Water Science & Technology

© 2022 The Authors Water Science & Technology Vol 00 No 0, 1 doi: 10.2166/wst.2022.023

Revising green roof design methods with downscaling model of rainfall time series

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ABSTRACT

Historically, green infrastructure for stormwater management has been event-based designed. This study aims to realign the green infrastructure design strategies with principles for robust decision making, through the example of green roofs design with the variational method and exemplified using the Norwegian context of the 3-step approach (3SA) for stormwater management. The 3SA consists of planning solutions to handle day-to-day rain at site scale through infiltration (step 1) and detention (step 2), and extreme events with safe floodways (step 3). An innovative framework based on downscaling of rainfall timeseries is suggested as follows: (i) long duration continuous simulation for retention variation and day-to-day discharge, corresponding to step 1 in the 3SA; (ii) intensive sampling of local extreme events to estimate reliability and robustness of solutions, corresponding to steps 2 and 3 in the 3SA. Comparing the traditional variational method to Highly-Informed-Design-Evaluation-Strategy (HIDES), it was found that the variational method possibly leads to incorrect decisions while the suggested novel approach was found to give more informed and reliable results by suggesting a design based on both operating mode and failure mode. It allows to embed solutions within the urban water system by facilitating the link between the steps of the 3SA. Such a framework was found to be data-wise applicable in the Norwegian context.

Key words: continuous simulation, event-based simulation, green infrastructure design, robust decision making, temporal downscaling

HIGHLIGHTS

- Variational Method for design was found to provide unreliable estimates compared to Local Event Sampling and continuous simulation.
- The HIDES framework for aligning design methods with the principle of robust decision making is developed.
- Continuous simulation and Local Event Sampling are necessary for overview of hydrological behaviour of the stormwater solution.

INTRODUCTION

In Norway, stormwater management follows a 3-step approach (3SA) (Lindholm *et al.* 2008). Different solutions at different scales (site-scale, neighbourhood scale, catchment-scale) are designed to cope with events of different magnitudes and return periods (RP). The approach is similar to many other countries around the world aiming to infiltrate small events, detain larger events and safe passage of larger more extreme events (e.g. 3PA in Denmark (Fratini *et al.* 2012)). There is still no consensus in Norway on which RP thresholds to apply to which steps (Paus 2018). However, designing solutions according to this philosophy requires quantification of their robustness and resilience (Liao 2012), which means studying their behaviour under failure condition (i.e. under rainfall events larger than the design events). Ultimately, the objective of the 3SA approach is to provide a decision-making-support framework to select robust or adaptative solutions to cope with increasing urbanization, climate change, and deep uncertainty (Walker *et al.* 2013).

The hydrological benefits for local green infrastructures, such as green roofs, lie in restoring the natural water cycle through retention (infiltration and evapotranspiration), detention, and efficient urban space management. Although some green roofs can be used to attenuate high RP events (e.g. >20-year RP) (Hamouz *et al.* 2020), they are usually not designed to cope with larger events.

Green infrastructures and green roofs are often sized using methods with design events (Kommune 2015; Kristvik *et al.* 2019) based on Intensity Duration Frequency (IDF) curves. These methods rely on design hyetographs that may be based on historical events or on predefined shapes such the Chicago-type hyetograph, the Blue hyetograph or constant intensity events (e.g., the rational method, RM, or the variational method, VM) (Alfieri *et al.* 2008). The design methods using such kind of events rely usually on a single hyetograph or a limited number of hyetographs. This design approach, selected to facilitate design with limited climate data (IDF curves and climate factors), is therefore not consistent with the 3SA for several reasons: (i) it investigates neither day-to-day rainfall (only detention according to a design rainfall event) nor rainfall lying in the failure domain (i.e. larger than design RP), (ii) it does not investigate long-term retention performances, and (iii) it does not provide information on the robustness of the solution.

Statistical temporal downscaling models allow to generate weather time series and especially precipitation time series. Some multiplicative random cascade models also include temperature dependence in order to improve the robustness of the models under climate change (Bürger *et al.* 2014, 2019; Pons *et al.* 2021).

This study aims to improve the green infrastructure design strategies through a method that realigns with robust decision-making principles. It is here exemplified for green roofs, in the Norwegian context of the 3-step approach as a case study, by proposing a framework including performance assessment for future climatic conditions using a downscaling model of rainfall time series. The new design framework will be demonstrated by addressing the following aspects: (i) Evaluating the limits of the VM by sampling local events to evaluate the distribution of performance depending on the RP and performing continuous simulation, (ii) Comparing the performance and robustness of different solutions similar in terms of VM-design, (iii) Suggesting additional steps to design practice to restore consistency with the 3SA.

METHODOLOGY

The methodology used in this work includes the following steps:

i) input data generation: design rainfall events, stochastic extreme rainfall events and future stochastic rainfall time series,
ii) input data applied to two different green roofs (extensive green roof and detention based green roof),
iii) performance analysis depending on the type of input,
iv) analysis of four different scenarios similar according to design rainfall events.

Downscaling model and event sampling strategy

A climate-change-robust downscaling model based on multiplicative random cascades was developed to generate rainfall time series for different cities in Norway and France (Pons *et al.* 2021). In this study, the model calibrated for Trondheim was used together with IDF curves to generate random extreme events for each RP (Local Event Sampling, LES). A climate factor of 1.4 was used to account for climate change (Dyrrdal & Førland 2019). The depth corresponding to 24-hour precipitation with each RP was downscaled from 1 day to a 6-minute timestep. The process was repeated to obtain 10^5 hyetographs for each RP.

Green roof model

Similarly to Pons *et al.* (2021), two green roofs were modelled in this study: an extensive green roof (E-green roof) and a detention-based extensive green roof (D-green roof). The model is based on a non-linear reservoir. In order to increase the robustness of the model and its range of validity under extreme events, the model was calibrated using data from extreme tests previously performed on a large scale pilot roof (Hamouz *et al.* 2020). Three parameters control the discharge function of the roof: (i) WC_0 represents the minimum water content in the roof to fully trigger the roof, (ii) S_k represents the transition from a dry roof to wet roof, (iii) K represents the slope of the outflow curve when the roof is fully triggered. The E-green roof consists of a 30-mm layer of substrate with a 10-mm layer of storage. It was represented with a single discharge function. The D-green roof consists of one 100-mm layer of clay aggregates and one 30-mm layer of substrate. It was represented with the sum of two discharge functions, one for each layer.

Performance evaluation

The 2015 regulations for the city of Trondheim (Kommune 2015) were used to set thresholds for appropriate comparison. The regulation for local stormwater management set the peak discharge allowed to be released in the sewer system during a 20-year RP rain event. When connected to a separate sewer system, the threshold is 6.4 L/s for a 800 m^2 area. When the area is connected to a combined sewer system, the threshold is stricter, 1.65 L/s for 300 m^2. Those two thresholds were used as references for two possible regulations in this study. For comparison purposes, they are converted and normalized as 0.48 mm/min and 0.33 mm/min.

Three performance evaluation strategies were used:

- The variational method (VM) (Alfieri *et al.* 2008) to account for strategies with a low number of events. It consists in using the constant intensity rainfall leading to the worst peak runoff according to each IDF curve.
- A continuous simulation (CS) to i) evaluate performances based on runoff distribution and ii) estimate the mean annual duration of runoff above threshold accounting for natural variation of the climate. It also allows evaluating the annual retention. A 29-year long time-series was used for this simulation.
- Local Event Sampling (LES) to sample a large number of probable hyetographs ($N=10^5$) according to the location and downscaling model properties. It allows to estimate the probability to cope with a RP rain under future climate conditions in accordance with the guidelines.

Scenario comparison

To analyse the consequences, in terms of hydrological performances, of sizing a solution with the VM, four different scenarios for the E and D green roofs were designed to cope with a 20-year RP in Trondheim according to the VM (Table 1). The resulting solutions were then evaluated using the LES and CS methods. The first scenario is based on the D-green roof and an impervious area. The minimal fraction of roof necessary to meet the discharge requirement was chosen. The second scenario was based on the E-green roof with an extra storage layer. The third scenario was based on a combination of both the E and the D green roof. The minimal proportion of D-green roof meeting the requirement was chosen. The fourth scenario was based on the E-green roof, with an outflow controller with limit set to, and an extra storage in the substrate media. The depth was set to the minimum depth, ensuring no overflow.

Framework for robustness assessment: Highly Informed Design Evaluation Strategy (HIDES)

The different solutions designed through the VM can be analysed with the framework presented in Figure 1. The approach is divided in three complementary approaches: (i) the long term simulation answering the question '*How is the solution going to behave in operating state?*' and corresponding to the first step of the 3SA (i.e. assessing the benefits that the solution is supposed to provide, retention and mild rain detention), (ii) the event based simulation to answer the question *'How is the solution going to behave under failure state?'* corresponding to steps 2 and 3 of the 3SA, and (iii) the climate change robustness answering the question '*Is the behaviour of the solution expected to be stationary?*' corresponding to the philosophy behind the 3SA.

RESULTS AND DISCUSSION

Green roof performance analysis

The comparison between VM and LES is shown in Figure 2 for current climates (opaque distributions) and future climate projections (transparent distributions) through the use of a 1.4 climate factor (Dyrrdal & Førland 2019) according to different RP (2-year on top to 200-year at the bottom). The performances of the E-green roof (left) and the D-green roof (right) are displayed. The VM led to single point estimates (blue dots). In the case of the D-green roof, VM tends to estimate a lower peak runoff than the mode of the LES distribution. For the E-green roof, similar observations appeared only for the 2-year RP events. It indicates that the VM is not necessarily conservative since, depending on the solution, a significant proportion

Table 1 | Details of the different scenarios designed using the VM to cope with a 20-year RP rain event

Solutions' components	Scenario 1 (Det)	Scenario 2 (Spl)	Scenario 3 (Mix)	Scenario 4 (Sto)
E-green roof	–	100% with 7.75 mm of extra storage	47% of the area	100% of the area
D-green roof	29% of the total area	–	53% of the area	
Other	71% of the total area discharging in the D-green roof	–	–	Discharge constrictor: 0.33 mm/min Equivalent storage: 1.3 mm/m^2

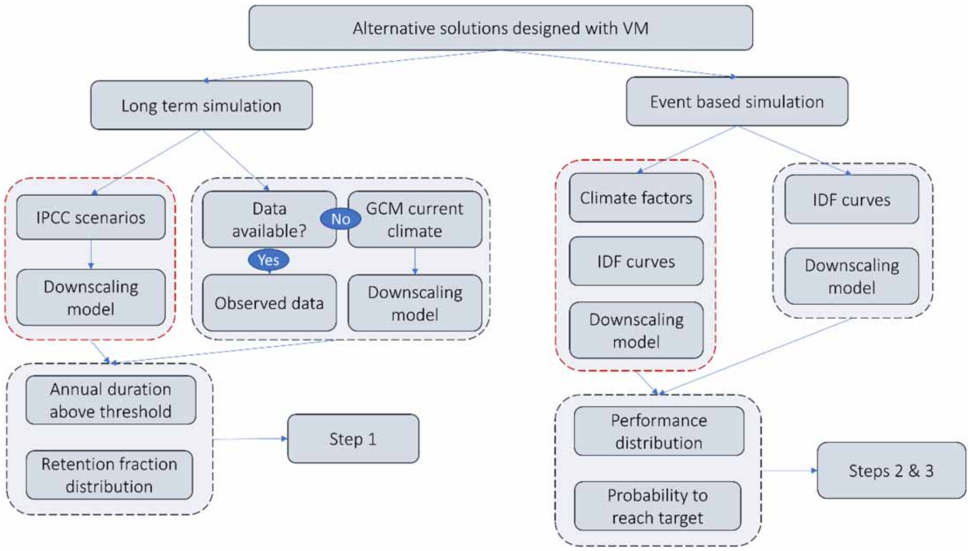

Figure 1 | HIDES framework for performance estimation and robustness assessment of designed solution, the red dotted line relates to climate change assessment. IPCC: Intergovernmental Panel on Climate Change, GCM: Global Circulation Model.

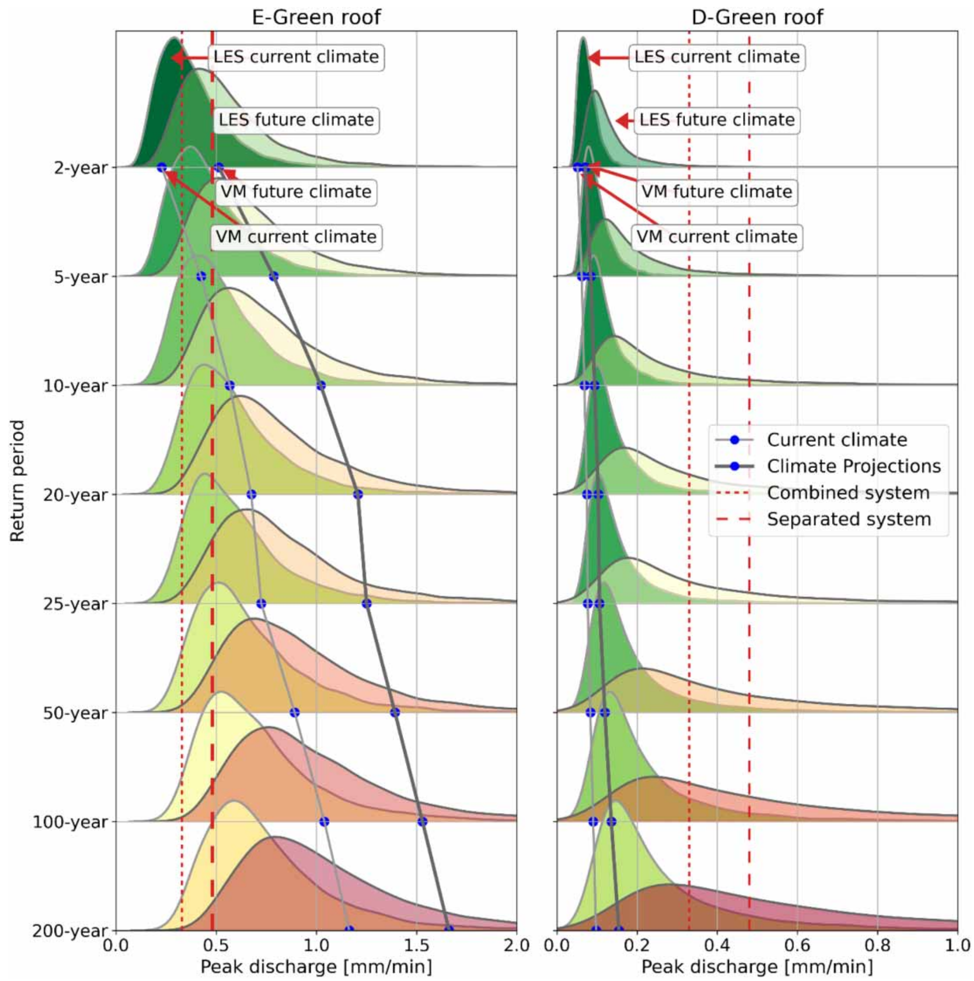

Figure 2 | Predicted peak runoff of the E-green roof (left) and the D-green roof (right) using variational method (thick grey line with blue dot markers) and local event sampling (distributions) under current climate (light grey) and projected climate RCP 8.5 (dark grey). The colour of distribution is conditioned by the centroid value: green for low, yellow for medium and red for high.

of hyetographs led to higher peak runoffs than the VM. For the D-green roof and a 20-year RP event in a current climate, 96% of the simulated events led to a peak runoff less than the 0.33 mm/min threshold (resp. 79% with climate factor). For the E-green roof only 10% of the peak runoff values were less than the threshold (resp. 0.5% with climate factor).

The robustness and reliability of a solution in terms of hydrological performance can be defined with regard to the distributions displayed in Figure 2. A distribution with similar orders of magnitude of deviation under different return periods and climate factors is considered reliable, indicating no shift in the performance range. A solution that meets the target under a large range of return periods and climate factors is robust (static robustness as defined by Walker *et al.* (2013)). Considering the 0.48 mm/min threshold, the E-green roof is reliable, but not robust. It has a deviation range from 0.17 to 0.45, and under high RP it can deal with fewer than 10% of the events. On the contrary, the D-green roof is robust as it can handle more than 50% of the events up to a 200-year RP with a 1.4 climate factor, but not reliable as the order of magnitude of its standard deviation changes from 0.02 to 0.5 with larger return periods.

Return periods larger than 20-year can be considered as the failure domain of the roofs in the second step of the three-step approach. The roofs are not designed to cope with those events; however, quantifying their behaviour within this failure domain can help to make a more informed decision when dealing with the next steps. Since the VM cannot estimate reliability and robustness of the solutions, it can result in wrong decisions or missed opportunities.

Table 2 shows the probability to reach the target depending on the green roof type, the return period and the method used. For example, considering the D-green roof, the probability to reach the target under a 200-year RP with a 1.4 climate factor was only 0.33 with LES contrary to 1 using the VM. Table 2 highlights that the VM does not allow the user to take a well-informed decision due to the nature of boolean estimates. They provide a deterministic value for each return period, while the solution behaviour differs depending on the hyetograph. Moreover, it should be pointed out that the shape of the hyetograph based on the VM (e.g. constant intensity rainfall) does not depend on the location. On the other hand, the LES method provides more robust estimates of the performance because a larger diversity of events likely to occur in the specific location are sampled, like in this case Trondheim, including events able to trigger high runoff discharge in each type of roof. In previous studies (Hamouz *et al.* 2020), the D-green roof was found sensitive to specific types of hyetographs, which supports the use of LES method. The VM does not include such hyetographs, which leads to low representativeness of the estimates. For comparison, a CS allows to estimate mean annual runoff duration above threshold, which would be low than 4 minutes per year in the case of the E-green roof, and 0 minutes for the D-green roof. The CS method is highly dependent on data availability, but directly estimates frequency of exceeded thresholds without using IDF curves or events.

Scenario robustness and reliability analysis

Figure 3 shows the cumulative distribution of peak runoff for different return periods based on the LES method for each of the solutions (Table 1). For the 2-year RP, 90% of the events were below 0.33 mm/min for the scenario 3 against only 50% of the events for the scenario 2. The figure also shows the proportion of events sampled above the VM estimates (dotted lines). For

Table 2 | Probability to reach the 0.33 mm/min target depending on the green roof, the return period and the method used

	E-green roof				D-green roof			
	Current period		With climate factors		Current period		With climate factor	
	LES	VM	LES	VM	LES	VM	LES	VM
2-year	0.45	1	0.14	0	1	1	0.98	1
5-year	0.26	0	0.04	0	1	1	0.88	1
10-year	0.16	0	0.01	0	0.98	1	0.79	1
20-year	0.10	0	0.005	0	0.96	1	0.68	1
25-year	0.09	0	0.003	0	0.95	1	0.65	1
50-year	0.05	0	0.001	0	0.90	1	0.53	1
100-year	0.03	0	0	0	0.84	1	0.41	1
200-year	0.01	0	0	0	0.77	1	0.33	1

The variational method (VM) can only provide a Boolean estimate.

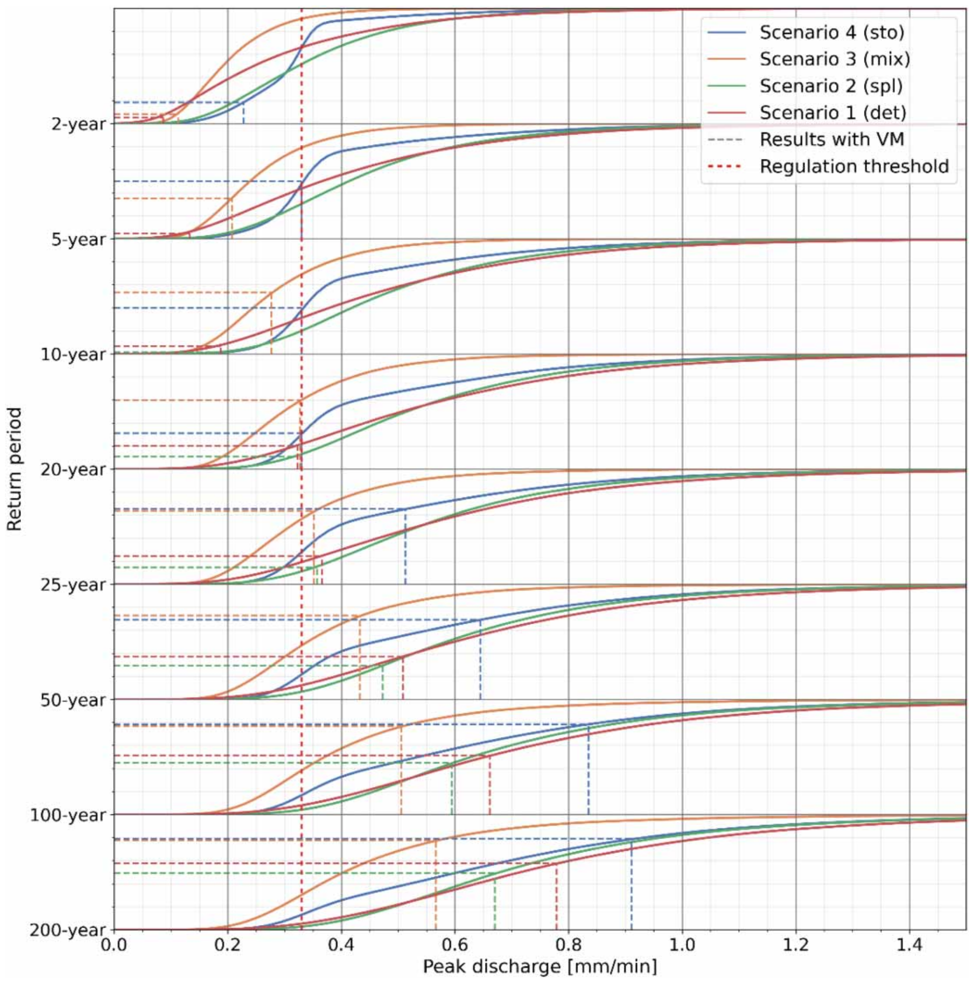

Figure 3 | Cumulative distribution functions for the four scenarios with the proportion of events below the estimate based on the variational method for different return periods.

the 50-year RP rainfall, the VM-estimate was above 70% of the events for scenario 3 and 4 against 30–40% for scenario 1 and 2. For the 20-year RP, the value of the VM-estimate is equal to 0.33 mm/min for each scenario since the solutions were designed using the VM.

According to the LES method and previously defined criteria, the scenario 3 is the most robust and reliable solution. It relies on a combination of both types of green roofs, and since each type of green roof is sensitive to a different type of rainfall, using both types of green roofs in a combined solution results in a solution that is able to cope reasonably well with most of the possible hyetographs. Such a property could not be demonstrated using the VM. The scenario based on a fraction of D-green roof (scenario 1) shows a great robustness to low return periods (<10-year) but behaved similarly to scenario 2 for larger return periods. The D-green roof had a larger storage capacity, which can handle a high volume of water without high runoff, but when the water content reaches the critical parameter $WC_{0,subs}$ the discharge increases rapidly. Table 3(a) shows the probability of reaching the threshold 0.33 mm/min for each scenario depending on the return period, including the 20-year RP for which the different scenarios have been designed. The table also shows the duration above threshold (ADT) in minutes calculated from the CS on an annual basis. For scenario 1 the ADT was found to be between 4 and 104 minutes, indicating a regular exceedance of the threshold value. On the other hand, the annual durations above threshold value for the other scenarios are all below 10 minutes. The use of a continuous simulation shows the capacity of the roof under operational conditions, where the D-green roof has a long detention time and therefore a higher risk of not being drained before the next event occurs (Hamouz *et al.* 2020). Table 3(b) shows the 95% shortest coverage interval (i.e. the shortest interval including 95% of the values, similar to a deviation-based confidence interval but more appropriate for skewed

Table 3 | (a) Probability to reach the threshold depending on the return period according to the LES method: Annual Duration above Threshold (ADT) using the CS method and (b) 95% shortest coverage interval of discharge depending on the return period

(a) Return Period	2-year	5-year	10-year	20-year	25-year	50-year	100-year	200-year	ADT (min)
Scenario 1	0.67	0.44	0.31	0.21	0.19	0.11	0.07	0.05	4–104
Scenario 2	0.52	0.30	0.19	0.12	0.10	0.06	0.03	0.02	0–4
Scenario 3	0.91	0.79	0.69	0.60	0.57	0.74	0.39	0.30	0–4
Scenario 4	0.67	0.5	0.40	0.31	0.29	0.21	0.16	0.12	0–8

(b) Return Period	2-year	5-year	10-year	20-year	25-year	50-year	100-year	200-year
Scenario 1	0.05, 0.72	0.09, 0.95	0.09, 1.05	0.12, 1.18	0.14, 1.22	0.17, 1.34	0.2, 1.44	0.22, 1.55
Scenario 2	0.1, 0.7	0.15, 0.87	0.18, 0.98	0.19, 1.09	0.21, 1.12	0.23, 1.22	0.27, 1.31	0.28, 1.41
Scenario 3	0.08, 0.39	0.1, 0.48	0.12, 0.54	0.13, 0.61	0.13, 0.64	0.16, 0.73	0.16, 0.81	0.17, 0.92
Scenario 4	0.12, 0.6	0.16, 0.79	0.19, 0.92	0.21, 1.05	0.21, 1.07	0.25, 1.21	0.26, 1.28	0.3, 1.41

distributions). According to the coverage intervals, Scenario 3 is robust and reliable. Scenario 2 was less robust and Scenario 1 is less reliable.

Figure 4 shows the results of the different scenarios based on CS. This allowed to estimate both retention metrics (e.g. retention fraction) and detention metrics (e.g. extreme values of discharge). The left plot with survival distributions can be used in a similar manner to flow duration curves, allowing estimation of the exceedance duration frequency. The probability for the discharge to exceed the threshold was found to be reasonably low for Scenarios 2, 3, and 4, but as stated in Table 3(a), the probability is higher for Scenario 1 (i.e. the ADT). It can be explained by the characteristics of the D-green roof. The water is detained in the roof for a longer time, which makes this roof more sensitive to antecedent rain events. This also demonstrates the necessity of CS: the event-based methods used in this study do not take into account antecedent rain.

In the context of CS, i) a solution is more reliable than another if the standard deviation is smaller, and ii) a solution is more robust than another if the mean performance is better. The right plot in Figure 4 shows that the retention fraction for Scenario

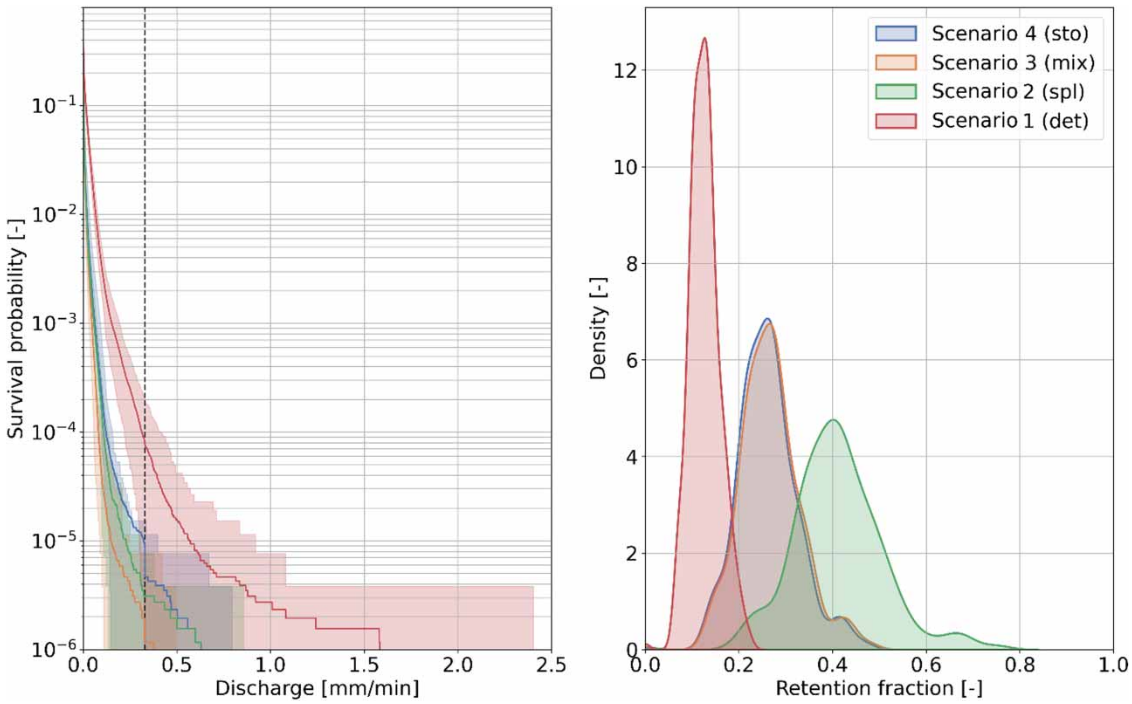

Figure 4 | Comparison of scenario using continuous simulation (CS). Survival distribution of discharge 5th and 95th percentile distribution using a 3-year moving window (shaded area) and 29-years long time series (full line) (left). Distribution of Retention fraction (right).

1 was lower, with a smaller deviation than with other scenarios. It is the less robust scenario but the most reliable. The roof covers only 29% of the area, which directly affects the retention fraction. On the opposite, Scenario 2 with an E-green roof and extra storage layer results in a higher retention fraction; however, the deviation of this retention fraction is higher than with other scenarios (ranging from 0.2 to 0.6 with a mode at 0.4), which indicates a lower reliability.

Design application potential

The proposed HIDES framework for green roof design is depicted in Figure 1. The framework includes CS and LES of solutions that are designed with a single hyetograph and will guide the user to select the most robust and reliable design. The CS will provide basis for decision making in step 1 of the 3SA and will require either long time series with higher temporal resolution or a downscaling model and long daily resolution time series. Since the distribution of retention fraction can be estimated based on a 1-year-long moving window with a step of 1 month, a minimal duration of 20 years leading to a distribution estimated with kernel density based on more than 200 points is suggested. The local event-based approach will provide a basis for decisions related to steps 2 and 3 in the 3SA and will require IDF curves and a downscaling model. The proposed framework is especially relevant in cities subject to increasing urbanization and climate change. In Norway, a downscaling model has already been developed for six large cities, and daily time series or projections are often available (Dyrrdal *et al.* 2018). In the case where no downscaling model is available, using a downscaling model calibrated in a similar area might add some uncertainty, but still can help understand the behaviour of the solutions, resulting in a more informed design than the one achieved through VM.

CONCLUSIONS

The VM was compared to LES and CS. The VM was found to fail to provide reliable estimates due to its single-estimate nature. The method was found to not necessarily be conservative depending on the roof, the return period and the climate condition. It demonstrated that in order to achieve a robust decision making following the 3SA philosophy, the method needs to be improved.

Four scenarios were designed to cope with a 20-year RP in Trondheim based on the VM. They were found to have significantly different hydrological behaviour, which cannot be highlighted using the VM. Following the 3SA philosophy and aiming for robust decision making, the four designed solutions were evaluated using a CS approach (for step 1) and the LES approach (for steps 2 and 3). The different solutions can be ranked according to different criteria and be used as the basis for a multi-criteria decision analysis depending on factor prioritisation (e.g. reliability and robustness).

The solution based on a mix of the two types of green roofs was found to be robust in terms of extreme events. The LES method demonstrated its robustness by sampling probable events. Both roofs being sensitive to different extreme events, the mixed solution could cope with a larger range of events (static robustness).

In countries such as Norway, sufficient data are freely available to apply such a design method, based on improving the VM with CS and LES to restore consistency with 3SA. The method proved to significantly improve the reliability and robustness of green infrastructure design.

ACKNOWLEDGEMENT

This study is part of a joint PhD between NTNU (Norway) and INSA Lyon (France) within the project Klima2050. It was realised within the Graduate School H2O'Lyon (ANR-17-EURE-0018) and Université de Lyon (UdL), as part of the programme 'Investissements d'Avenir' run by Agence Nationale de la Recherche (ANR).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

FUNDING

The study was supported by the Klima2050 Centre for Research-based Innovation (SFI) and financed by the Research Council of Norway and its consortium partners (grant number 237859/030).

DATA AVAILABILITY STATEMENT

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

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First received 10 January 2022; accepted in revised form 10 January 2022. Available online 25 January 2022