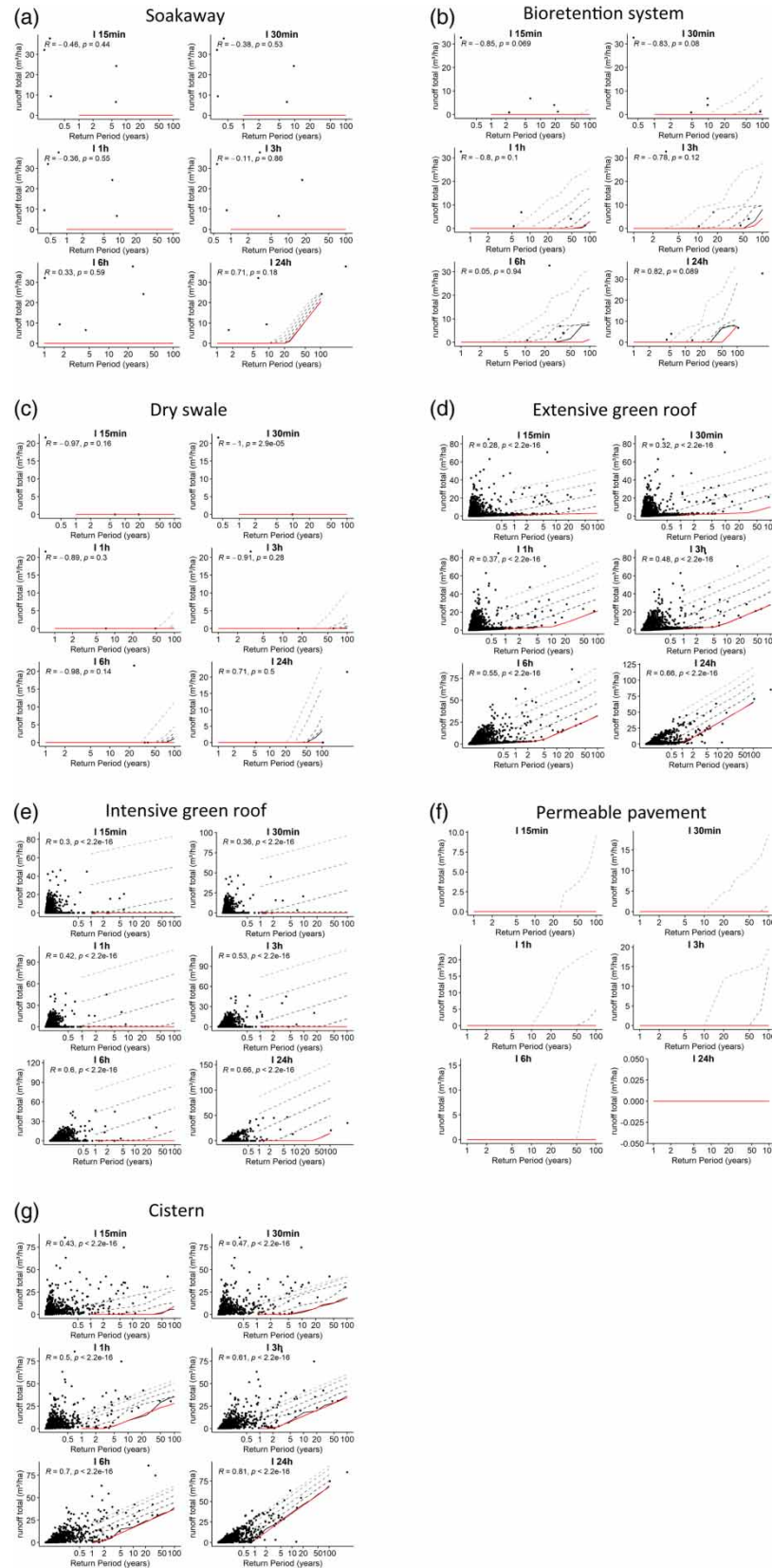


Figure 6 | (a-g) Correlation between the return period of the IDF curve intervals of >9,000 rainfall events and the total runoff from the single SUDS model. The lines show the total runoff for single synthetic rain events for block rain (red) and Euler 2 rain (black) of the same interval length and return period as the natural rain events. For the synthetic Euler 2 rain events, pre-moisture conditions between 0% (black) and 100% (light grey) were tested. Note that most of 9,000 rainfall events do not result in runoff.

influencing factors, such as pre-moisture, storage level, and seasonality, play an important role. Only extensive and intensive green roofs and rainwater cisterns show a significant correlation between rainfall return period and total runoff. For all SUDS, the highest correlation values are found for the longest event lengths (24 h). This implies that the total runoff from these infrastructures is mainly driven by the total precipitation and does not require a specific rainfall intensity threshold to result in runoff. Peak runoff, on the other hand, shows the highest correlation for extensive green roofs and rainwater cisterns for the shortest event lengths, with decreasing correlation for longer events. Intensive green roofs have the highest correlation between peak runoff and the 6-h rainfall event, suggesting that a certain threshold of total rainfall is required for runoff to occur. For both synthetic rainfall types without initial saturation, the total runoff for the same return periods is much lower than that for the measured rain events (Figure 5(a)–5(g)). This is due in part to the lack of pre-weathering, which can reduce the amount of storage available prior to the event, and also because the rainfall interval analyzed is typically part of a larger rainfall event.

Sensitivity to malfunctions

Single SUDS model

Each of the seven single SUDS is tested for up to three common malfunctions that could affect its hydrologic performance over its lifetime. The malfunction scenarios and associated changes to the SWMM LID parameters are shown in Table 4. All scenarios are analyzed for their effect on the total number of runoff events and total runoff volume over the modeled 60-year period (Table 7).

The soakaway is investigated in terms of sedimentation at the bottom, which affects the storage volume and filter media conductivity. Both light and strong sedimentation have a strong effect on the hydrological performance of the soakaway, increasing the number of runoff events from 5 to 10–38 (+100–660%) and the total runoff volume from 110 to 218–527 m³ (+98–378%).

The bioretention system is investigated for three possible malfunctions: swale erosion, swale sedimentation, and storage clogging. All three malfunctions significantly increase the number of runoff events and total runoff volume, with swale erosion having the greatest impact. It increases runoff events by 160–840% and the total runoff volume by 251–1,073%. This indicates that the swale storage volume has a significant effect on swale hydrologic performance, surpassing the importance of soil conductivity and storage porosity.

The dry swale is investigated for two malfunctions, swale erosion and sedimentation, and shows a similar picture to that of the bioretention system. Swale erosion has the largest effect, with an increase in runoff events of 467–36,733% and a total runoff volume of 213–5,957%. Swale sedimentation has a much smaller effect, increasing runoff events by 33–667% and a total runoff volume by 37–246%.

The extensive green roof is investigated for three possible malfunctions: substrate erosion, erosion of fine particles, and area reduction. Based on the already high number of runoff events in the extensive green roof model without malfunctions, there is only a small increase in runoff events from the malfunction scenarios. The erosion of fine particles shows the largest increase of 1.5–2.9%. For the total runoff volume, area reduction shows the largest increase with a change of 12.6–31.4%. Overall, all three malfunctions are relatively close to each other.

The intensive green roof is investigated for the same malfunctions as the extensive green roof, but shows relatively higher effects due to malfunctions. The largest increase comes from area reduction, which results in 78.7% more runoff events and 35.5–88.4% more total runoff volume. Substrate erosion and erosion of fine particles show very similar results with slight increases in runoff events (12.6–33%) and total runoff volume (25.3–58.6%).

The permeable pavement is investigated for light and strong clogging, which has little effect on the SUDS. Heavy clogging would result in three runoff events and a total runoff volume of 4.2 m³, which is a slight increase from no runoff.

The rainwater cistern (rainwater tank) is investigated for two possible malfunctions: pump failure and sediment accumulation. Both result in a visible increase in runoff events (+23.2–92.6%) and total runoff volume (+16.9–83.8%). Sediment accumulation shows higher values than pump failure for both criteria.

In conclusion, the investigation of malfunction in SUDS in the single SUDS model showed the following results:

- Almost all malfunction scenarios lead to a decrease in the SUDS hydrological performance and an increase in runoff values.

Table 7 | Results of the single SUDS model for the base and all malfunction scenarios

LID	Scenario	Malfunction magnitude	Runoff events (60 years)	Change (%)	Total runoff (m ³)	Change (%)
Soakaway	Base		5	–	110.1	–
	Sedimentation	Light	10	100	217.7	97.8
	Sedimentation	Strong	38	660	526.6	378.4
Bioretention system	Base		5	–	45.8	–
	Swale erosion	Light	13	160	160.5	250.5
	Swale sedimentation	Light	7	40	65.8	43.8
	Storage clogging	Light	8	60	72.3	57.8
	Swale erosion	Strong	47	840	537.5	1,073.4
	Swale sedimentation	Strong	15	200	164.8	259.8
	Storage clogging	Strong	10	100	106.8	133.1
Dry swale	Base		3	–	21.6	–
	Erosion	Light	17	466.7	212.6	882.2
	Sedimentation	Light	4	33.3	37.2	71.8
	Erosion	Strong	1,105	36,733.3	5,956.7	27,415.8
	Sedimentation	Strong	23	666.7	246.3	1,037.6
Extensive green roof	Base		7,009	–	10,179.7	–
	Substrate erosion	Light	7,093	1.2	11,235.3	10.4
	Erosion of fine particles	Light	7,116	1.5	11,262.1	10.6
	Area reduction	Light	7,009	0	11,463.3	12.6
	Substrate erosion	Strong	7,118	1.6	12,826.3	26.0
	Erosion of fine particles	Strong	7,215	2.9	12,473.6	22.5
	Area reduction	Strong	7,009	0	13,378.5	31.4
Intensive green roof	Base		3,737	–	5,080.0	–
	Substrate erosion	Light	4,209	12.6	6,365.5	25.3
	Erosion of fine particles	Light	4,264	14.1	6,426.6	26.5
	Area reduction	Light	6,679	78.7	6,882.0	35.5
	Substrate erosion	Strong	4,751	27.1	8,058.1	58.6
	Erosion of fine particles	Strong	4,971	33	7,954.3	56.6
	Area reduction	Strong	6,679	78.7	9,570.6	88.4
Permeable pavement	Base		0	–	0.0	–
	Clogging	Light	0	0	0.0	0
	Clogging	Strong	3	Inf	4.2	Inf
Cistern	Base		933	–	5,382.8	–
	Pump failure	Light	1,149	23.2	6,293.9	16.9
	Sedimentation	Light	1,246	33.5	6,997.8	30.0
	Pump failure	Strong	1,579	69.2	8,221.0	52.7
	Sedimentation	Strong	1,797	92.6	9,893.1	83.8

- The three green infrastructures (soakaway, bioretention system, dry swale) that have the lowest runoff values in the no malfunction (base) condition are the most affected in terms of percentage increase. In particular, swale erosion in the dry swale and bioretention system and the associated decrease in storage volume show very high increases.
- Infrastructures that have already have high runoff values, such as green roofs and rainwater cisterns, only see an increase in runoff values of up to 93%.
- The permeable pavement is the only infrastructure that is resilient to the investigated malfunction scenarios, with only a small increase in runoff values.
- Comparing the two criteria for all scenarios, only soakaway and rainwater cistern malfunctions show a higher increase in the number of runoff events than in the total runoff volume. All other infrastructures show the opposite.
- For the three SUDS designed for a 5-year return period (soakaway, bioretention system, and dry swale), two out of six light malfunction scenarios result in more frequent overtopping events than intended by the design. For

Table 8 | Results of the distributed SUDS model for the base and all malfunction scenarios

LID	Scenario	Malfunction magnitude	CSO volume (m ³)	Change (%)	Flooding volume (m ³)	Change (%)
Soakaway	Base		12,300	–	290	–
	Sedimentation	Light	13,500	9.8	510	75.9
	Sedimentation	Strong	16,300	32.5	745	156.9
Bioretention system	Base		9,630	–	166	–
	Swale erosion	Light	10,300	7	336	102.4
	Swale sedimentation	Light	9,690	0.6	209	25.9
	Storage clogging	Light	9,700	0.7	223	34.3
	Swale erosion	Strong	11,900	23.6	592	256.6
	Swale sedimentation	Strong	10,500	9	378	127.7
	Storage clogging	Strong	9,860	2.4	272	63.9
Dry swale	Base		9,430	–	60	–
	Erosion	Light	10,100	7.1	324	440
	Sedimentation	Light	9,460	0.3	71	18.3
	Erosion	Strong	32,400	243.6	945	1,475
	Sedimentation	Strong	10,300	9.2	379	531.7
Extensive green roof	Base		15,100	–	103	–
	Substrate erosion	Light	16,400	8.6	103	0
	Erosion of fine particles	Light	15,100	0	103	0
	Area reduction	Light	17,700	17.2	141	36.9
	Substrate erosion	Strong	18,800	24.5	373	262.1
	Erosion of fine particles	Strong	15,100	0	103	0
	Area reduction	Strong	22,100	46.4	213	106.8
Intensive green roof	Base		10,200	–	66	–
	Substrate erosion	Light	10,700	4.9	66	0
	Erosion of fine particles	Light	10,200	0	66	0
	Area reduction	Light	12,700	24.5	100	51.5
	Substrate erosion	Strong	11,900	16.7	66	0
	Erosion of fine particles	Strong	10,200	0	66	0
	Area reduction	Strong	17,200	68.6	167	153
Permeable pavement	Base		34,300	–	458	–
	Clogging	Light	34,300	0	458	0
	Clogging	Strong	34,300	0	460	0.4
Cistern	Base		43,900	–	565	–
	Pump failure	Light	45,900	4.6	566	0.2
	Sedimentation	Light	44,400	1.1	572	1.2
	Pump failure	Strong	48,800	11.2	565	0
	Sedimentation	Strong	45,200	3	592	4.8

the strong malfunction scenarios, this occurs in five out of six scenarios. Thus, for light malfunctions, the design usually has sufficient safety factors to statistically ensure a SUDS failure only every 5 years. In the case of strong malfunctions, this cannot be maintained, and SUDS fail significantly more often.

Distributed SUDS model

The effects of SUDS malfunctions are also investigated in the distributed SUDS Model, a real-world case study, focusing on the effects of CSO and flood volume. The Austrian case study consists of the same infrastructure and malfunction scenarios as the single SUDS model and is run over the same 60-year period time series (Table 8).

The soakaways in the distributed SUDS Model (45 infrastructures) are investigated for sedimentation at the bottom of the infrastructure, resulting in a small increase in CSO volume (+9.8–32.5%) and a larger increase in flooding volume (+75.9–156.9%) for the light and strong malfunction scenarios, respectively.

Bioretention systems were tested for three possible malfunctions: swale erosion, swale sedimentation, and storage clogging, and the order of influence is similar to that of the single SUDS Model. Swale erosion has the

greatest impact on hydrologic performance, resulting in a 7–23.6% increase in CSO volume and a 102.4–256.6% increase in flood volume. Swale sedimentation and storage clogging have almost no effect on the CSO volume (+0.6–9%) and a larger effect on flood volume (+25.9–127.7%).

Dry swales were tested for two malfunctions, erosion and sedimentation of the swale body, and were similar to the single SUDS model, showing much higher impacts on hydrologic performance. Sedimentation resulted in only a small increase in CSO volume (+0.7–9.2%) and a larger increase in flood values (+18.3–531.7%), whereas erosion showed higher values for CSO volume (+7.1–234.6%) and flood volume (+440–1,475%).

Extensive green roofs are installed on 45 plots in the distributed SUDS model and investigated for three possible malfunctions: substrate erosion, erosion of fine particles, and area reduction. The erosion of fine particles has no effect on the CSO or flood volume for both the light and strong malfunction scenarios. Area reduction results in an increase in CSO volume (+17.2–46.4%) and flood volume (+36.9–106.8%), while substrate erosion results in a small increase in CSO volume (+8.6–24.5%) and a large increase in flood volume in the strong scenario (+262.1%).

Intensive green roofs are implemented on 45 plots with a greater substrate depth than extensive green roofs. They are investigated for the same malfunctions as the extensive green roof, with slightly different results. Only the area reduction results in a significant increase in the CSO volume (+24.5–68.6%) and flooding volume (+51.5–153%). The erosion of fine particles has no effect, and substrate erosion has only a small effect on the CSO volume (+4.9–16.7%).

Permeable pavement in the distributed SUDS model is the only SUDS scenario that does not treat runoff from roofs, but is implemented on other sealed surfaces such as sidewalks and parking lots. Therefore, the effects of permeable pavements are limited. Clogging of permeable pavements has almost no effect, with only a negligible increase in flood volume (+0.4%).

Cisterns store and use rainwater for irrigation from 45 roofs in the distributed SUDS model. They are studied for pump failure and tank sedimentation. Both showed only small increases in CSO volume (+1.1–11.2%) and flood volume (+0–4.8%) and are therefore not relevant for the hydraulic properties of the catchment.

In conclusion, the investigation of malfunction in the SUDS in the distributed SUDS model showed the following results:

- Almost all malfunction scenarios lead to an increase in CSO and flooding volumes.
- Strong malfunction scenarios often result in much higher CSO and flooding volumes than light scenarios.
- SUDS that significantly reduce CSO and flood volumes compared to the baseline, such as soakaways, bioretention systems, dry swales, and extensive and intensive green roofs, show greater impacts of malfunctions on catchment hydraulic properties.
- SUDS that show less reduction, such as permeable pavements and rainwater cisterns, are also less affected by malfunctions.
- For all infrastructures and malfunctions, the effect on flood volume is greater than the effect on CSO volume because the malfunctions affect SUDS performance particularly during heavy rainfall events that also cause flooding. Rainfall during most CSO events is much smaller and therefore less likely to overload the malfunctioning SUDS.
- Permeable pavement is the only infrastructure whose malfunctions do not affect CSO and flooding.

In the modeled scenarios, all properties of the distributed SUDS model are treated by SUDS and are affected by malfunctions, thus making the effect of malfunctions significant. In a real-world case study where not all properties are treated by SUDS, or not all SUDS are affected by malfunctions, the impact of SUDS malfunctions would therefore be smaller.

CONCLUSIONS AND FUTURE WORK

The findings of this study clearly demonstrate the significant potential of single SUDS in reducing urban runoff, CSO events, and flood volumes. Properly designed and maintained SUDS were found to be highly effective in reducing both total and peak runoff compared to untreated sealed surfaces. These benefits have been observed over a wide range of rainfall events over an extended period of time.

In addition, the study revealed significant differences in the hydrologic performance among the tested SUDS. Infrastructure that promote rainwater infiltration, such as soakaways, bioretention systems, dry swales, and permeable pavements, show superior results in reducing the total runoff volume compared to green roofs and rainwater cisterns.

When implemented in a small urban catchment, all of the SUDS tested showed significant reductions in the frequency and volume of CSO events and flooding. Soakaways, bioretention systems, dry swales, and intensive green roofs were most effective in reducing CSO events and volume, while extensive green roofs also proved beneficial in reducing flood volume.

Analysis of linear correlations between rainfall return periods and runoff showed that only extensive and intensive green roofs and rainwater cisterns had statistically significant relationships. In addition, longer interval lengths (24 h) showed the highest correlation with runoff volume. Synthetic design rainfall events with the same interval length and return period showed less runoff than the measured rainfall events when modeled with 0% initial saturation. Higher initial saturation values indicate results closer to the measured rainfall events.

In assessing the influence of rainfall characteristics on SUDS runoff, initial saturation emerged as a critical factor affecting the available storage volume and infiltration. Additionally, seasonality influences evaporation and thus the overall hydrological performance of the SUDS.

Regular maintenance and asset management are essential to ensure the effective functioning of SUDS, as the study identified a variety of failure modes and malfunctions that can lead to significant increases in runoff, particularly during intense rainfall events. Notably, the vulnerability to malfunction was higher for SUDS with greater reductions in CSO and flood volume, highlighting the importance of proactive maintenance for these infrastructures.

On the other hand, SUDS with lower mitigation capacity, such as permeable pavement and rainwater cisterns, showed greater resilience to malfunctions and may therefore be less critical for urban flood management.

For all infrastructures and malfunctions, the impact on flood volume is greater than the impact on CSO volume because malfunctions affect SUDS performance particularly during heavy rainfall events that also cause flooding. The rainfall during most CSO events is much smaller and, therefore, less likely to overload malfunctioning SUDS. While the results are likely to be applicable to similar small urban catchments, they may not be fully generalizable to larger catchments.

In conclusion, this research highlights the importance of properly designed and maintained SUDS in sustainable urban water management, helping to reduce runoff, CSO events, and flooding, and contributing to overall urban resilience.

SUDS designed for a return period of 5 years according to the Austrian design guidelines (soakaway, bioretention cell, and dry swale) overperformed significantly in the base (no malfunction) scenario. Even under the influence of different light malfunctions, the SUDS achieved the goal of a return period of at least 5 years in most cases (4 out of 6). Under strong malfunctions, the SUDS were only able to meet the return period in only 1 out of 6 cases. This means that, in practice, the design guidelines have sufficient safety factors to provide flood protection, even under most of the light malfunction scenarios. This applies to the measured climate in the past, while an increase in extreme precipitation events (Maraun *et al.* 2022) and thus, additional uncertainties are expected in the future. With regard to stronger malfunctions, it is not economically feasible to change the design guidelines, but it is possible to improve the asset management of SUDS. To ensure the expected hydrological performance and maintain flood protection, it may be appropriate to focus on specific SUDS malfunctions. In particular, malfunctions that reduce the storage volume of SUDS (e.g., soakaway sedimentation or dry swale erosion) significantly increase flood risk. However, as SUDS usually have many other functions besides hydraulic mitigation (e.g., groundwater recharge, improvement of microclimate, increase of biodiversity) (Prudencio & Null 2018), the pure focus of asset management on hydraulic performance must be questioned. Further research is needed to better understand other malfunctions and their impact on all SUDS performance indicators.

The study shows that the runoff characteristics of the SUDS are only partially dependent on the rainfall characteristics and other factors such as the conditions at the beginning of the event are relevant. Therefore, the design of SUDS with single synthetic rainfall events, with ideal hydrological preconditions can be misleading.

A systematic analysis of possible malfunctions (potentially related to maintenance) can further complement stormwater management planning.

As the SWMM 5.2 model represents the SUDS in a very simplified way, it is planned to continue the investigation with the SWMM Urban-EVA attachment (Hörnschemeyer *et al.* 2021) and an improvement of the soil LID. This will also allow the investigation of malfunctions affecting the vegetation. In addition, a coupled 1D–2D model (Abdelrahman *et al.* 2018) will be used to investigate the impact of single events and malfunctions on urban flooding (Funke *et al.* 2022).

ACKNOWLEDGEMENTS

The presented work was carried out in the framework of the project 'BEJOND', funded by the Federal Ministry of Agriculture, Forestry, Regions and Water Management Austria (project number C000204), the project 'Blue-GreenCities' funded by the Austrian Climate and Energy Fund (project number KR21KB0K00001) and the project 'netWORKS4', funded by the German Federal Ministry of Education and Research (funding number 01 UR1622C). Data from the Berliner Wasserbetriebe and geoportals of Berlin are acknowledged.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 3 October 2023; accepted in revised form 9 January 2024. Available online 18 January 2024