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Constructing an inventory for fast screening of hydraulic and hydrologic performance of stormwater control measures

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ABSTRACT

Stormwater control measures (SCMs) are effective and sustainable complementary means of managing stormwater in cities. Unlike underground drainage systems, they require space on the city surface, and therefore must be included in initial sketches of urban planning and design. These initial sketches are often made by architects and urban planners, who are usually not trained in hydrology, and therefore require simple and robust tools to inform their initial plans with respect to stormwater management. There may be local guidelines for dimensioning SCMs, but their applicability is often limited with regard to the range of SCMs, and the methodology behind them may be oversimplified, including a lack of assessment of benefits on the urban hydrological cycle. We developed a methodology for estimating multiple performance indicators of a wide range of SCMs and applied it to Danish meteorological conditions. The methodology includes consulting expected end users, configuring an SWMM model for each SCM type and choosing applicable parameter ranges, running multiple simulations for each type covering the parameter space, and post-processing the results using python and PySWMM. The outputs can be used to draw general recommendations regarding effective application ranges for different SCMs, and to quickly assess the performance of case-specific configurations.

Key words: Nature-Based Solutions, SWMM, urban water management, water balance

HIGHLIGHTS

- An inventory was created for stormwater control measures' performance in Denmark.
- Performance was simulated using SWMM with carefully selected model parameters.
- The inventory contains tens of thousands of parametrizations and simulation results.
- The inventory can be used to quickly assess plausible performance of SCMs.
- The methodology can easily be adapted to other locations.

1. INTRODUCTION

Existing stormwater systems are under pressure for several reasons, including urban growth and densification, changing rain patterns due to climatic changes, and increasing demands for sustainability and liveability. Retrofitting with above-ground, nature-based stormwater control measures (SCMs) such as bioretention units, raingardens and temporary inundation spaces may improve the performance of the drainage system, while at the same time offering local benefits such as improved aesthetics and enhanced opportunities for recreation. Furthermore, these systems often have a reduced environmental impact compared to expansion of the underground pipe-based system (Brudler *et al.* 2016; Sørup *et al.* 2019). For these reasons many cities around the world have adopted visions and strategies to invest in multifunctional, green, above-ground SCMs, collectively referred to as Green Stormwater Infrastructure (GSI), Low Impact Development (LID), Sustainable Urban Drainage Systems

(SUDS), Water Sensitive Urban Design (WSUD), Nature-Based Solutions (NBS), Sponge Cities, and more (Fletcher *et al.* 2015; Jia *et al.* 2017; Liu & Jensen 2017).

The uptake of SCMs is however not happening as fast as some would hope; the barriers to implementation of the strategies are many, including system inertia, rigid regulatory frameworks, lack of knowledge (Madsen *et al.* 2018). An inherent complicating factor for above-ground SCMs is that their successful implementation requires collaboration between many stakeholders, including urban planners, landscape architects, drainage engineers, and more (Fratini *et al.* 2012; Sørup *et al.* 2016; Andersen *et al.* 2017; Skrydstrup *et al.* 2020). In the early planning phase, such collaboration is often too expensive, and the initial layout of a greenfield development plan or urban retrofitting plan is thus often drawn by architects alone, who have limited skills and tools for understanding and designing water flows. If early layouts are based on faulty assumptions with regard to water management, e.g., disregarding topography or allocating too little space for SCMs, it may require costly redesign of the layout or costly below-ground drainage solutions to compensate. Fast and simple tools are thus needed to help inform early layouts so that they include feasible solutions and exclude infeasible solutions.

Existing tools employ varying levels of complexity, and typically respond to local needs and framings of implementation strategies, often only considering very simple setups, and focusing on assessing the hydraulic performance of the SCM (Lerer *et al.* 2015; Kuller *et al.* 2017; Wu *et al.* 2020; Ferrans *et al.* 2022). A quantitative tool that targets the initial, collaborative planning and design phase, was described by van de Ven *et al.* (2016); however, this tool is not publicly available, and the quantitative methods applied are not described in detail. A spreadsheet-based tool is commonly used in Denmark for dimensioning of a set of simple SCMs (a rain garden, an infiltration unit, a soakaway, and a permeable paving (spildevandskomiteen.dk)). However, this selection is very limited compared to the variety of SCMs applied in practice. Like the majority of existing simple design tools the calculations are based on statistical intensity–duration–frequency relationships to calculate the hydraulic performance of the SCMs for high return periods, although another key contribution of SCMs is improvements to the urban water balance, as indicated by example (Li & Lam 2015; Locatelli *et al.* 2015; Henrichs *et al.* 2016). More elaborate design methods are based on statistical analysis of the output from hydrological models run using long rainfall time series as input, but these are typically too slow and require too many technical skills to be used in early stage collaborative design processes.

In this study, we developed a methodology for creating a performance inventory of SCMs including both hydraulic performance indicators (relating to dimensioning criteria) and hydrologic performance indicators (relating to impact on the urban water balance). The inventory can be used to make rapid assessment of many different configurations of a variety of SCM types in a wide spectrum of plausible site conditions. The methodology is based on identifying relevant key performance indicators (KPIs) and relevant SCM types and designs in collaboration with end users, setting up appropriate SCM models in the open source urban drainage modelling software SWMM (Rossman 2015), which has a state-of-the-art module for simulating LID performance, choosing and defining relevant model parameters and parameter ranges for the considered designs, applying python and the PySWMM package (McDonnell *et al.* 2020) to automatically run thousands of SWMM simulations with varying inputs and post-processing the resulting output time series, and storing the final KPIs in an SQLite database. This way, the results of the inventory can be accessed through lookup tables and provide fast responses on expected performance of SCMs, to be used in the early design phases.

2. METHODOLOGY

2.1. Defining relevant SCMs and KPIs

Based on our knowledge of commonly applied SCMs in Denmark and our dialogue with expected end users of the tool, we identified seven different types of commonly used SCMs to include in the inventory:

(1) Bioretention unit with infiltration to native soil and no drainpipe.
(2) Bioretention unit with a drainpipe and no infiltration to native soil.
(3) Bioretention unit with both infiltration to native soil and a drainpipe.
(4) Rain garden, i.e., a simplified bioretention unit allowing for infiltration to native soil with no subsurface storage and no drainpipe.
(5) Soakaway unit with infiltration to native soil and no drainpipe.
(6) Extensive green roof.

(7) Wet detention pond with a permanent pool, constant drain rate when water is above the permanent pool level, and no infiltration to native soil.

The following three KPIs were likewise chosen based on expected end users' needs, and the hydraulic and hydrologic requirements to improve the service level of the surrounding drainage system typically set by authorities and other external partners in Denmark:

(1) The return period of overflow from the SCM. In Denmark, SCMs are often implemented either as standalone solutions in greenfield developments, or as add-ons to combined sewer systems in retrofit projects. In both cases it is relevant to assess whether an SCM will comply with the service level decreed for the area, which is defined through how often the drainage system is allowed to have its capacity exceeded, often set to every 5 or 10 years (Locatelli *et al.* 2015; Lund *et al.* 2019). Although the concept of the Three Point Approach (3PA) was introduced to the Danish water sector over a decade ago (Fratini *et al.* 2012; Sørup *et al.* 2016), there are still misunderstandings regarding which rainfall domain different SCMs are suitable for managing, i.e., many practitioners believe that SCMs performs well for higher return periods than what is realistic with respect to space allocation (Madsen *et al.* 2018).
(2) The annual water balance of the catchment, before and after implementation of the SCM. Generally, and especially in green field developments, it is considered desirable for a drainage system to achieve a water balance that is as close to the natural water balance of the area pre-development (Burns *et al.* 2012; Fletcher *et al.* 2013; Petrucci *et al.* 2013; Henrichs *et al.* 2016), although there can be good reasons to deviate from this (e.g., parts of Copenhagen were originally quite swampy, which is not a practical state of drainage for an urban area). Furthermore, generally speaking, the larger the reduction in runoff volume released to receiving waters, the larger the reduction in pollution released to receiving waters (Sage *et al.* 2016, 2015). When SCMs are implemented in an area with a combined sewer system, any change in water balance that moves outflow from drainpipe or overflow to infiltration or evaporation, entails reduced flow towards the wastewater treatment plant (WWTP), which is a net sustainability gain in terms of saved energy expenditure at the WWTP, as well as a lower-emission alternative to upgrading existing pipes (Brudler *et al.* 2016; Sørup *et al.* 2020).
(3) The effective volume fraction of the SCM, i.e., the part of the maximum storage volume of an SCM that is usually available at the onset of a rain event. A high effective volume fraction indicates that the SCM configuration is efficient, while a low effective volume fraction indicates a design that should be reconsidered, since the SCM is too small or not emptying fast enough to be 'ready to serve' at the next rain event (also used in Davidsen *et al.* (2018)).

Other KPI's could have been chosen, e.g., relating to water quality performance of SCMs. Here the assumption is often that reducing the volumetric load to the surrounding urban drainage system through implementation of SCMs implicitly reduces the pollution from the urban drainage system to the environment (combined sewer overflows, etc.). Furthermore, considering water quality impacts at the local scale would require considering several pollution impact categories (surface water, soil/groundwater) and a range of different pollutants, including general water quality parameters typically in focus when using simulation models like SWMM (suspended solids, organic matter, nitrogen, and phosphorus, e.g., Baek *et al.* (2020)) but also a range of other pollutants like heavy metals, PAH, herbicides industrially derived compounds (e.g., Eriksson *et al.* 2007) where no generally accepted simulation models are yet available. Such analysis is beyond the scope of the present paper.

2.2. Intended workflow with the performance inventory

The purpose of the workflow is to provide simple and robust information about site-specific SCM performance in a fast manner with a minimum of inputs from the user. The results must be instantly available to support a dynamic process where the user can tune relevant design parameters to achieve a desired response. Figure 1 outlines the intended interaction between end users and the inventory and sets the overall frame for the information needed in the inventory.

2.3. Structuring and populating the performance inventory

The inventory was stored in an SQLite database with a separate table for each type of SCM. The general structure of these tables contains columns for the input parameters that were varied (these depend on the SCM type) and

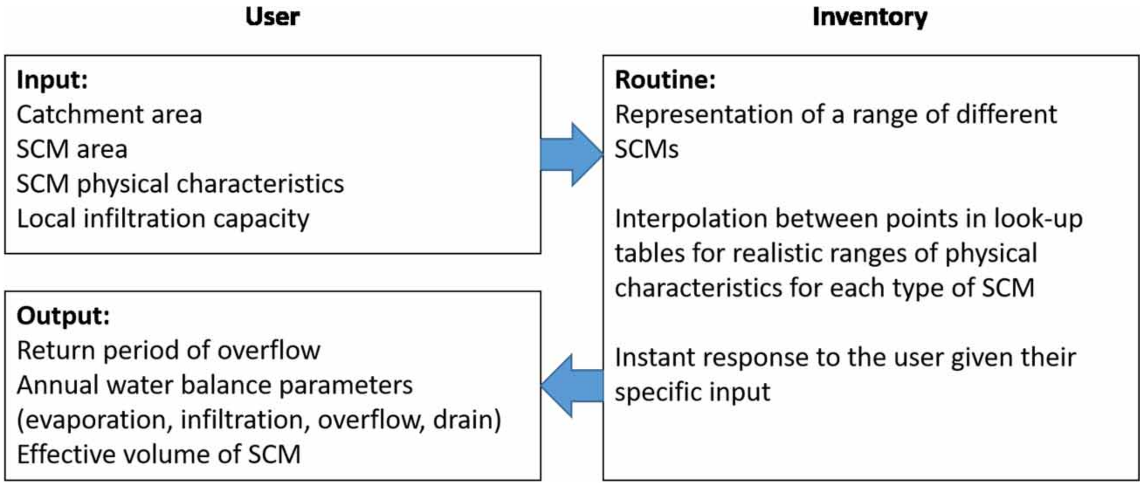

Figure 1 | Intended interaction between end users and the inventory. The inventory is designed to support end users in the early screening phase by instant provision of performance indicators of site-specific designs of SCMs.

columns for the KPIs. Every entry in the inventory is a based on a long-term simulation of the specific SCM. The SQLite database for Danish conditions is available through Lerer *et al.* (2022).

2.3.1. Generic model structure

All seven types of SCM were modelled using SWMM (Rossman 2015); the first six SCM types were modelled using the LID module, while the detention pond was modelled using a storage node. The LID module in SWMM is built into the catchment rainfall–runoff model. To clearly distinguish the rainfall–runoff process on the catchment from hydrological processes in the SCM, we set the six first types of SCM up on a separate catchment (the ‘SCM catchment’, i.e., a catchment that represents the SCM only), which receives water from an upstream catchment (the ‘runoff catchment’, i.e., a catchment that represents the area that drains to the SCM). The inflow to the SCM is thus the sum of runoff from the runoff catchment and rainfall falling directly on the SCM catchment. The outflows from the SCM are evaporation (where applicable), infiltration into native soil (where applicable), drain through drainpipe (where applicable), and overflow (when the capacity of the SCM is exceeded). To distinguish between drain flow and overflow, each is directed to its own outfall node. Figure 2 illustrates this setup of catchments and flows.

2.3.2. Choosing model parameters

2.3.2.1. SCM models’ parameters. For each type of SCM there are many model parameters that need to be defined. In order to effectively find the most appropriate parameter values and ranges, we defined three groups of parameters:

(1) Model parameters that are subject to design considerations ‘in real life’, and have a notable influence on the performance, such as the berm height of a bioretention unit.

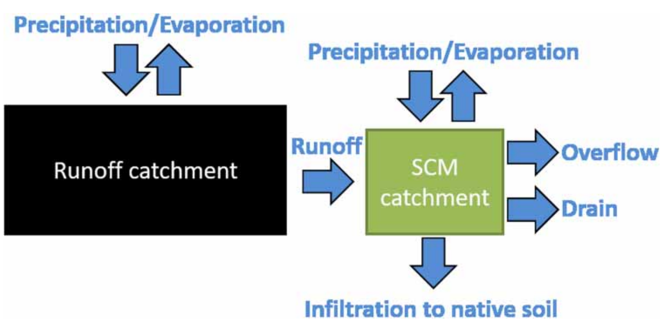

Figure 2 | Schematic illustration of the water flows in the SWMM models used to simulate SCM performance.

(2) Model technical parameters that are usually not considered in a design process 'in real life', and have relatively little influence on the performance, such as the porosity of the soil layer in a bioretention unit.
(3) Model parameters that reflect local site conditions, such as the infiltration rate of the native soil under a bioretention unit, or the allowable drain rate from a wet detention pond.

Through a consultation process with relevant practitioners (two consulting engineers, two architects, and two water utility employees) we divided the parameters into the three groups and identified realistic and relevant value ranges for the parameters in groups 1 and 3. For the model technical parameters (group 2), we consulted relevant literature and made assessments of likely parameter ranges based on the available literature. The chosen parameters and parameter ranges are presented in the results section 3.

2.3.2.2. Catchment models' parameters. The total area of the two catchments (the runoff catchment and the SCM catchment) were kept constant between simulations, i.e., the upstream catchment area was lowered when SCM area was increased in order to maintain a constant total site area and a constant total rainfall volume. We used a total area of 0.1 ha to be able to ignore the time of concentration within the upstream catchment. We applied a gentle slope of 0.5%, considered representative for Danish conditions, and used a width $= 0.5 \times \sqrt{\text{area}}$ as proposed by Randall *et al.* (2019). The area ratio between the SCM catchment and the runoff catchment was varied between 0.02 and 0.2 in the simulations as a realistic range of SCM configurations and area constraints.

The runoff catchment, providing runoff to the SCM, was defined as 100% impermeable. In case of pervious areas within the upstream catchment it was assumed that these will contribute with a negligible amount of runoff compared to the impermeable surfaces. We applied a moderate value for the Manning number of 0.2 $(\mathrm{s/m}^3)$ and a depression storage of 1.5 mm in line with the suggestions of Randall *et al.* (2019) and Rossman & Huber (2016).

The SCM catchment was set to be completely covered by an SCM element, hence the only significant parameter for this catchment is the catchment area. In the submenu 'LID usage editor' the number of units was set to 1, the area of each unit was set to match the area of the catchment, the surface width was set to zero (this variable is not active for the types of SCMs we are deploying), the percent initially saturated was set to zero (this variable plays an insignificant role in long-term simulations) and the percent of impervious and pervious areas treated was set to 100.

2.3.3. Climate data

2.3.3.1. Rainfall and evaporation data. As rainfall input to the model we used a historical time series of approximately 40 years length (January 1979–December 2019) from Kløvermarken, Copenhagen, Denmark, from the gauge network operated by The Water Pollution Committee of The Society of Danish Engineers (Jørgensen *et al.* 1998; Madsen *et al.* 2009). 40 years length allows calculating relevant return periods (up to 5–10 years) without significant statistical uncertainty. Given the relatively homogeneous precipitation fields in Denmark (Madsen *et al.* 2017) this series is considered sufficiently representative for the country. The original data is in 1-min temporal resolution, but for this study it was converted to 10-min temporal resolution to reduce computation time, given that this resolution is adequate for simulating processes in the SCMs.

As potential evaporation input, we used mean daily values per calendar month based on data from Scharling & Kern-hansen (2012). This is a daily gridded data product for Denmark covering 1989–2010, from which we extracted values from the grid cell where the rain gauge is located and calculated a mean for the period.

2.3.4. Running many SWMM simulations through Python

We set up a routine where SWMM simulations are run automatically through Python using the PySWMM package (McDonnell *et al.* 2020). This way, parameters that need to be varied between simulations can be defined in python and forwarded to SWMM at the beginning of each new simulation, and the KPIs can be retrieved after the simulation and pushed to the SQLite database. Some KPIs, such as the water balance, can be directly retrieved from the SWMM simulation output files, while others, such as the return period for overflow, must be calculated in Python based on detailed result time series which are not standard output from SWMM. For this reason, we ran the simulations stepwise, to retrieve and store water levels and overflow volumes from each simulation time step. A time step of 10 min was used for all simulations.

A Python script was used to loop through parameter combinations that are relevant for a given SCM type, and the PySWMM module was used to manipulate these variables at the beginning of each simulation. This way an efficient workflow was secured allowing simulations to be parallelized using Pythons joblib package (Varoquaux 2022). All parameters in the SWMM LID module can be set this way, but other parameters cannot be set through PySWMM and for these parameters, the SWMM input file was manipulated through text editing from the Python script. This was, e.g., the case for depth–area curves for wet detention ponds. This workflow is less efficient than the direct manipulation through PySWMM since it prevents parallelization of the simulations.

2.3.5. Calculating KPIs

The three KPIs (cf. Section 2.1) were calculated as follows:

The return period for overflow was calculated based on a time series for overflow extracted from the simulation. A python function counts how many continuous periods of overflow appear throughout the simulation period, considering a minimum separation time between individual overflow events of 24 h, in order to avoid overestimation of the number of events due to numerical instabilities resulting in alternating overflow/no overflow. Finally, the return period is calculated by dividing the length of the simulation period by the number of overflow events (corresponding to the California plotting position formula).

The water balance components were calculated for the full catchment (i.e., the sum of the runoff catchment and the SCM catchment). Rainfall is the only input flow, and the possible flows out are evaporation, infiltration to native soil, drainage through a drainpipe, and overflow (not all output flows are relevant for all types of SCMs). The PySWMM SystemStats package (McDonnell *et al.* 2020) is used to retrieve the relevant volumes from the simulation. The output flows are recalculated as volumetric percentages of the input flow, as an average taken over the entire simulation period.

The effective volume fraction is calculated based on the time series for overflows, rainfall and volume stored in the different compartments of the SCM, extracted from the simulations. The process is:

- Identify times steps where overflow starts in the overflow time series.
- For each of these, identify in the rainfall time series the time step where the rain event, that was ongoing at the moment of overflow, began.
- For each of these time steps, calculate the total volume stored (as sum of water stored in the different compartments), subtract from the full volume of the SCM, and divide by the full volume.

3. RESULTS

3.1. Parameters for SCM models

We used the bioretention unit in SWMM to simulate all three types of bioretention (SCM types 1–3) as well as the rain garden (SCM type 4) and soakaway unit (SCM type 5). This is possible because the different compartments and flow options, see Figure 3, can be turned on and off (by setting them to zero). The green roof (SCM type 6) was simulated using the specific green roof module in SWMM and the wet detention pond (SCM type 7) was simulated using the storage node in SWMM.

3.1.1. Bioretention units

Table 1 lists all the required model parameters for the three types of bioretention units we defined (see Section 2.1). For model parameters of group 1 (parameters subject to active design choices) and group 3 (parameters subject to site-specific constraints) the table includes the range of plausible values identified together with the practitioners (see Section 2.3.2). For group 2 (parameters that are not subject to active design choices and have little influence on the results) the table includes the parameter value chosen to reflect most plausible conditions. For all parameters, the table furthermore includes relevant literature values from Rossman & Huber (2016), Liu & Fassman-Beck (2017a, 2017b) and Randall *et al.* (2019).

Note that the parameter 'void ratio' for the storage layer has a limited value range that requires a workaround in order to properly represent a typical Danish configuration. The void ratio is defined as 'The volume of void space relative to the volume of solids in the layer', and can only go up to 1. The typical storage layer in a bioretention unit in Denmark is made using a plastic cassette, which has a porosity of 95%. A porosity of 95% translates to a void ratio of 19, which is out of bound in SWMM. The workaround we use is to double the depth of the layer and half the porosity to achieve the desired total storage volume. Hence, the thickness

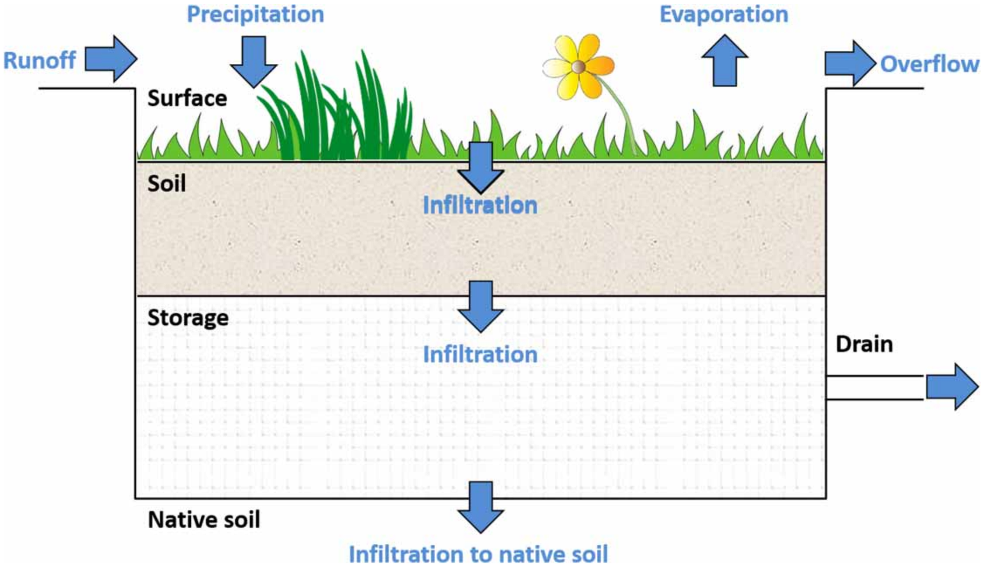

Figure 3 | Schematic figure of the bioretention unit model.

Table 1 | Parameter values and parameter ranges used for simulating bioretention units, raingarden, and soakaway units in SWMM (SCM types 1–5)

Layer	Parameter	Unit	Value/range	Group	Rossman & Huber 2016	SWMM Help pages	Randall *et al.* 2019	Liu & Fassman-Beck 2017a, 2017b
Surface	Berm height	(mm)	100–600	1	150–300	NA	300	300
	Vegetation Volume Fraction	(–)	0.1	2	0.0–0.2	0.0–0.2	0.1	NA
	Roughness	(–)	0	2	NA	0	0.1	NA
	Slope	(–)	0	2	NA	0	2	NA
Soil	Thickness	(mm)	300–600	1	600–1,200	450–900	500	500–1,000
	Porosity	(–)	0.5	2	0.52 (0.45–0.6)	NA	0.4	0.51–0.65
	Field capacity	(–)	0.25	2	0.15 (0.15–0.25)	NA	0.1	0.29–0.32
	Wilting point	(–)	0.05	2	0.08 (0.05–0.15)	NA	0.05	0.03–0.05
	Conductivity	(mm/h)	120	2	120 (50–140)	NA	72	900–3,000
	Conductivity slope	(–)	10	2	39 (30–55)	30–60	10	7.4–8.1
	Suction head	(mm)	50	2	50 (50–100)	NA	50	NA
Storage	Thickness	(mm)	800–2,000	1	150–900	150–450	NA	NA
	Void ratio	(–)	0.905	2	0.2–0.4	0.5–0.75	NA	NA
	Clogging factor	(–)	0	2	NA	NA	NA	NA
	Seepage rate	(mm/h)	For SCM type 2 = 0; For SCM types 1, 3, 5 = 0.5–120	3	NA	NA	NA	NA
Drain	Flow coefficient	(l/s/ha) (mm/h)	For SCM type 1 and 5 = 0; For SCM type 2 and 3 = (0.1–100) 1.8–18,000	3	NA	NA	NA	NA
	Flow exponent	(–)	0	2	NA	0.5	NA	NA
	offset	(mm)	0–1,000	1	NA	NA	NA	NA

range of 800–2,000 mm in Table 1 (with a porosity of 47.5%) serves to represent a thickness range in the real world of 400–1,000 mm (with a porosity of 95%). The soil parameters for the local soil are described by the parameter 'seepage rate' in Table 1, and the chosen span covers conditions from 'much too bad to consider local infiltration' to 'you don't really need storage, just pour water directly on the ground'. This way we secure that there are always data points available for interpolation as long as the user keeps within the plausible conditions that would be appropriate in real-life applications of the tool.

For the drain we would like to achieve a constant outflow rate of 0.1–100 l/s/ha (the range of plausible permittable outflow rates). Given that our total catchment area is 0.1 ha, this translates to 0.01–10 l/s. To achieve a constant flow rate, rather than a rate that fluctuates with the water level in the unit, we set the flow exponent to zero as suggested in Rossman (2015). The flow coefficient, C, must be specified in units of length per time, which is then multiplied with the SCM area to produce a flow in units of volume per time. Given that we vary the area of the SCM between our different simulations, we need to reset this parameter for each simulation depending on the current area allocated to the SCM, using the following equation:

$$C = \frac{Q}{A_{\mathrm{SCM}}} \times 3,600(\mathrm{s/h})$$

for C in mm/h, Q in l/s and A_{SCM} in m^2.

The field capacity (FC) of the soil layer is set relatively high based on results from Liu & Fassman-Beck (2017a), who monitored columns of engineered media in laboratory experiments and measured their FC. When using these values in a model of a bioretention unit in SWMM they found that a calibrated FC value performed better than the measured value (volume error reduced from 16–70% to 1–2%), reflecting that in reality, drainage occurs later than when FC is achieved in the model (which simulates the average FC in the soil compartment), because moisture content in the soil is in reality not uniformly distributed as the model assumes (it moves slowly downwards). This entails that low (measured) FC values result in too much water being infiltrated through the bottom of the soil layer. However, setting FC values higher (to match the calibrated values suggested by Liu & Fassman-Beck (2017a) results in more water being retained in the soil compartment in the model, allowing for more evaporation – potentially too much evaporation compared to reality. The referenced studies are short term and do not monitor evaporation so this cannot be confirmed. We chose to go with high values of FC to achieve as correct results for infiltration as possible, since this is a more significant flow component for our conditions (relatively cold and moist climate with little potential evaporation).

The parameter ranges chosen in Table 1 (column 'Value/range') result in 21,840 combinations for a bioretention unit with infiltration and no drainpipe, 2,025 combinations for a unit with a drainpipe and no infiltration, and 28,350 combinations for a unit with both infiltration and an offset drainpipe.

3.1.2. Rain garden

The rain garden model is a simplified version of the bioretention unit with no subsurface storage unit and no drain, see Figure 4 for a schematic illustration. The parameters and parameter ranges used here are identical to those for the relevant layers in the bioretention unit, i.e., the surface layer and the soil layer (see Table 1). The parameter ranges result in 286 different combinations for this SCM.

3.1.3. Soakaway

The soakaway model is also a simplified version of the bioretention unit, here only the subsurface storage unit is included, see Figure 5 for a schematic illustration. Again, the parameters and parameter ranges are identical to

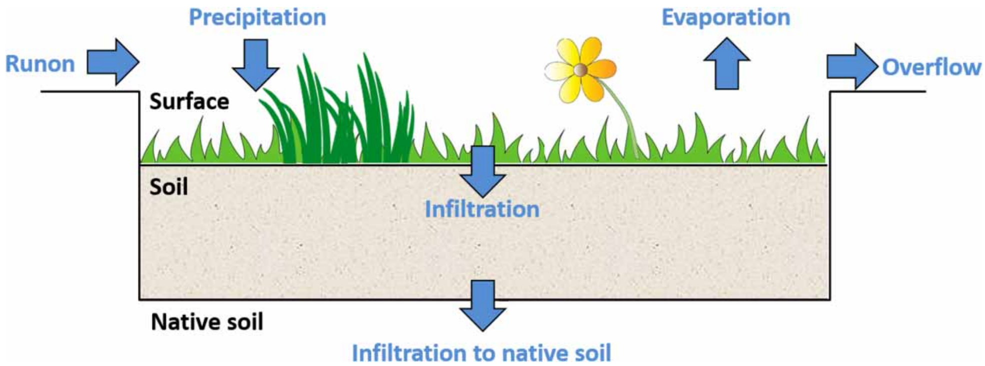

Figure 4 | Schematic figure of the the rain garden model.

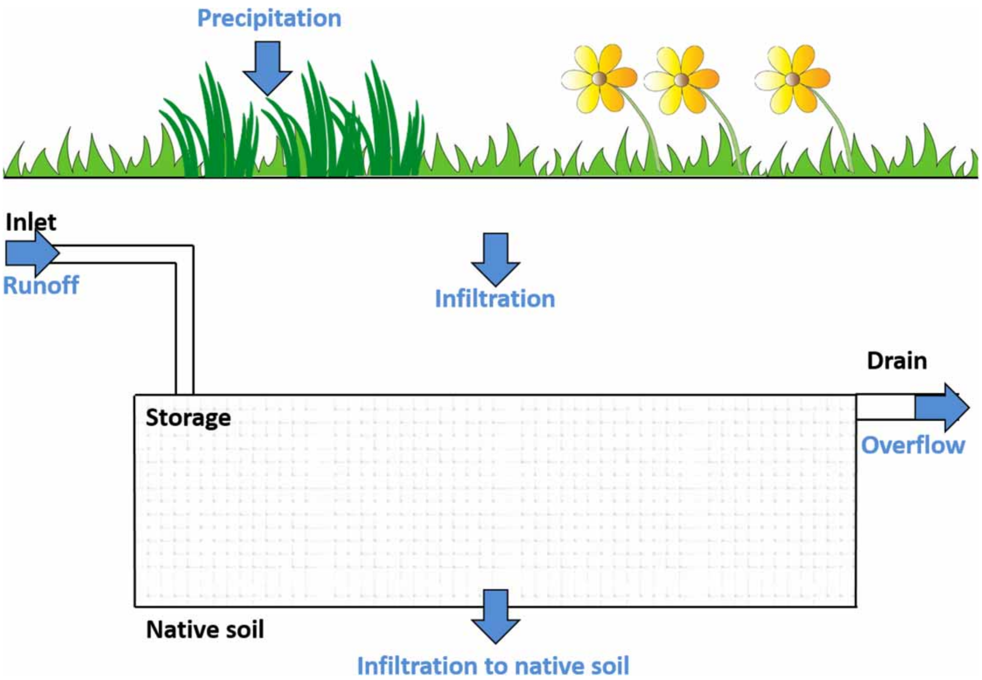

Figure 5 | Schematic figure of the soakaway model.

those for the relevant layer of the bioretention unit (see Table 1). As for the raingarden, the parameter ranges result in 286 different combinations being simulated.

3.1.4. Green roof

The green roof model in SWMM includes a surface layer, acting as catchment, a soil layer, acting as growing medium, and a unique layer beneath the soil layer representing a drainage mat with storage capacity, see Figure 6 for a schematic illustration and Table 2 for an overview of the parameters used. The only parameter which has significant influence on the KPIs (group 1) is the depth of the soil layer, where we used a value range corresponding to configurations commonly implemented in Denmark. For the model technical parameters (group 2) we used values based on the academic literature (Locatelli *et al.* 2014; Krebs *et al.* 2016; Rossman & Huber 2016), and calibrated the FC and wilting point of the soil layer to yield annual water balances similar to those reported by Locatelli *et al.* (2014). With only one parameter to vary, 11 different configurations of the green roof were simulated.

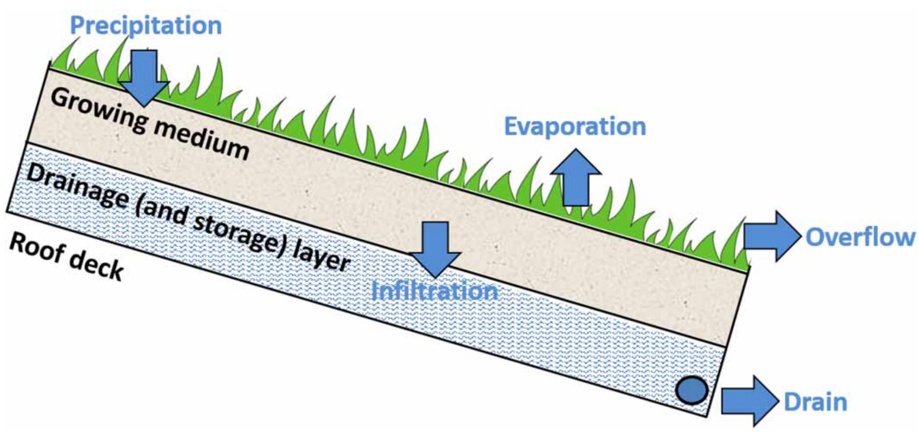

Figure 6 | Schematic figure of the green roof model.

Table 2 | Parameter values used for simulating the green roof in SWMM

Layer	Parameter	Unit	Value/ range	Group	Rossman & Huber 2016	SWMM help pages	Danish NBS method catalogue	Locatelli et al. 2014	Krebs et al. 2016
Surface	Berm height	(mm)	0	2	0–7.5	NA	NA	0	30
	Vegetation Volume Fraction	(–)	0	2	0–0.2	0.0–0.2	NA	0	0.1
	Roughness	(–)	0.15	2	NA	0.15	NA	NA	0.168
	Slope	(%)	5	2	NA	NA	1–20	7–17	8
Soil	Thickness	(mm)	30–80	1	50–150	75–150	30–80	30–60	100
	Porosity	(–)	0.5	2	0.45–0.6	NA	NA	NA	0.41
	Field capacity	(–)	0.3	2	0.3–0.5	NA	NA	NA	0.29
	Wilting point	(–)	0.1	2	0.05–0.2	NA	NA	NA	0.02
	Conductivity	(mm/h)	100	2	100–350	NA	NA	NA	38
	Conductivity slope	(–)	40	2	30–55	30–60	NA	NA	40
	Suction head	(mm)	100	2	50–100	NA	NA	NA	61
Drainage mat	Thickness	(mm)	40	2	13–50	25–50	40–70	40	3.8
	Void fraction	(–)(–)	0.5	2	0.2–0.4	0.5–0.6	NA	NA	0.41
	Roughness	(–)	0.1	2	0.01–0.03	0.1–0.4	NA	NA	0.01

3.1.5. Wet detention pond

The wet detention pond was implemented as a rectangular storage unit with a permanent wet volume of 250 m^3/ha, as recommended in Denmark for water quality purposes (Hvitved-Jacobsen *et al.* 1994). It was designed with gently sloping sides (1:3) to match best practice in Denmark for making safe and easily maintainable detention ponds. The storage volume was fitted on top of the wet volume, and for this part the slope was varied between 1:3 and 1:9. Figure 7 shows a schematic illustration and Table 3 presents the parameters used.

The storage volume of the wet detention ponds is in SWMM described through storage curves with depth–area information. We constructed storage curves from the depth, volume, side slope and width/length ratio reported in Table 3. Since some of the parameters in Table 3 are interdependent, the parameter ranges resulted in 3,774 different combinations for this SCM.

3.2. Examining resulting data in the inventory

Statistical analysis of the results stored in the inventory reveals some general trends regarding site conditions and configurations for efficient SCM implementation. Figure 8 illustrates the three KPIs (return period for overflow, water balance, effective volume fraction) as functions of the area ratio (between SCM catchment and runoff catchment) and the hydraulic conductivity of the native soil for a bioretention unit that only empties through infiltration to native soil (SCM type 1). The following conclusions can be drawn:

(1) The average annual evaporation fraction of the water balance is completely controlled by the area of the SCM – the larger the area ratio, the larger fraction is evaporated, and the hydraulic conductivity does not influence this. The evaporation fraction varies approximately between 25 and 37%, so it is relatively stable compared with the other fractions.

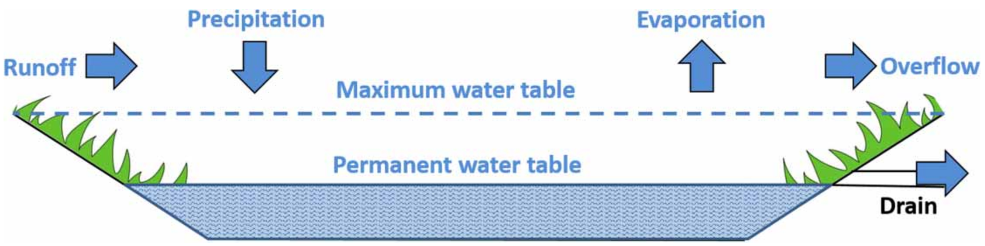

Figure 7 | Schematic illustration of the wet detention pond model.

Table 3 | Parameters used for simulating the wet detention pond in SWMM

Layer	Parameter	Unit	Value/range	Group	Notes (based on Hvitved-Jacobsen *et al.* (1994) and Danish design practice
Permanent pool	Volume	mm	25	2	Expressed relative to the total contributing area
	depth	m	1	2	Shallow ponds are more vulnerable to resuspension of settled matter while deeper ponds are subject to oxygen depletion during the summer season.
	Width/length ratio	(–)	1/3	2	The flow path should be maximized to secure settling
	Side slopes	(–)	1/3	2	Minimum side slopes for safety and maintenance
Storage volume	Volume	mm	2–148	1	Expressed relative to the total contributing area
	Width/length ratio	(–)	1/3	2	Same as for the permanent pool
	Side slopes	(–)	1/3–1/9	1	The gentler the slope, the more accessible the pond is to the public (adding recreational value)
	Drainage flow	(l/s/ha)	0.5–100	1	Decreed by local authorities, critical for the return period of overflow
	Maximum area	m^2/ha	350–8,700	2	Calculated based on the volume and side slopes

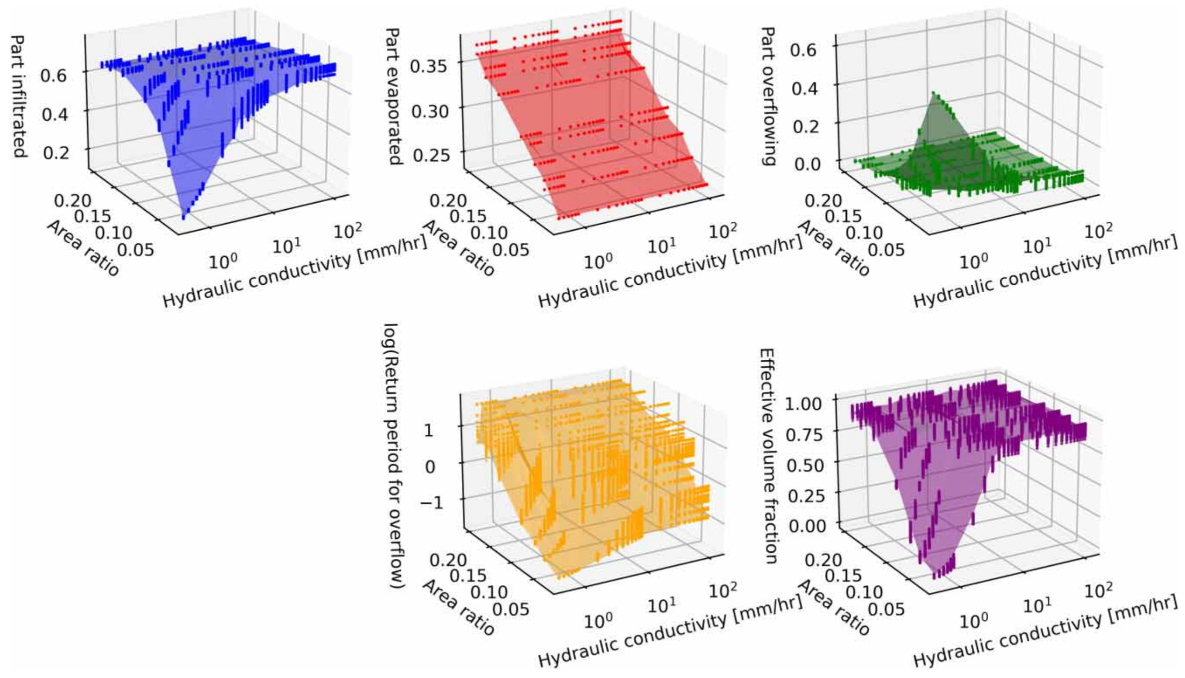

Figure 8 | Illustration of the water balance components (infiltration, evaporation, and overflow), the return period for overflow, and the effective volume fraction as a function of hydraulic conductivity of the native soil and the area ratio of the SCM to the runoff catchment, for a bioretention unit with infiltration to native soil and no drainpipe (SCM type 1). The vertical lines of dots represent differences in installed storage volume for equal area ratios and hydraulic conductivities. The planes are fitted as the equally weighed mean for each point.

(2) The infiltration fraction and the overflow fraction have inverse patterns: Systems with high area ratio and high soil infiltration reaches a threshold of 60% infiltration with no or very small overflows. Systems with low area ratio and low native soil infiltration capacity have a very low infiltration fraction. There seems to be a combination of parameters that essentially leads to the SCM being a delayed runoff system, since the majority of the water is overflowing. To avoid this, bioretention units which empty only through infiltration should be avoided if, e.g., the bioretention unit cannot be allocated an area ratio of at least 5% or the native soil has a hydraulic conductivity below 2 mm/h, to make sure that less than 10% percent of the water ends up as overflow.

(3) The return period of overflow follows a pattern closely related to both the infiltration and the evaporation. Not surprisingly, when these fractions are high, less overflow occurs, and the overflow return period becomes high. There is a relatively large variation for similar area ratios and hydraulic conductivities, which is caused by variations in the installed volumetric capacity of the SCM (e.g., variations of thickness of the storage layer as explained in Table 1, expressed in Figure 8 as the vertical lines of dots most clear in the infiltration sub plot). Larger capacity results in slightly higher return period of overflow, but the area ratio and hydraulic conductivity have a much larger influence on the return period of overflow.
(4) The effective volume fraction is closely linked to the infiltration fraction. SCMs with good infiltration capacity will drain fast and be close to empty when the next rain event occurs, whereas SCMs with little infiltration capacity will drain slowly and may not be empty when the next rain event occurs (since this bioretention type has no drainpipe, and evaporation is very slow).

Figure 9 illustrates the KPIs for a bioretention unit that is also equipped with a drainpipe (SCM type 3). Here, the fraction evaporated is the same as in Figure 8 (bioretention units with no drainpipe), while the sum of the fraction infiltrated and the fraction drained is nearly constant, and the part overflowing is always very low (less than 8%), and mostly dependent on the area ratio. The return period of overflow is likewise only dependent on the area ratio. The effective volume fraction still has some dependence on the hydraulic conductivity, but the large variations within similar area ratios and hydraulic conductivities show that this is also very much dependent on other parameters: the installed volume capacity has some influence (as discussed for Figure 8), but here also the offset and drain rate capacity of the drainpipe are influential, especially for situations with low area ratios and low hydraulic conductivities, where the drain is almost exclusively responsible for emptying the SCM (Figure 10).

These analyses demonstrate that the SWMM simulations result in consistent results between parameter combinations for each SCM type as well as between SCM types with marginal differences (e.g., the different bioretention units investigated), i.e., small changes in the input generally lead to small changes in the output. Figure 8 shows how the water balance components behave quite linearly as a function of relative SCM size (area ratio) and infiltration capacity in the native soil, and Figure 9 shows how introduction of a drainpipe can modify the SCM performance and further reduce the amount of water that overflows from the SCM.

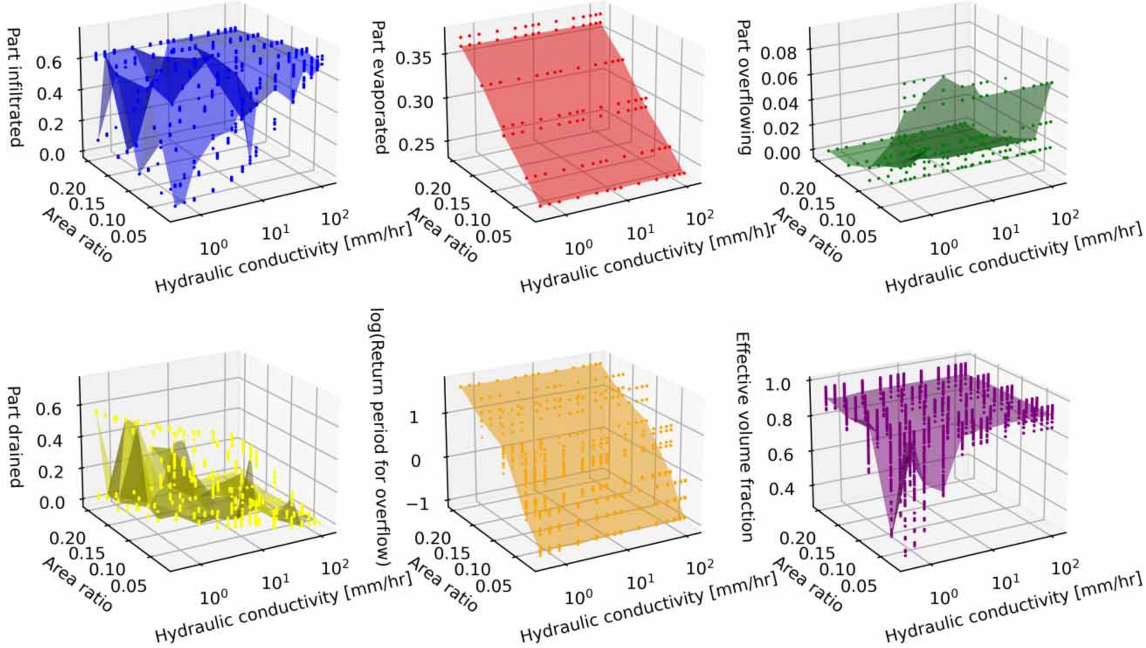

Figure 9 | Illustration of the water balance fractions (infiltration, evaporation, drain, and overflow), the return period for overflow, and the effective volume fraction as a function of hydraulic conductivity of the native soil and the area ratio of the SCM to the upstream catchment, for a bioretention unit with infiltration to native soil and a drainpipe (SCM type 3).

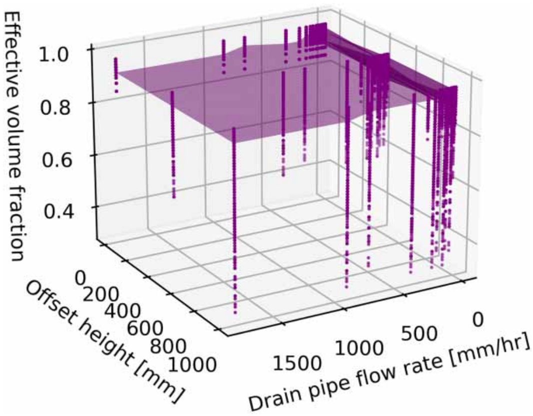

Figure 10 | The effective volume fraction as a function of the drainage capacity and the offset height of the drainage pipe for a bioretention unit with infiltration to native soil and a drainpipe (SCM type 3).

3.3. Use case: site-specific screening of SCM options using the inventory

To make the inventory accessible to end users we developed a user interface in Excel. In the following we illustrate a hypothetical use case, where a user investigates the performance of different SCMs at a typical Danish site.

Figure 11(a) illustrates how the different SCMs perform given an area ratio of 0.075 and relatively low hydraulic conductivity of 2×10^{-7} m/s. The different SCMs have parameters that can be tuned (group 1), but for this example we kept the parameters that are common for different SCM type constants. As Figure 11(a) nicely illustrates, the different SCMs have different hydraulic and hydrologic performances, indicated by differences in their water balances as well as in differences in effective volume fraction and return period for overflow. Figure 11(b) illustrates the same SCMs where the infiltration capacity of the native soil is more favourable (2×10^{-6} m/s). In either scenario the user can tune parameters for an SCM that seems promising until the performance is optimal, and thus a qualified provisional design can be settled until later planning stages require more detailed dimensioning.

Figures like this may help decision makers realize that they must survey the hydraulic conductivity at the site. Given that they trust their knowledge of the hydraulic conductivity, they may be able to quickly rule out SCMs that perform very badly under low conductivity conditions, or, in the opposite situation, where conductivity conditions are favourable, they could rule out SCMs that lead large volumes directly to the sewer system or receiving waters.

One interesting detail to observe in Figure 11(b) is that the soakaway seems to perform better (more infiltration, higher return period for overflow) than the most basic bioretention unit, even though the latter has more volume. This is a consequence of the infiltration rate through the intermediate soil layer in the bioretention unit being a limiting factor for high intensity rainfall events (120 mm/h $= 33.3 \times 10^{-6}$ m/s, which is very close to the soil hydraulic conductivity), where the bioretention unit will overflow even though the underground storage volume is not fully utilized. In reality, in Denmark, bioretention units are often installed with a by-pass (from the surface layer to the storage layer) to avoid this limitation (accepting that a negligible amount of pollution will follow); such by-pass can unfortunately not be included in SWMM's LID module for bioretention units.

4. DISCUSSION

Our inventory was created to fit Danish conditions in terms of climate variables as well as choice of KPIs, SCM types, and SCM plausible designs (through choice of model parameter ranges). These inputs and definitions must be adapted if the methodology is to be implemented in other settings. The Danish climate zone is temperate, relatively cold and moist, entailing relatively low rates of evaporation. In drier and warmer climates, the evaporation fraction of the water balance is expected to be larger. Soils in Denmark have a very broad range of hydraulic conductivity, starting at very low rates for clayey soils, which limit the infiltration fraction substantially. In regions dominated by more sandy soils, the infiltration fraction is expected to become larger, which also entails that lower area ratios become more feasible.

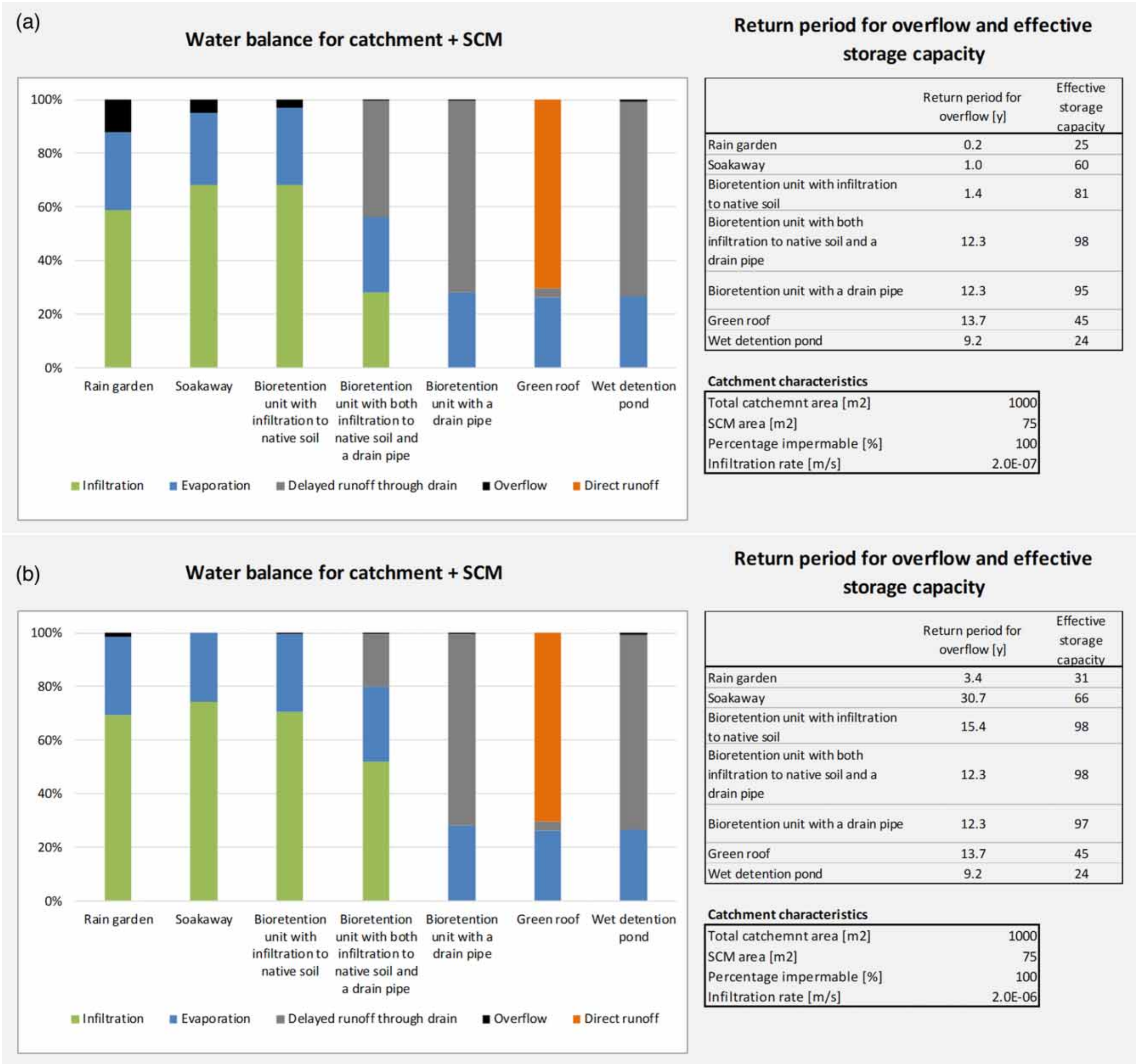

Figure 11 | Example of expected KPIs of different SCMs given the same boundary conditions in the form of the catchment area, SCM area, and hydraulic conductivity of the native soil.

SCMs are often constructed in series, also denoted treatment trains, to increase overall performance through larger overall volume and complementary features. It would be great if the inventory could be used to predict the performance of SCMs in series, but non-linear performance such as seen in Figure 9 jeopardizes such calculations. Predicting performance of SCMs in series is only possible for certain combinations of SCM trains or for making crude assessments (for a study of the challenges in simulating performance of SCMs in series see Sørup & Lerer (2021)).

Further work is needed on tools that enable assessments like the one developed here. Modelling concepts of the past consider well constrained problems with corresponding specialized tools, e.g., sewer system models, groundwater models, and river models. Today's more mixed and complex framings require new tools that can bridge traditional water analysis tools. Our work included both hydraulic and hydrologic aspects of SCMs but neglected other important aspects such as water quality, impacts on micro-climate and the potential to mitigate urban heat island effects, recreational value, and more. It is equally important to develop more simplified tools for end users, but still based on sufficiently complex modelling, targeted at non-water-professionals, so that all the important aspects of water management can be duly considered in early planning and design phases. This cannot be done without compromising complexity and risking misuse, but the potential gains in improved sustainable management of water outweighs the risks of 'too creative' solutions (which would be identified and corrected in later design phases where the water-professionals get called in).

5. CONCLUSIONS

We successfully developed a methodology that enabled us to create an inventory of SCM performance covering both hydraulic and hydrologic impacts. The methodology involves identifying relevant SCM types and designs as well as relevant KPIs in collaboration with end users; setting up appropriate models of in SWMM and choosing appropriate model parameters and parameter ranges; building a code package in python that uses PySWMM to automatically run the (very large) number of simulations that was necessary to cover the parameter spaces; post-processing the simulation results into KPIs; and storing the results in an SQLite database that enables fast lookup of plausible SCM configurations. We showed that the inventory can be analysed to bring forth some general recommendations regarding design of SCMs under Danish conditions such as critical hydraulic conductivities in native soils. Furthermore, we developed a user interface for the inventory, which can be used for screening SCM options for specific sites in early design phases. This empowers end users without hydrological modelling skills, such as architects and urban planners, to make qualified preliminary designs for managing stormwater in a local and sustainable manner.

The developed inventory for Danish conditions in the form of an SQLite database is available through Lerer *et al.* (2022). The Excel-based user interface to the inventory (in Danish) can be downloaded from https://www.klimatilpasning.dk/vaerktoejer/lar-potentiale/.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories https://doi.org/10.11583/DTU.20971198.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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