Assessing the effects of four SUDS scenarios on combined sewer overflows in Oslo, Norway: evaluating the low-impact development module of the mike urban model

Ragni R. Hernes, Ashenafi S. Gragne, Elhadi M. H. Abdalla,
Bent C. Braskerud, Knut Alfredsen and Tone M. Muthanna

ABSTRACT

Paved surfaces, increased precipitation intensities in addition to limited capacity in the sewer systems, cause a higher risk of combined sewer overflows (CSOs). Sustainable drainage systems (SUDS) offer an alternative approach to mitigate CSO by managing the stormwater locally. Seven SUDS scenarios, developed based on the concept of effective impervious area reduction, have been implemented in the Grefsen catchment using the Mike Urban model. This study evaluated the hydrological performance of two SUDS controls (i.e. green roof (GR) and rain garden (RG)) modules of the model and the effect of the SUDS scenarios on the CSOs using event-based and continuous simulations. The Nash–Sutcliffe efficiency (NSE) along with flow duration curves (FDCs) has been used for evaluating the model performance. Event-based evaluations revealed the superior performance of the RG in reducing CSOs for larger precipitation events, while GRs were proven to have beneficial outcomes during smaller events. The study illustrated another way of assessing the continuous simulations by employing the FDCs. The FDCs were assessed against a discharge threshold at the outlet (which authorities can set as design criteria) of the catchment in terms of the extent, each scenario reduced occurrence and duration of outflow that invokes flow in the overflow pipe.

Key words | bioretention cell, flow duration curve, green roof, rain garden, sustainable urban drainage system

Ragni R. Hernes
Sweco Norge AS,
Dammensveien 260, Postboks 80, Skøyen, 0212 Oslo,
Norway

Ashenafi S. Gragne
Elhadi M. H. Abdalla
Knut Alfredsen
Tone M. Muthanna (corresponding author)
Department of Civil and Environmental Engineering,
Norwegian University of Science and Technology (NTNU),
Trondheim,
Norway
E-mail: *tone.muthanna@ntnu.no*

Bent C. Braskerud
City of Oslo, Agency for Water and Wastewater Services,
Herslebsgate 5, 0561 Oslo,
Norway

HIGHLIGHTS

This paper deals with sustainable drainage system (SUDS) measures, which are novel urban drainage management paradigm for reducing frequency and duration of combined sewer overflows (CSOs). It demonstrates merits of the SUDS concept for mitigating the challenges climate change pose on combined sewer systems using two SUDS controls and seven SUDS scenarios. It gives example on how flow duration curve (FDC) based evaluation approach can be of great practical significance, thereby contributing for the discussion on adaptation of such design criteria in the future. Furthermore, it evaluates efficiency of the implemented SUDS measures extensively by employing a range of performance evaluation techniques. As far as we know, the use of Mike Urban Model's low-impact-development module for implementing SUDS controls makes this manuscript a pioneering research work, which attracts practitioner- and researcher-readers of the Hydrology Research Journal across the world.

---

doi: 10.2166/nh.2020.070

INTRODUCTION

The impact of urbanization on the local environment and the health and well-being of humans have long been recognized (e.g. Shuster *et al.* 2007; Jacobson 2011). Reduction in pervious area is one of the effects of urbanization, among others, which limits the natural infiltration and evaporation processes in urban areas. Urbanization coupled with population growth, climate change, and aging infrastructure has pressed the capacity of combined sewer systems (CSSs) to their limits (Nilsen *et al.* 2011). This could grow worse in the future due to climate change. Increased precipitation volumes and intensities are expected in most part of Norway (Sorteberg *et al.* 2018). In general, frequent flooding is one of the undesired phenomena caused by the growing imperviousness of urban catchments, which often translates into combined sewer overflows (CSOs) in areas served by CSSs. This is typically measured in the effective impervious area (EIA), the impervious areas that are directly connected to the CSS (Walsh *et al.* 2005).

CSOs are an unfortunate mixture of waste, toxic materials, pollutants, and plastics (USEPA 2011) and significant contributors of wastewater polluting receiving waters (Garofalo *et al.* 2017). Approximately 40% of Oslo City is served by CSSs. Out of all CSO weirs, 67 are categorized as problematic by the municipality. Studies show that the changing climate will present further challenges to the management of CSSs in Norway. Based on a study of a sewer system in Fredrikstad City (Norway), Nie *et al.* (2009) report that a 20% increase in precipitation would lead to a 36% increase in total CSOs generated compared to the recorded occurrences in 2004. They further demonstrate that if the precipitation would increase by 30 and 50%, the total CSOs volume would grow exponentially. Another study by Nilsen *et al.* (2011) simulates the flood effects by the end of this century in a sewerage network in Oslo using a delta-change method. It predicts a substantial increase in CSO volume, which could amount to 33 and 83% of the maximum CSO volumes observed in 1980 (i.e. year with maximum overflow) and 1988 (i.e. the wettest year in the study period), respectively. Similar findings are reported in studies that assessed the impact of climate change elsewhere. For example, Semadeni-Davies *et al.* (2008) report that the CSO volume in Helsingborg City (Sweden) could increase by 450% due to the combined impact of urbanization and climate change, and a 200% increase due to urbanization alone. Likewise, Gooré Bi *et al.* (2015) report that in 2050, the CSO discharge in Longueuil City (Québec, Canada) could increase by up to 148% due to climate change. These and other studies draw a similar conclusion with regard to the daunting impact of climate change on CSOs. Therefore, this paper investigates strategies to cope with the impact of climate change through assessing the viability of a new urban drainage management paradigm to reduce frequency and duration of CSOs.

The essence of sustainable management concepts is twofold (Yazdanfar & Sharma 2015). First, to safeguard the water cycle and the environment through natural means, and secondly to decentralize the measures employed. Fletcher *et al.* (2015) provide a thorough review of the origins, evolution, and application of terminologies surrounding urban drainage management techniques. This paper, henceforth, uses ‘Sustainable Drainage Systems’ (SUDS), a terminology commonly used in Europe.

SUDS are a category of technologies offering decentralized solutions to water quantity and quality problems in urban areas. This involves employing control mechanisms relevant to the targeted hydrologic processes (e.g. runoff, infiltration, evapotranspiration) in order to manage stormwater at the site instead of the conventional end-of-catchment solutions. The control mechanisms can be retention-based (e.g. green roofs (GFs), wetlands, ponds) and infiltration-based (e.g. rain gardens (RGs), swales, permeable pavements). Eckart *et al.* (2017) give extensive descriptions of each technique and mechanism. In addition to the multifaceted benefits SUDS render, which have been documented in multiple studies, among others Eckart *et al.* (2017), Fenner (2017), and Johnson & Geisendorf (2019), the SUDS can be seen as technologies for incorporating regulatory requirements.

A large number of studies have implemented different SUDS and demonstrated capabilities to reduce CSOs (e.g. Liao *et al.* 2015; Liu *et al.* 2015; Lucas & Sample 2015). These studies used various computer models (of which Eckart *et al.* (2017) give a good summary) in order to assess the merits of sustainable management alternatives. The Storm Water Management Model (SWMM) and its variants developed by the United States Environmental Protection Agency (USEPA) is the most commonly used model. Another model employed for evaluating the effects of SUDS is Mike Urban (MU) of the Danish Hydraulic Institute (DHI). At present, MU offers catchment- and drainage network-based approaches as options for modeling SUDS (DHI 2017). MU exclusively allows the use of a kinematic wave (KW) surface runoff model to model the controls and runs with the MIKE 1D engine (DHI 2017).

Urban drainage system models often comprise routines for modeling rainfall-runoff process and flows in the pipe network (e.g. MU and SWMM). Although SUDS controls influence the rainfall-runoff process, the models integrate them as add-on modules. Values of the SUDS control parameters can be derived from field measurements and/or estimated using different calibration techniques. A few examples, Russwurm *et al.* (2018) calibrated parameters of SWMM's GF module through an event-based calibration using a Shuffled Complex Evolution algorithm. Johannessen *et al.* (2019) evaluated the SWMM GF model performance and the transferability of parameters between different geographical locations with the same roof build up. Peng & Stovin (2017) set up both event-based and continuous models to, respectively, calibrate parameters of the detention and retention processes of SWMM's GF module. Rosa *et al.* (2015) illustrate the merits of calibrating quality- and quantity-related parameters of SWMM's LID module. No previous examples of calibrating the LID modules in the MU could be found in the literature.

Two essential elements of a modeling exercise are defining an objective function to optimize (i.e. while tuning the parameters) and a criterion to measure the model efficiency. The Nash–Sutcliffe efficiency (Nash & Sutcliffe 1970) is one of the indexes widely used as an objective function and a performance metric (cf. Gooré Bi *et al.* 2015; Liu *et al.* 2015; Peng & Stovin 2017; Rosa *et al.* 2015; Russwurm *et al.* 2018). With respect to quantitative assessment of the effects of SUDS controls, measuring the reduction in peak flows, runoff volumes, and CSO frequency and duration are simple and effective techniques used (e.g. Lucas & Sample 2015; Palla & Gnecco 2015; Chui *et al.* 2016; Garofalo *et al.* 2017). From the perspective of planning and designing SUDS alternatives, the flow duration curve (FDC)-based method might offer a more robust assessment. Traditionally, an FDC represents a cumulative frequency curve that summarizes flow characteristics a data series exhibits over its entire flow range. Lucas & Sample (2015) redefine FDC as a flow rate versus duration exceedance curve and demonstrate how greatly the SUDS alternatives reduce the duration exceedance of CSOs. Likewise, Palhegyi (2010) employs FDC-based approach for sizing bioretention and other low-impact development structures in three watersheds. Wherever regulations impose FDC-based criteria, FDC can serve as a practical tool for designing and for comparing SUDS scenarios.

This paper implements two SUDS controls and assesses the effects of four SUDS scenarios on reducing the volume and duration of CSOs in the Grefsen catchment (Oslo, Norway) using the MU model. The paper further investigates the model parameter sensitivity and parameter correlations for the GFGR and rain garden (RG) modules. Oslo municipality has a long-term goal to minimize the frequency of CSOs to 1 occurrence over 3 years by implementing SUDS solution through the Stormwater three-step approach (S3SA); step 1: infiltrate the small rain; step 2: delay the larger events, and step 3: safely convey the cloud burst on the surface. This paper addresses the following three research questions: (i) what are the most sensitive parameters of each SUDS control of the MU model? (ii) What is the effect of GR and RG implementation scenarios on the CSOs in the Grefsen catchment? (iii) To what extent can FDCs work as a practical tool for planning and design of SUDS?

STUDY AREA AND DATA

Description of sites

The sites selected for this study were Grefsen, Langmyrgrenda 34B (L34B), and Nils Bays Vei 21 (NB21). They are all located in the Oslo municipality, in the northern outskirts of the city (Figure 1(a)). Grefsen is the study site for testing the four SUDS scenarios, while L34B and NB21 are experimental sites for parametrizing and evaluating the performance of the MU model's low-impact development modules independently. Description of each site follows.

Grefsen is an urban catchment that represents a typical Norwegian urban residential area with a mix between combined and separate sewer systems, as a result of the incremental urbanization. About 50% of the gutters in the Grefsen catchment are disconnected from the CSS. This study focused on the part served by the CSS (see Figure 1(b)), which roughly accounts for 37% of the total area. The area connected to the CSS, which hereafter is referred to as Grefsen-CS, is a relatively flat area of roughly 50 ha size subdivided into 136 sub-catchments. The impervious area accounts for 27% (i.e. 18% roof coverage and 9% roads and parking lots) of Grefsen-CS's area with 793 buildings

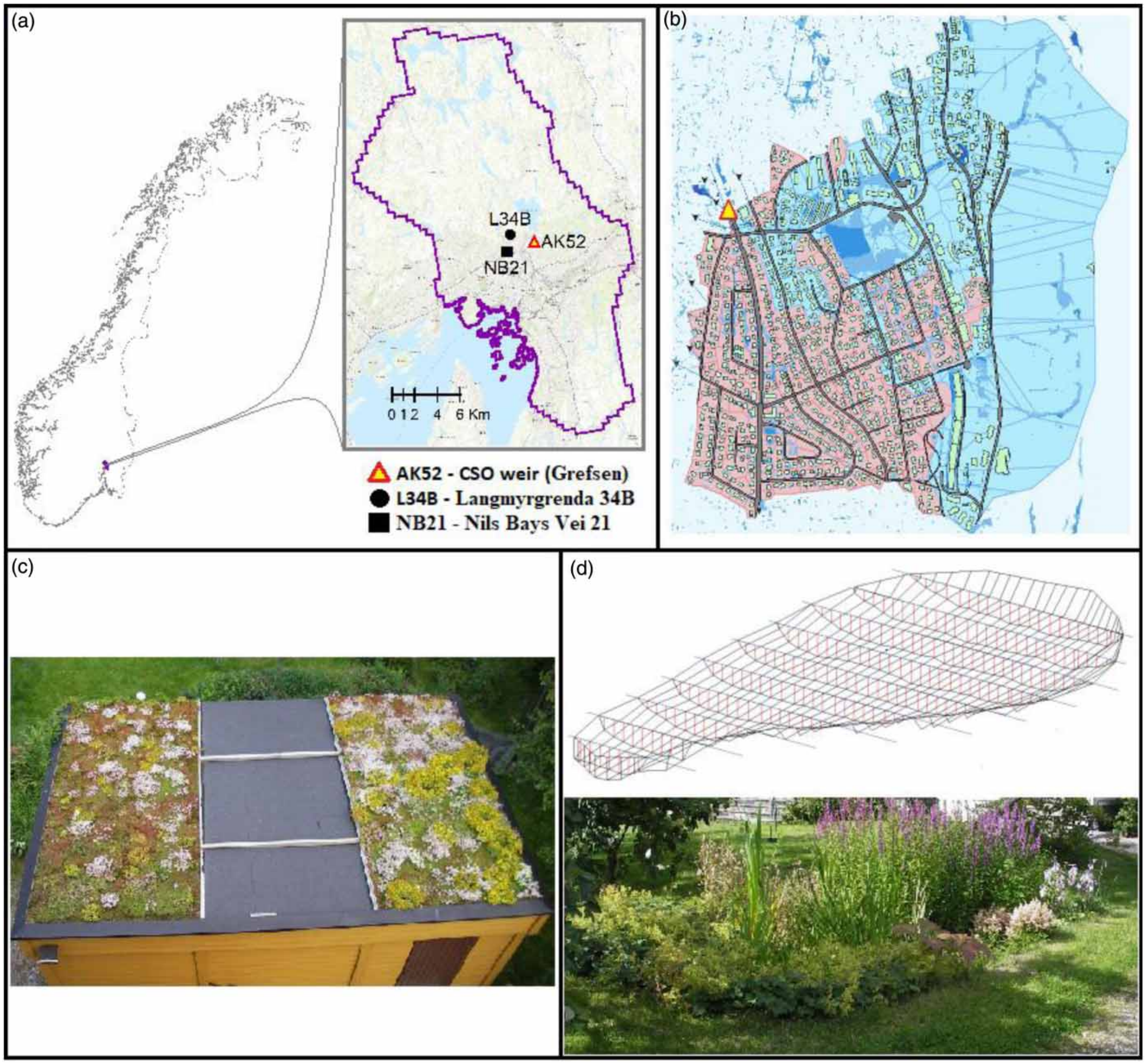


Figure 1 | (a) Location of the study and experimental sites within Norway. All sites are located inside the Oslo Municipality. AK52 refers to the CSO weir in Grefsen catchment. (b) The Grefsen catchment and subdivision of the drainage system. The red, blue, and green shaded areas, respectively, denote area served by the CSS (Grefsen-CS), stormwater system (Grefsen-SW), and separate sewer system (Grefsen-SS). (c) Photo of the green roof testbed at L34B; of the two green roofs, the one on the left has been used in this study. (d) Upper panel: schematic illustration of the RG at NB21 (*Source*: Saksæther & Kihlgren 2017); Lower panel: Photo of the RG at NB21.

and 2,299 person equivalents (PE) (46 PE/ha). The area experiences basement floodings and repeated CSOs, which makes the recipient, Akerselva river prone to pollution. The sum of CSO durations for all events between years 2011 and 2017 equals 1,594 min. According to Oslo Municipality's Agency of Water and Wastewater Services (Oslo VAV), up to 12 CSO events can occur annually.

The experimental site L34B represents a 24-m^2 garage roof that has been operating since 2009 as a GR test site. It consists of three roofs (a reference and two 30 mm substrate deep extensive vegetated roofs) of 5.5% slope and 8-m^2 area each (Figure 1(c)). For a thorough description of the test beds and their construction, please see Braskerud (2014). This study used one of the test beds with the most common GF constructions in Norway. The RG at NB21 is an experimental system setup from 2011. It has a catchment area of 100 m^2. Its total storage volume is 2.6 m^3 (i.e. 1.68 m^3 depression and 0.92 m^3 filter media storage) with the top and bottom surface area of 10.3 and 7 m^2, respectively. Figure 1(d) presents a schematic illustration and photo of the RG. Saksæther & Kihlgren (2012) and Paus & Braskerud (2014) give detailed descriptions of this site.

Hydrologic data sets

Precipitation data used at each site came from three different precipitation data sets. For the Grefsen-CS catchment, four synthetic precipitation events were constructed based on the IDF (Intensity–Duration–Frequency) curves from the Blindern station in Oslo (period 1968–2017) obtained from Oslo VAV. These events take future changes in precipitation intensities into account by introducing a climate factor (CF), as is the common practice in Norway. With reference to Table 1, *E1CS* and *E2CS*, respectively, refer to events of 2- and 5-year return periods with no CF. Whereas *E3CS* and *E4CS* are for return periods of 5 and 30 years, respectively, and were estimated taking the appropriate CF into consideration. Summary information of these events can be found in Table 1. Besides the four events described above, a 1-min interval precipitation series from 1993 obtained from Oslo VAV was used for continuous simulation of the SUDS scenarios.

The events applied at the experimental sites L34B and NB21 were derived from precipitation data recorded by the rain gauge at the respective sites. As can be seen in Table 1, three events (Russwurm *et al.* (2018) refer to these events as "Event 1", "Event 10" and "Event 11", respectively) of varying durations (2.75–20.50 h) were used at the GR site (L34B). These events were identified from precipitation measurements in the years 2011 and 2014. The total volume and maximum intensities of the three events differ from one another. Two of these events (i.e. *E1GR* and *E3GR*) have a 5-year return period while *E2GR* is a 20-year event. Data collected by Saksæther & Kihlgren (2012) during a field experiment in 2011 were used at the RG site (NB21). They produced synthetic precipitation events by pouring water from a tank into the RG with a known volume over time, based on which the approximate return period for the events was estimated. Two of these synthetic events designated as *E1RG* and *E2RG* were used. A

Table 1 | Summary information of the precipitation events selected and the corresponding response runoff at sites L34B and NB21

	Precipitation event						Runoff	
Site	Code	Start time	Duration (h)	Volume (mm)	M_X intensity (l/s/h)	Return period (Y)	Peak (l/s)	T_{TP} (min)
Grefsen-CS	*E1CS*	18:00	1		194.8	2		
	E2CS	18:00	1		258.0	5		
	E3CS	18:00	1		385.7	5		
	E4CS	18:00	1		521.2	30		
L34B (Green roof)	*E1GR*	2011/06/07 07:09	2.75	29.5	1.22	5	0.099	52
	E2GR	2011/08/28 21:05	20.50	56.4	0.43	20	0.028	742
	E3GR	2014/06/03 15:47	14.35	45.0	2.06	5	0.025	19
NB21 (Rain garden)	*E1RG*	2011/08/31 15:36	0.5	20.4		5–10	0.385	29
	E2RG	2011/09/01 08:03	0.33	24.1		25–30	0.476	22

Note: M_X and T_{TP} designate maximum and time to peak, respectively.

complete summary of the precipitation events is presented in Table 1. Discharge series corresponding to the above precipitation events were obtained from the same sources. In the case of Grefsen-CS, the reference discharge series used is the simulated flow from the existing MU model. The discharge observed at the GR and RG test sites has a 1-min temporal resolution. Table 1 summarizes the response runoff data used for setting up each SUDS control and provides the peak runoff and the time to peak for every event. For further details on the type of rain- and discharge-gauges, please see Braskerud (2014) and Russwurm *et al.* (2018) for the L34B site and Saksæther & Kihlgren (2012) for NB21.

Drainage network model

Oslo VAV maintains a calibrated model for the urban drainage network system of Oslo City. The drainage network model of the Grefsen-CS catchment obtained and used in this study was set up using DHI's MU modeling environment. The CSS network consists of 145 manholes, 158 pipes, and one CSO weir (AK52) distributed over the 136 sub-catchments Grefsen-CS comprises. The existing MU model employed the time-area (TA) surface runoff model, which this study modified due to the MU model's restrictions in relation to simulating SUDS controls. Accordingly, the KW surface runoff model along with the MIKE 1D engine was used.

METHODS

This paper assesses the effects of four SUDS scenarios on CSO generation and evaluates the performance of low-impact development modules of the MU model. The present research work implemented the methods in four steps described in detail here. A conceptual overview of the method, which can be seen as a roadmap, is presented in Figure 2.

Calibration and sensitivity of SUDS controls at experimental sites

The parameters of GF and RG modules in MU are presented in Table 2. Before the calibration process, efforts were made to reduce the number of parameters for calibration.

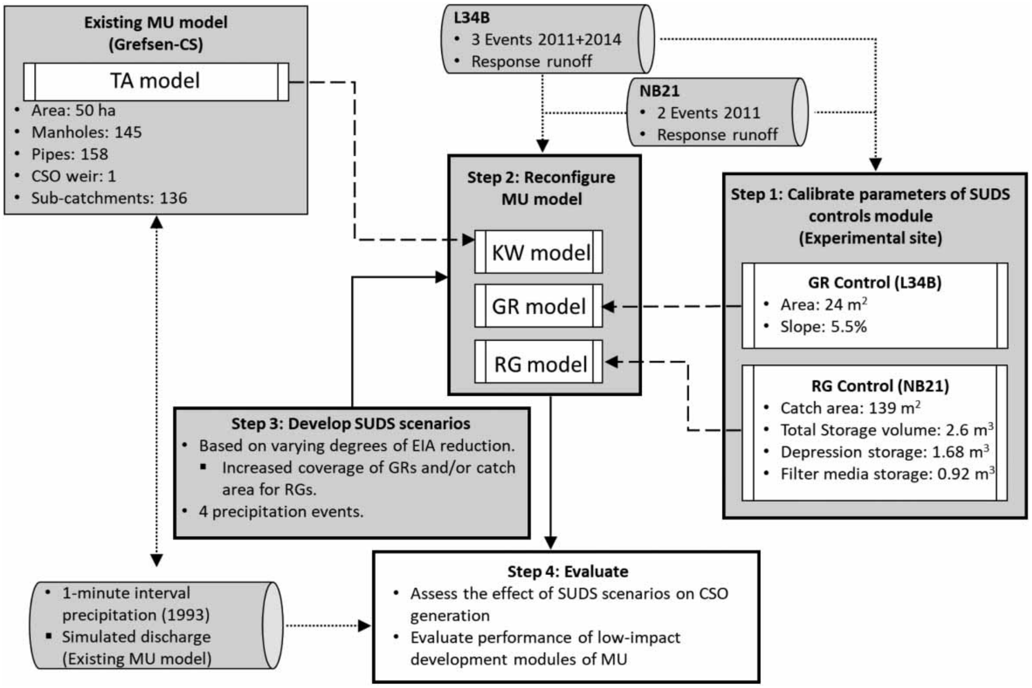


Figure 2 | Conceptual flowchart of the methods used and the available data sets.

Table 2 | List of fixed (F_{XD}) and calibrated (C_{AL}) parameters of the kinematic wave (KW), green roof (GR) and RG models

			KW		**GR**		**RG**	
Layer	**Parameter**	**Symbol**	**F_{XD}**	**C_{AL}**	**F_{XD}**	**C_{AL}**	**F_{XD}**	**C_{AL}**
General	Impervious area [%]			☐				
	Initial saturation [%]						☐***	
	Pervious area [%]			☐				
	Slope [%]		☐					
Drain	Drain capacity flow [mm/h]						☐***	
	Drain mat roughness [M]	DMRough				☐		
	Drain mat thickness [mm]				☐**			
	Drainage pipe diameter/outlet [mm]						☐†	
	Exponent [–]	Expon						☐
	Mannin's/Surface roughness [–]				☐**			
	Offset height [mm]						☐***	
	Suction head [mm]				☐**			
	Thickness [mm]				☐**			
	Void fraction [%]	DMVFraction				☐		
Soil	Field capacity [1/1]	FC				☐		☐
	Hydraulic conductivity [mm/h]	Ksat				☐	☐†	
	Hydraulic conductivity slope [–]	Kcoeff				☐		☐
	Initial saturation [%]				☐			
	Porosity [1/1]	por				☐		☐
	Suction head [mm]	Suct			☐			☐
	Thickness [mm]				☐**		☐†	
	Wilting point [%]	WP			☐**			☐
Storage	Clogging factor [–]						☐‡	
	Height [mm]						☐†	
	Infiltration capacity [mm/h]						☐‡	
	Porosity [1/1]	SVratio						☐
Surface	Height [mm]						☐†	
	Mannin's/Surface roughness [–]	Rough		☐	☐**			☐
	Berm height [mm]				☐**			
	Vegetation cover [%]						☐‡	

Note: (a) the ☐ mark denotes whether the parameter was calibrated or fixed, and (b) the marks †, ‡, ** and ***, respectively, denote parameter values adopted from Paus & Braskerud (2013), Chui *et al.* (2016), Russwurm *et al.* (2018), and Saksæther & Kihlgren (2012).

Parameters related to physical properties (e.g. Drain mat Thickness) were obtained from Russwurm *et al.* (2018) and Saksæther & Kihlgren (2012) for the GF and RG sites, respectively. Additionally, initial saturations were collected from pre-event measurements. The GF surface roughness was fixed during calibration since GFs are designed with highly porous materials to avoid surface ponding. No clogging conditions were assumed in the RG. Hence, the clogging factor was assumed to be zero. Eventually, six and eight parameters were selected for calibration for the GF and the RG, respectively, as shown in Table 2.

To find optimal parameters sets, MU was run 10,000 times using different ensembles of parameters for the different precipitation events. The upper and lower boundary values for each parameter were assigned from recommended ranges based on the SWMM user manual (Rossman 2015) and previous work by Russwurm *et al.* (2018). Average NSE values were calculated for each parameter ensemble for each of the precipitation events. The top 30 parameter ensembles, which gave the best simulation performance, were selected to plot the uncertainty bounds, while the parameter with the highest NSE value was considered as the optimal in further analysis.

To assess parameters sensitivity, scatterplots between each parameter and the NSE values were made. Furthermore, histograms of the parameters that gave the best performance (above

NSE 0.65) were plotted. Insensitive parameters were assumed to give similar performances regardless of their value, while sensitive parameters have distinct values where the model is 'more likely' to perform well (Hamby 1994). Moreover, the Pearson correlation coefficients were determined between parameters that gave an NSE above 0.65 to demonstrate interactions between model parameters.

Reconfiguration of the existing drainage network model

In order to use the existing MU model obtained from Oslo VAV for the objectives of this study, two important modifications were made: (1) replacing the time–area (TA)-based surface runoff model with the KW model; (2) integrating the selected SUDS structures into the model.

The KW model has moderate data requirements and a larger number of parameters than the TA model, which is a simple model with minimum data requirements (DHI 2017). All KW parameter sets (e.g. initial losses, and Horton's infiltration model) were fixed at the default parameter values the MU model generated with the exception of parameters shown in Table 2. Consequently, these parameters were calibrated manually using event-based simulations. Precipitation event *E2CS* was used for calibration while events *E1CS*, *E3CS* and *E4CS* were applied for validation.

During calibration, attempts were made to associate the parameters shown in Table 2 with certain physiographic properties of the study area in order to achieve parameter variability across the 136 sub-catchments. As shown in Equation (1), KW model's imperviousness parameter (I_{KW}) at every sub-catchment was estimated as a function of the physical imperviousness (I_{Phys}) calculated from the land use map of the study area. The calibration focused on tuning coefficients a and b of Equation (1). MU model offers options for providing fractions of the impervious area in steep and flat surfaces, which were allocated based on fraction of roofs and roads.

$$I_{\mathrm{KW}} = a \cdot I_{\mathrm{Phys}}^{b} \tag{1}$$

The SUDS scenarios

Seven scenarios were developed for assessing the effect of integrating SUDS measures on the frequency and duration of CSO occurrences in the Grefsen-CS catchment. The impact of each scenario was evaluated against scenario 0, which refers to the 'do-nothing' scenario. The main comparison criteria taken into consideration when developing the scenarios was the degree of EIA reduction implementation of the SUDS controls could yield.

Table 3 presents the scenarios created along with the EIA reduction each SUDS implementation results in. Assuming the impervious areas are hydraulically connected to the drainage system, the impervious area fraction designated for each SUDS measure is accounted as EIA (Shuster *et al.* 2007). Scenarios I–VI considered isolated implementation of either GR or RG measure to treat the runoff from the roofs to achieve a certain EIA reduction. Ultimately, a combined solution (Scenario VII) with a complete EIA reduction (27% of the total area) was created where the GR and RG were, respectively, applied to reduce the EIA of the fraction of roofs and roads.

Performance evaluation

The NSE (Equation (2)) was used as a metric for measuring the goodness of fit and as an objective function during calibration of the KW, GR, and RG modules in the models.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{N} (Q_t - \hat{Q}_t)^2}{\sum_{t=1}^{N} (Q_t - \bar{Q})^2} \tag{2}$$

Table 3 | SUDS scenarios developed for the Grefsen-CS catchment

		SUDS controls and target impervious area		**SUDS control**	
Scenarios	**EIA reduction**	**Roof area**	**Road area**	**GR**	**RG**
0	0	'do-nothing'	'do-nothing'	–	–
I	3.6%	20% (GR)	–	✓	–
II	3.6%	20% (RG)	–	–	✓
III	9%	50% (GR)	–	✓	–
IV	9%	50% (RG)	–	–	✓
V	18%	100% (GR)	–	✓	–
VI	18%	100% (RG)	–	–	✓
VII	27%	100% (GR)	100% (RG)	✓	✓

The table presents a percentage increase in coverage of GR and provision of RG relative to the percentage of rooftops in the catchment. Along with that, it shows the envisaged reduction in the EIA.

where t is the time interval, Q is the observed runoff, $\hat{Q}$ is the simulated runoff, and $\bar{Q}$ is the mean observed runoff.

In relation to evaluating the effects of the SUDS measures, the efficiency criteria used included relative percentile reduction in peak flows and reduction in CSO frequency and duration. Additionally, a more robust FDC-based method, which plots the flow observed at the CSO weir against the exceedance duration, was applied to assess to what degree the SUDS alternatives reduced the exceedance duration of CSOs. The present system triggers flow in the CSO pipes when the outflow from the study catchment exceeds 0.14 m^3/s, which is referred to as CSO threshold hereafter. Performances of the SUDS scenarios were assessed with reference to this threshold, and the extent to which the measures reduced the exceedance duration of the flows that could result in CSOs.

RESULTS AND DISCUSSION

The calibration process illustrated the complexity of assessing parameters related to some physiographic characteristics. The results illustrate the potential and some of the limitations of the current generation SUDS control modules in MU.

Calibration of SUDS controls at experimental sites

A total of 10,000 parameter values were used to simulate runoff from different events with different initial saturations. For the GF, the initial saturations before the onset of the events E1GR, E2GR, and E3GR were set at 20, 40, and 12%, respectively, while an initial saturation value of 34% was used for the RG. Each parameter set gives different NSE value for each event and therefore average NSE values were determined for each parameter ensemble. The 30 sets that gave the best average NSE values were used to plot the simulated discharge against the observed (Figure 3).

For the GF, the simulated peak runoff exceeded the observed peak flow. The lag time was longer for the simulated compared to the observed, with the largest difference between observed and simulated peaks for event E3GR followed by E1GR and then E2GR, which might indicate the effect of initial saturations on the simulated runoff. The SUDS modules in MU are identical to those in the SWMM model (DHI 2017), which makes comparisons to previous studies using SWMM relevant. Peng & Stovin (2017) argue that a quicker response of the SWMM GF modules might be due to an initial saturation that already exceeds the field capacity. Additionally, Peng & Stovin (2017) discussed the lack of proper representation of the temporary storage within the drain mat layer. This causes the model to assume that the drainage layer is empty at the start of an event to be empty of water, resulting in that runoff cannot occur until the soil layer is fully saturated causing an increased lag. Initial saturation of the drainage layer can initiate runoff before complete soil saturation which is illustrated by the lag between observed and simulated runoff. Moreover, the temporal storage can dampen runoff peaks which might explain the peak overestimation by the current model.

The lack of temporary storage representation in the drain mat layer is compensated for in the GR model in several ways, either by increasing the friction in the drain layer or decreasing the porosity or conductivity in the soil layer or by combination of these factors. This can be proven by the strong correlation between GR parameters compared to RG parameters as shown in Figure 4. These strong correlations allow the model to produce results with equal goodness of fit from different parameters sets, define as Equifinality by Beven (Beven 1993). An example is shown in Figure 3 for the E2GR event; the model parameter set with high drain mat roughness and high soil conductivity produces a result close to the model parameter set with low mat friction and low soil conductivity. Previous studies on the application of GR as SUDS measures using SWMM reported challenges with the parametrization of the GR module. For example, Peng & Stovin (2017) demonstrate that the GR module parameters depend on every unique roof and many uncertainties depend on the estimation of the parameter values. Likewise, Johannessen *et al.* (2019) report complexity of transferring parameters among different GR locations.

In contrast, the MU RG module allows for deep percolation and maintains storage before releasing runoff into underground drainage pipe which reduces the potential peak overestimation. Nevertheless, the simulated runoff of RG lags the observed in the two selected events. The synthetic precipitation event, which was constructed for the

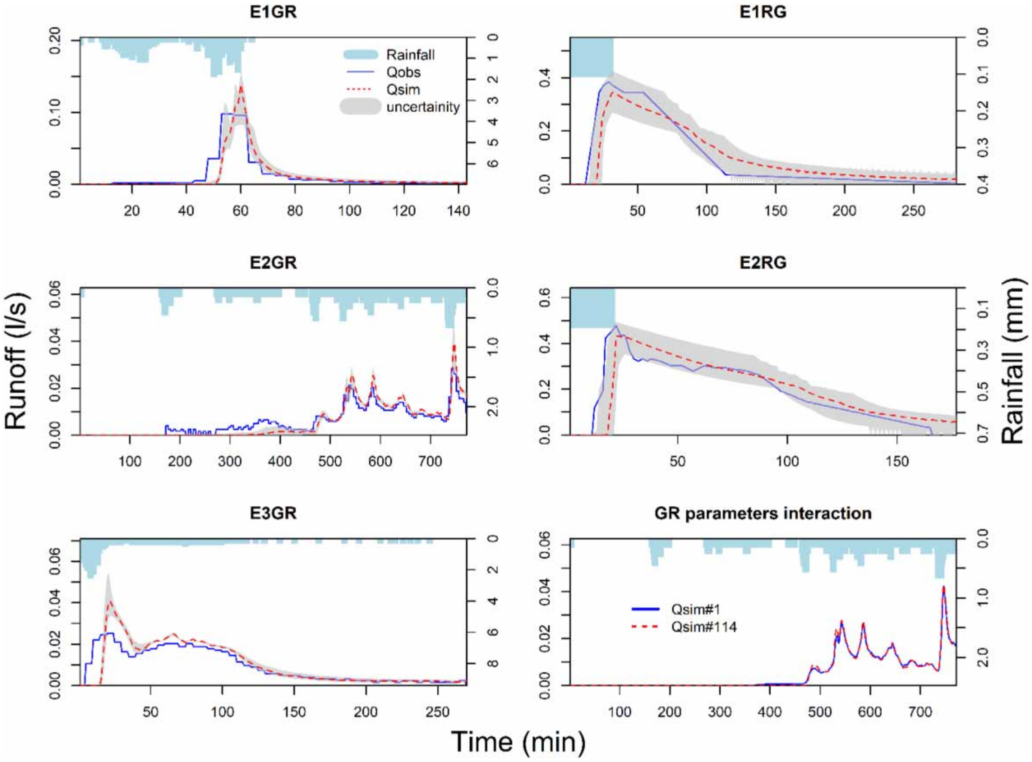


Figure 3 | Simulation and uncertainty bounds of runoff from SUDS controls at the experimental sites. E1GR, E2GR, and E3GR events for green roof (left) and E1RG and E2RG for RG. Uncertainty bounds show the range from the minimum to the maximum simulated values each time step while Qsim is the median simulated runoff. 'GR parameters interaction' shows an example of similar runoff simulations from E2GR event using different set of parameters (set#1 and set#114).

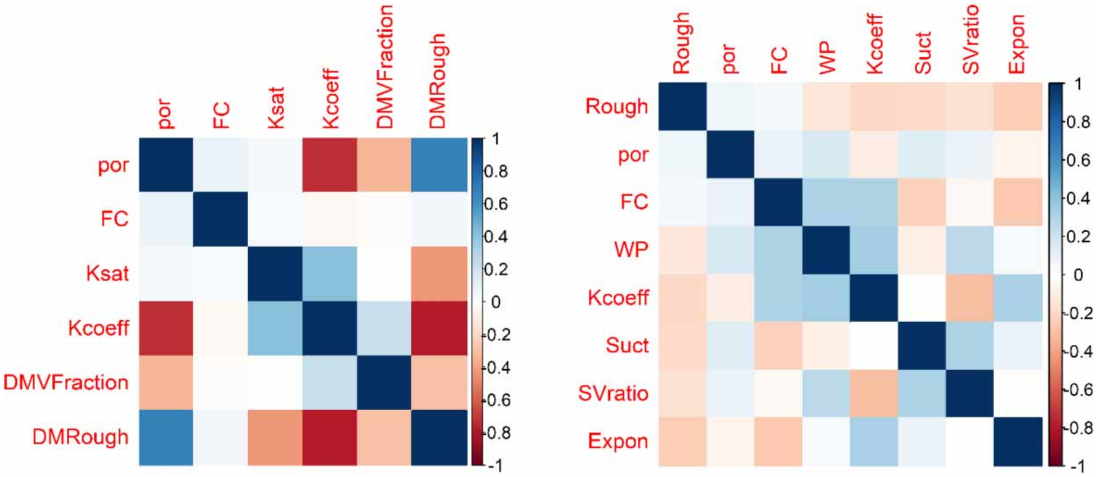


Figure 4 | Pearson correlation coefficients between model parameters of green roof (left) and RG (right) modules with NSE above 0.65.

modeling purpose, did not necessarily represent a typical inflow to the RG. The inflow was generated by water being released from a tank during the experiments for which the field data for the RG was collected. This will give a more adequate representation of inflow for the larger event than smaller events.

Sensitivity of GR and RG parameters

Figure 5 shows the scatterplot between each parameter and model performance (NSE), while Figure 6 presents the histograms of parameters from simulations with NSE of above 0.65. From Figure 5, it is difficult to assess the parameter sensitivity of the GR module while it is more obvious to conclude that soil porosity and drain void fractions are the most sensitive parameters for RG module. Accordingly, it can be seen that the soil porosity and drain mat roughness have distinct values where simulations are more likely to be accurate for the GR module (Figure 6), followed by the Drain void fraction and soil conductivity parameter, and to a lesser extent the soil conductivity slope. A study analyzing the sensitivity of the SWMM GF parameters following the GLUE procedure by Kerbs *et al.* (2016) concluded that soil porosity and drain mat roughness were the most sensitive parameters. The soil field capacity was found to be insensitive. However, these were all event-based simulations where the effect of field capacity can be compensated by other parameters while it is expected that the field capacity would be more sensitive in a continuous simulation as earlier found by Peng & Stovin (2017).

For the RG, many parameters were found to be sensitive with distinct optimal values. The most sensitive were the drain void fraction, soil porosity, and soil conductivity slope. Surface roughness was found to be an insensitive parameter, which can be expected as many green infrastructure solutions are designed to avoid surface ponding situations. The wilting point was found to be more sensitive than soil field capacity, though this would have limited practical implication for runoff generation.

The uncertainty bounds of the simulated runoff were wider for the RG module results compared to the GR module results as shown in Figure 3. This can be explained by parameter sensitivity; since the RG parameters, in general, were found to be more sensitive than GR parameters. The correlations between RG parameters were weaker, resulting in that changes in the parameter values lead to a unique model response.

Calibration and performance of the KW model

It was necessary to tweak the KW to obtain approximately the same results as the TA model yielded, which was needed for baseline comparisons with the TA-calibrated model as the starting point. Manning's *n* was the calibrated parameter, where optimal values of 0.0125 and 0.0143 were obtained for the steep and flat surfaces, respectively, and zero for the permeable surfaces, assuming the runoff infiltrates. The characteristic length was set to 10 m across all sub-catchments in an effort to match the rising-limb of the observed hydrograph. Sensitivity assessment revealed that the Manning's *n* for the permeable surfaces was the most sensitive parameter followed by the Manning's *n* for steep impervious and flat impervious areas. Slope and length were the least sensitive parameters.

The calibration process illustrated the complexity of assessing parameters related to some physiographic characteristics. The results show the potential and some of the limitations of the current generation SUDS control modules in MU. For instance, uniform values were set across all subcatchment for the parameters: slope, length, and Manning's *n*. This neither fully replicates the reality nor makes the optimized parameters physically meaningful. In hydrologic modeling, a uniform characterization of the impervious area calls for methodological improvement in the future (Shuster *et al.* 2007).

The SUDS scenarios

The results of the SUDS scenarios simulation demonstrated that, overall, implementation of RGs could lead to a greater reduction of peak flows than the extensive use of GRs would. The RGs performed better for the larger events, namely *E3CS* and *E4CS*, in both peak flow and volume reduction. These are comparable to findings in similar studies (e.g. Liu *et al.* 2015; Chui *et al.* 2016). However, for the smaller events, the GR performed as good as the RGs in volume reduction (i.e. events *E1CS* and *E2CS*). The comparison of scenarios V and VI for event *E2CS* revealed a marginally better total CSO volume reduction with the GRs over the RGs. All scenarios resulted in a delay in time to peak, but with no noticeable differences between the two SUDS control measures. Not surprisingly, the combined solution produced the best results for all events and reduced CSOs 100% in relation to events *E1CS* and *E2CS*. Figure 7 illustrates results associated with each scenario sorted for events *E1CS, E2CS, E3CS*, and *E4CS*.

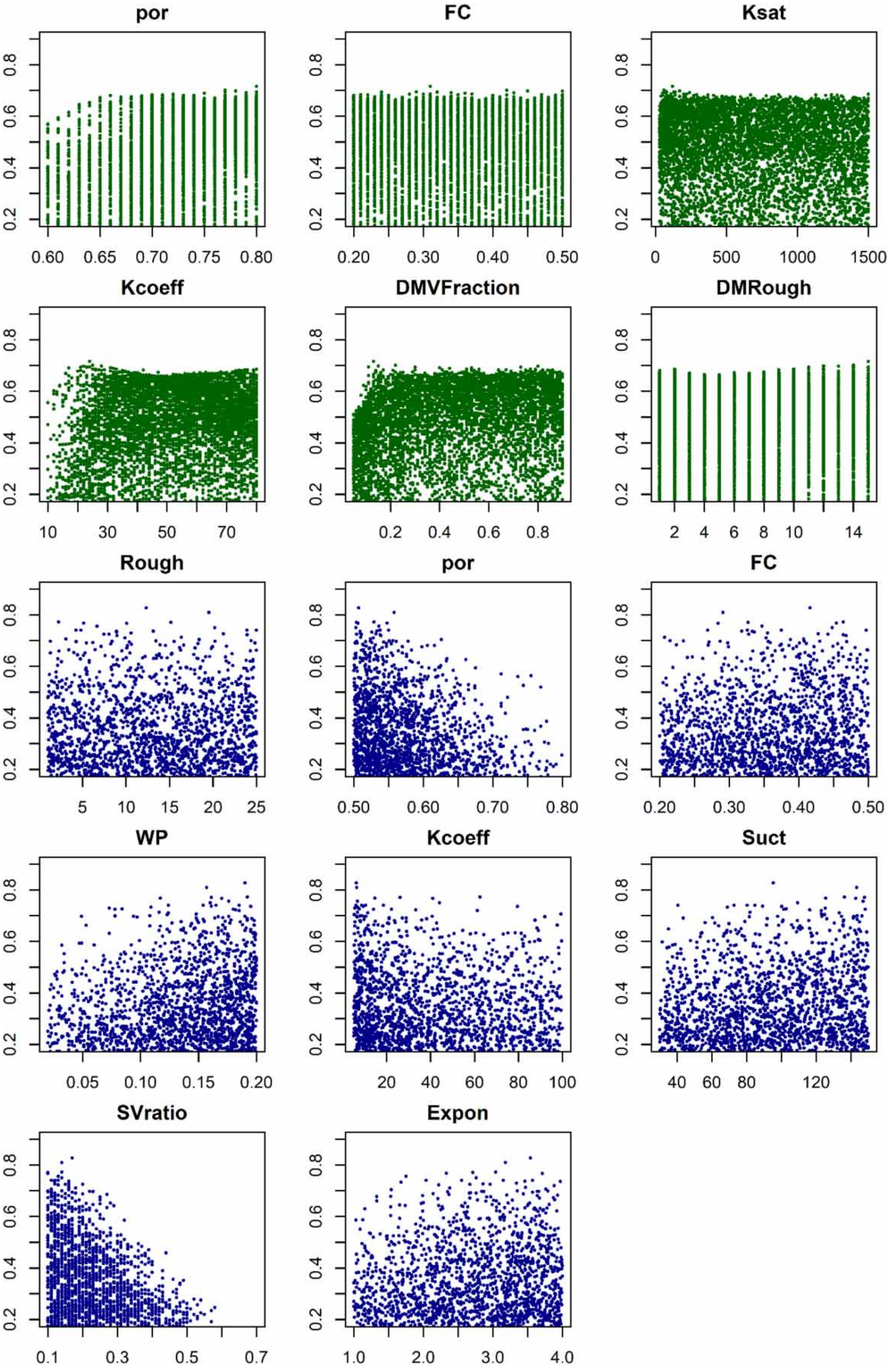


Figure 5 | Scatterplots between model parameters and simulation performance (NSE) (green roof parameters in green colors and RG parameters in blue colors).

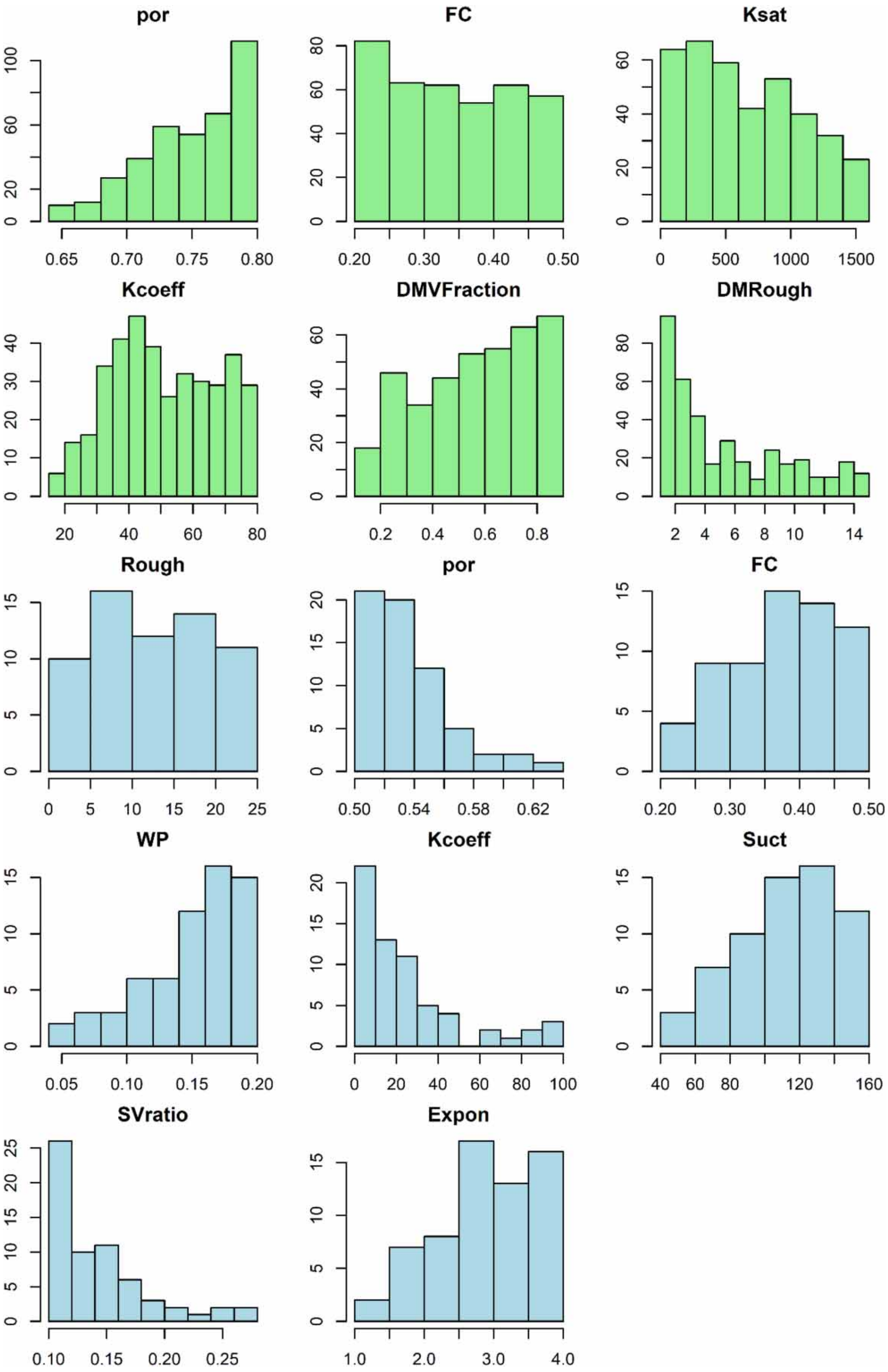
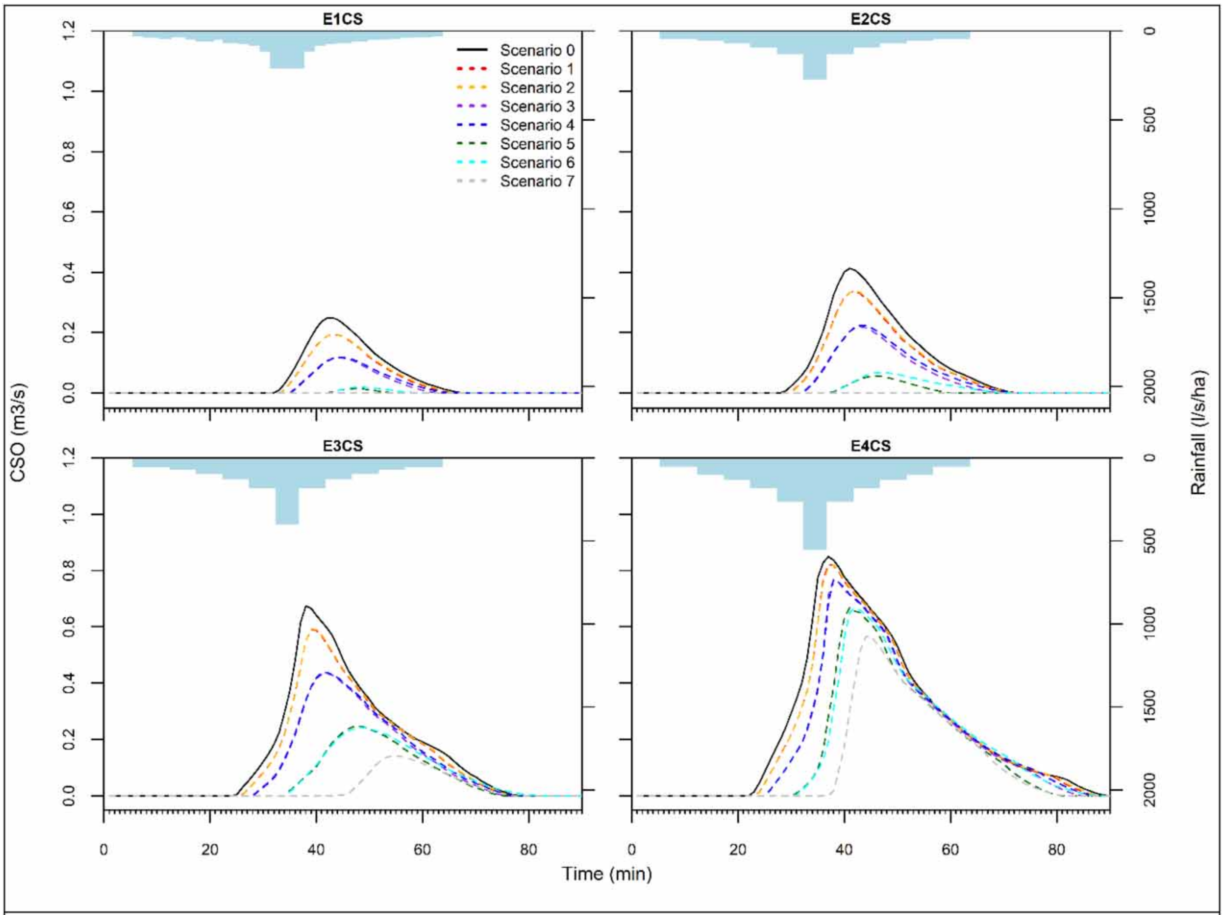


Figure 6 | Histograms of the model parameters that give above 0.65 NSE simulation performance (green roof parameters in green colors and RG parameters in blue colors).



Scenario #	Volume reduction (%)				Peak reduction (%)				Peak delay (min)			
	E1CS	E2CS	E3CS	E4CS	E1CS	E2CS	E3CS	E4CS	E1CS	E2CS	E3CS	E4CS
1	24.5	19.7	12.3	6.8	22.1	18.3	12.3	3.2	0	1	1	0
2	23.0	18.8	11.7	6.3	22.0	17.9	12.0	3.5	0	1	1	1
3	57.6	49.9	31.5	17.9	53.2	46.8	35.6	9.6	1	2	4	1
4	54.4	45.8	29.8	16.1	52.8	45.7	35.1	9.5	2	2	4	1
5	97.2	90.5	62.2	36.2	94.1	86.5	63.3	21.2	4	5	10	4
6	95.4	84.6	59.0	32.8	92.3	83.5	64.1	21.4	5	6	11	5
7	100.0	100.0	82.7	50.6	100.0	100.0	78.9	33.3	-	-	17	8

Figure 7 | Results from the event-based simulation of the seven scenarios. With reference to Scenario 0, the diminishing area enveloped under the CSO hydrographs corresponding to the seven scenarios demonstrates success of the SUDS controls in improving the performance of the CSSs. The CSO is activated when the outflow from the catchment exceeds the CSO threshold (0.14 m^3/s). In addition to reducing the volume of CSO, the implemented measures delayed the peak CSO by 2 to 17 min.

Palla & Gnecco (2015) argue that a minimum 5% EIA reduction is necessary to benefit from the implementation of GRs and permeable pavements in reducing surface runoff. In this study, a reduction of the EIA by 3.6% proved to give noticeable results in reducing CSOs. One would expect this to be catchment specific where 3.6 and 5% both represent similar minimum implementation levels. All simulated events achieved a minimum volume reduction of 7% for scenarios I and II.

SUDS controls are expected to produce longer detention time and consequently delay the responses, thereby improving the efficiency of the combined sewer system. The CSO hydrographs (Figure 7) show that all SUDS scenarios, compared to scenario 0, reduced the proportion of the outflow that was flowing over the overflow weir: a more or less simultaneous end time for all events, on the other hand, shows that a volumetric reduction of the CSO might not always guarantee a reduced CSO duration. In general, the SUDS measures successfully attenuate and delay the hydrograph peaks. Four CSO events, active for about 2 h duration, were noted from Scenario 0. Implementation of scenarios I and II reduced the CSO to three events and the duration to 80 and 81 min, respectively. Scenarios III and IV further reduced the number to two CSO events with a duration to 66 and 70 min, respectively. Scenarios V and VI reduced the duration of the two CSO events further to 59 and 65 min, respectively. The combined solution (scenario VII) led to two CSO occurrences and 48 min of activated CSOs, which is only a marginal reduction in duration and no reduction in number of events, for a much higher initial investment cost.

The event-based simulations show an almost linear reduction of peak flow and volume from the smallest to the largest event for the scenarios. From the assessments, it can be concluded that the RGs respond superiorly for large and intense precipitation events. This way of assessing the effect of SUDS controls may give a simplified evaluation and exclude other aspects. The FDCs, on the other hand, demonstrate how the GRs play an important role for flows reduction under the CSO threshold. This corresponds to the recommendations in the strategy for stormwater management of implementing GRs in step 1 according to the S3SA. Besides the reduced CSO frequency and duration, the effects of the SUDS controls were further assessed using the FDC strategy.

SUDS and FDCs

Figure 8 presents the FDCs constructed for all scenarios based on the simulated outflows at the Grefsen-CS for the year 1993. Quantitatively, the SUDS controls were important in reducing the maximum flow from 0.70 m^3/s (scenario 0) to: 0.62 (scenarios I and II), 0.52 (scenario III), 0.49 (scenario IV), 0.38 (scenario V), 0.31 (scenario VI) and 0.24 m^3/s (scenario VII). In terms of total volume, scenario VII yielded a 48 m^3 CSO compared to 476 m^3 in scenario 0, a reduction in the order of magnitude of 10. In addition to the observation of the change in peak outflow performance of each scenario with reference to the duration of flows that exceed the CSO threshold 0.14 m^3/s was assessed visually. FDCs of scenarios I–VII illustrate a leftwise shift relative to that of scenario 0 implying success of the SUDS measures to detain large volume of discharge from the Grefsen-CS catchment. For example, scenario VII has not reduced all discharges under 0.14 m^3/s, the flow at which the CSO pipe is triggered; however, it has reduced the duration exceedance of flows of magnitude equal to the CSO threshold from 1.9 to 0.65 h. From the perspective of environmental services, this is a very useful outcome. Lucas & Sample (2015) argue that the volume of CSOs is more strongly associated with negative impacts on the environment rather than the number of occurrences.

Limitations of the study

The GRs and RG models do not account for the evapotranspiration process which is one of the limitations of the present study. The study did not analyze alternatives which may improve the infiltration capacity of the permeable areas, nor did it included other measures such as disconnection of the downspouts from every house leading roof runoff to the garden bushes, trees, and lawn (e.g. step 1 in the S3SA). This study has focused only on evaluating the GR and RG modules in MU, without altering runoff from pervious areas. Hence, the above issues need to be taken into consideration for devising optimal low-impact development plan for Grefsen-CS catchment.

CONCLUSION

In this study, the hydrological performance of the RG and the GR modules in MU was evaluated and tested in a typical residential area in Oslo, Norway, served by CSS.

The calibration and sensitivity analysis revealed that the MU GR parameters are strongly correlated to each other which results in equifinality. The GR module lacks a proper representation for the storage within the drainage layer which is compensated for in the model through different manners, including increasing friction in the drain layer while increasing soil conductivity or the opposite. This compensatory factor affects the sensitivity of GR parameters. In contrast, the parameters in the RG module are more sensitive and have weaker intra-correlations, which indicate a better realization of the hydrological processes in MU RG module compared to GR.

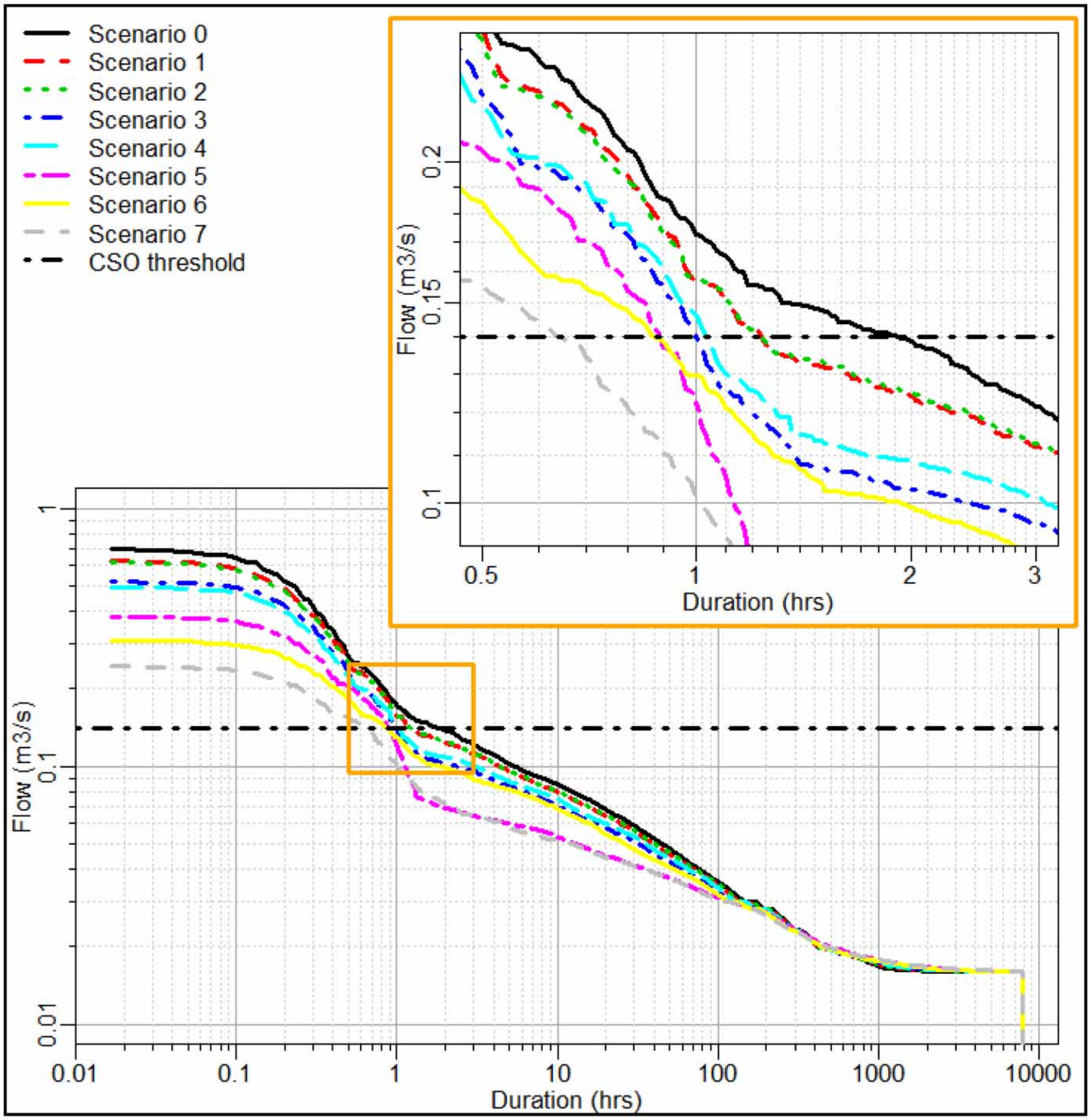


Figure 8 | FDCs for all scenarios constructed based on a 1-min resolution simulated inflows into AK52 for the year 1993. All SUDS scenarios reduced the annual peak outflow Grefsen-CS; scenario VII that combines GR and RG to handle the runoff process in the roofs and roads, respectively, performed best. All scenarios successfully lowered the duration exceedance of outflows exceeding the CSO threshold 0.14 m^3/s.

- The overall hydrological performance of the GR and the RG modules of MU was satisfactory. However, the transfer of parameters between different hydrological models is complex and finding calibration parameters that work everywhere is difficult.
- Implementation of the calibrated SUDS modules to the Grefsen-CS catchment showed that an EIA reduction of 3.6% could result in CSO volume reduction greater than 7% for all applied scenarios.
- The RGs responded best in reducing peak flows and CSO volumes for the larger events. Whereas GRs performed as good as the RGs for the smaller events. The combined scenario reduced the CSO by 100% for event *E1CS* and

E2CS, and halved the total number of CSO events from 4 to 2.

- The FDC provided a better understanding of the long-term efficiency of implementing SUDS controls which the event-based analysis did not reveal. It showed that the GRs efficiently handled smaller events without activating CSOs.
- FDC can be a practical decision-making tool to establish and monitor specific performance criteria that SUDS measures should meet, for example, reducing CSOs.

ACKNOWLEDGEMENTS

The Agency of Water and Wastewater Services (Oslo VAV) provided the existing urban model of the study area along with the historic precipitation time series (year 1993) and CSO duration records. The first author thanks Alexander Pham, Samatar Abdi, and Urzula Zühlke of Oslo VAV for their support in providing the data. DHI provided the license and organized workshops, and the first author is grateful to Odd Adler-Gjerde, Karen Birnchmann, and Kristina Tvedalen of DHI.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Beven, K. 1993 Prophecy, reality and uncertainty in distributed hydrological modeling. *Advances in Water Resources* **16** (1), 41–51.

Braskerud, B. C. 2014 *Grønne tak og Styrtregn (Green Roofs and Cloud Burst Precipitation)*. NVE, Rapport nr. 65/2014, Oslo.

Chui, T. F. M., Liu, X. & Zhan, W. 2016 Assessing cost-effectiveness of specific LID practice designs in response to large storm events. *Journal of Hydrology* **533**, 353–364.

DHI 2017 *MIKE URBAN Collection System. Modelling of Storm Water Drainage Networks and Sewer Collection Systems*. User Guide, Danish Hydraulic Institute (DHI).

Eckart, K., Mcphee, Z. & Bolisetti, T. 2017 Performance and implementation of low impact development – a review. *Science of the Total Environment* **607–608**, 413–432.

Fenner, R. A. 2017 Spatial evaluation of multiple benefits to encourage multi-functional design of sustainable drainage in blue-green cities. *Water* **9**, 953.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. 2015 SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. *Urban Water Journal* **12** (7), 525–542.

Garofalo, G., Giordano, A., Piro, P. & Spezzano, G. 2017 A distributed real-time approach for mitigating CSO and flooding in urban drainage systems. *Journal of Network and Computer Applications* **78**, 30–42.

Gooré Bi, E., Monette, F., Gachon, P., Gaspéri, J. & Perrodin, Y. 2015 Quantitative and qualitative assessment of the impact of climate change on a combined sewer overflow and its receiving water body. *Environmental Science and Pollution Research* **22**, 11905.

Hamby, D. M. 1994 A review of techniques for parameter sensitivity analysis of environmental-models. *Environmental Monitoring and Assessment* **32** (2), 135–154.

Jacobson, C. R. 2011 Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. *Journal of Environmental Management* **92**, 1438–1448.

Johannessen, B. G., Hamouz, V., Grangne, A. S. & Muthanna, T. M. 2019 Transferability of SWMM model parameters between green roofs with similar build-up. *Journal of Hydology* **568**, 816–828.

Johnson, D. & Geisendorf, S. 2019 Are neighborhood-level SUDS worth it? An assessment of the economic value of sustainable urban drainage system scenarios using cost-benefit analyses. *Ecological Economics* **158**, 194–205.

Liao, Z. L., Zhang, G. Q., Wu, Z. H., He, Y. & Chen, H. 2015 Combined sewer overflow control with LID based on SWMM: an example in Shanghai, China. *Water Science and Technology* **71**, 1136–1142.

Liu, Y., Bralts, V. F. & Engel, B. A. 2015 Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. *Science of the Total Environment* **511**, 298–308.

Lucas, W. C. & Sample, D. J. 2015 Reducing combined sewer overflows by using outlet controls for green stormwater infrastructure: case study in Richmond, Virginia. *Journal of Hydrology* **520**, 473–488.

Mallari, K. J. B., Arguelles, A. C. C., Kim, H., Aksoy, H., Kavvas, M. L. & Yoon, J. 2015 Comparative analysis of two infiltration models for application in a physically based overland flow model. *Environmental Earth Sciences* **74**, 1579–1587.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptual model. Part 1 – a discussion of principles. *Journal of Hydrology* **10**, 282–290.

Nie, L., Lindholm, O., Lindholm, G. & Syversen, E. 2009 Impacts of climate change on urban drainage systems – a case study in Fredrikstad, Norway. *Urban Water Journal* **6**, 323–332.

Nilsen, V., Lier, J. A., Bjerkholt, J. T. & Lindholm, O. G. 2011 Analysing urban floods and combined sewer overflows in a changing climate. *Journal of Water and Climate Change* **2**, 260–271.

Oslo Municipality 2014 *Strategi for Overvannshåndtering I Oslo 2013–2030 (Strategy for Stormwater Management in Oslo 2013–2030)*. Municipality of Oslo.

Palhegyi, G. E. 2010 Modeling and sizing bioretention using flow duration control. *Journal of Hydrologic Engineering* **15**, 417–425.

Palla, A. & Gnecco, I. 2015 Hydrologic modeling of low impact development systems at the urban catchment scale. *Journal of Hydrology* **528**, 361–368.

Paus, K. H. & Braskerud, B. C. 2014 Suggestions for designing and constructing bioretention cells for a nordic climate. *Journal of Water Management and Research* **03**, 139–150.

Peng, Z. & Stovin, V. 2017 Independent validation of the SWMM green roof module. *Journal of Hydrologic Engineering* **22**.

Rosa, D. J., Clausen, J. C. & Dietz, M. E. 2015 Calibration and verification of SWMM for low impact development. *Journal of the American Water Resources Association* **51**, 746–757.

Rossman, L. A. 2015 *Storm Water Management Model User's Manual Version 5.1*. U.S. Environmental Protection Agency.

Russwurm, I. L., Johannessen, B. G., Gragne, A., Lohne, J. & Muthanna, T. M. 2018 Modelling green roof detention performance in cold climates. *EPiC Series in Engineering* **3**, 1804–1813. HIC 2018.

Saksæther, V. & Kihlgren, K. S. 2012 *Regnbed som tiltak for overvannshåndtering i småhusbebyggelse (Rain Gardens as Measures for Stormwater Management in Areas with Individual Housin)*. Norwegian University of Life Sciences.

Semadeni-Davies, A., Hernebring, C., Svensson, G. & Gustafsson, L. G. 2008 The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: combined sewer system. *Journal of Hydrology* **350** (1–2), 100–113.

Shuster, W. D., Bonta, J., Thurston, H., Warnemuende, E. & Smith, D. R. 2007 Impacts of impervious surface on watershed hydrology: a review. *Urban Water Journal* **2**, 263–275.

Sorteberg, A., Lawerence, D., Dyrrdal, A. V., Mayer, S. & Engeland, K. 2018 *Climatic Changes in Short Duration Extreme Precipitation and Rapid Onset Flooding – Implications for Design Values*. Report NCCS/1/2018, Norwegian Centre for Climate Services, Oslo, Norway, pp. 91–99.

Sun, Y.-W., Wei, X.-M. & Pomeroy, C. A. 2011 Global analysis of sensitivity of bioretention cell design elements to hydrologic performance. *Water Science and Engineering* **4**, 246–257.

USEPA 2011 *Keeping Raw Sewage & Contaminated Stormwater Out of the Public's Water*. United States Environmental Protection Agency.

Walsh, C. J., Fletcher, T. D. & Ladson, A. R. 2005 Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. *Journal of North America Benthological Society* **24** (3), 690–705. http://dx.doi.org/10.1899/04-020.1.

Yazdanfar, Z. & Sharma, A. 2015 Urban drainage system planning and design – challenges with climate change and urbanization: a review. *Water Science and Technology* **72** (2), 165–179.

First received 23 May 2019; accepted in revised form 17 May 2020. Available online 7 July 2020