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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) to 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 step 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 lead 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.
- Developed HIDES framework for aligning design methods with the principle of robust decision making.
- 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 with a focus 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 require 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 designed using the rational or variational method (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 (variational and rational method) (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 neither investigates 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 allows 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 using green roofs, in the Norwegian context of the 3-step approach as a case, 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 VM-design, (iii) Suggest additional steps to additional design practice to restore consistency with the 3SA.

METHODOLOGY

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 on 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 was 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 represent 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 represent the slope of the outflow curve when the roof is fully triggered. The D-green roof consists of one layer of clay aggregates and one layer of substrate, it was represented with the sum of two discharge functions, one for each layer.

Performance evaluation

The regulations for the city of Trondheim (Kommune 2015) was used to set thresholds for appropriate comparison (it should be noted that new guidelines are in preparation in this city). The regulations for local stormwater management set the peak runoff discharge threshold to 0.48 mm/min (6.4 L/s) when connected to a separate sewer system and an area of 800 m^2 and 0.33 mm/min (1.65 L/s) for a combined sewer system and an area of 300 m^2 with regards to a 20-year RP rain event.

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 intensity duration frequency (IDF) curve.
- A continuous simulation (CS) to evaluate performances based on runoff distribution and estimate the mean annual duration of runoff above threshold accounting for natural variation of the climate. It also allows for evaluating the annual retention fraction. A 29-year long time-series was used for this simulation.

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

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 area	–	53% of the area	
Other	71%	–	–	Discharge constrictor: 0.33 mm/min Equivalent storage: 1.3 mm/m^2

- 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 based on the E and D green roofs were designed to cope with a 20-year RP in Trondheim (Table 1). The resulting solution where then evaluated using the LES and CS. The first scenario is based on the performance of the D-green roof, where the fraction of roof on the total surface is optimized. In the 2nd scenario the depth of an extra storage layer in the E-green roof was optimized. For the 3rd scenarios the optimal fraction of E and D green roof was found. The 4th scenario was based on a regular E-green roof, but the outflow was limited to the 0.33 mm/min threshold, to allow for extra storage in the substrate media. The depth of the discharge constrictor was set to ensure no overflow with the use of the VM.

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 approach: (i) the long term simulation answering the question '*How is the solution going to behave in operating state?*' and corresponding to the 1st step of the 3SA (i.e. assessing the benefits that the solution is supposed to provide, retention and mild rain detention), the (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, (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.

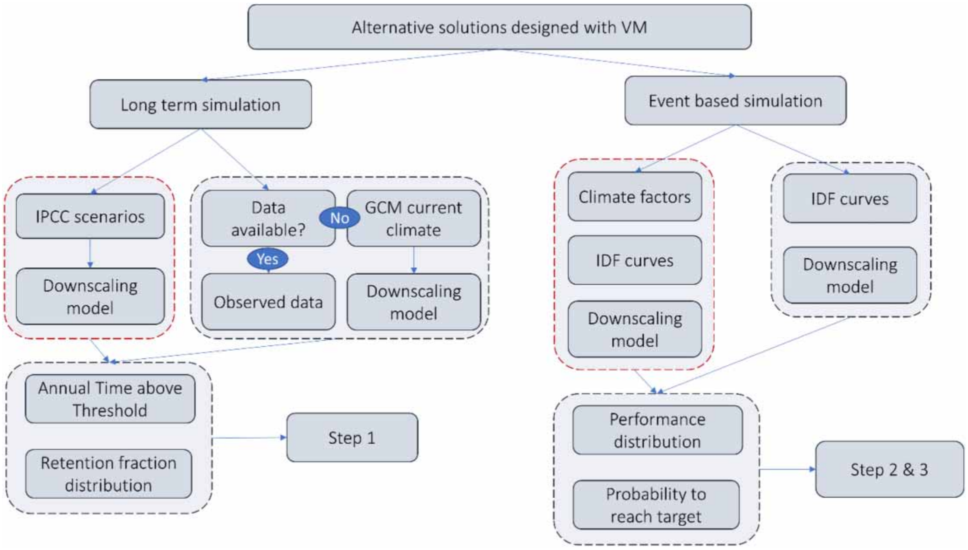

Figure 1 | HIDES framework for performance estimation and robustness assessment of designed solution, the red dotted line relates to climate change assessment.

RESULTS AND DISCUSSION

Green roof performance analysis

The comparison between the variational method (VM) and the local event sampling (LES) can be seen 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 in the bottom). The performance of the E-green roof (left) and the D-green (right) roof are displayed. The VM led to single point estimate (blue dots). In the case of the D-green roof, VM tend to estimate a lower peak runoff than the mode of the LES distribution. For the E-green roof, similar observations were only seen for the 2-year RP events. It indicates that the VM is not necessarily conservative. For the D-green roof and a 20-year RP event in a current climate, 96% of the simulated events lead to a peak runoff less than the 0.33 mm/min threshold (resp. 79% with climate factor). For the E-green roof only 10% 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 regards to the distributions displayed in Figure 2. A distribution with similar order of magnitude of deviation under different return periods and climate factor is considered reliable, indicating no shift in the performance range. A solution that meet 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 less than 10% of the events. On the contrary the D-green roof is robust as it can handle more

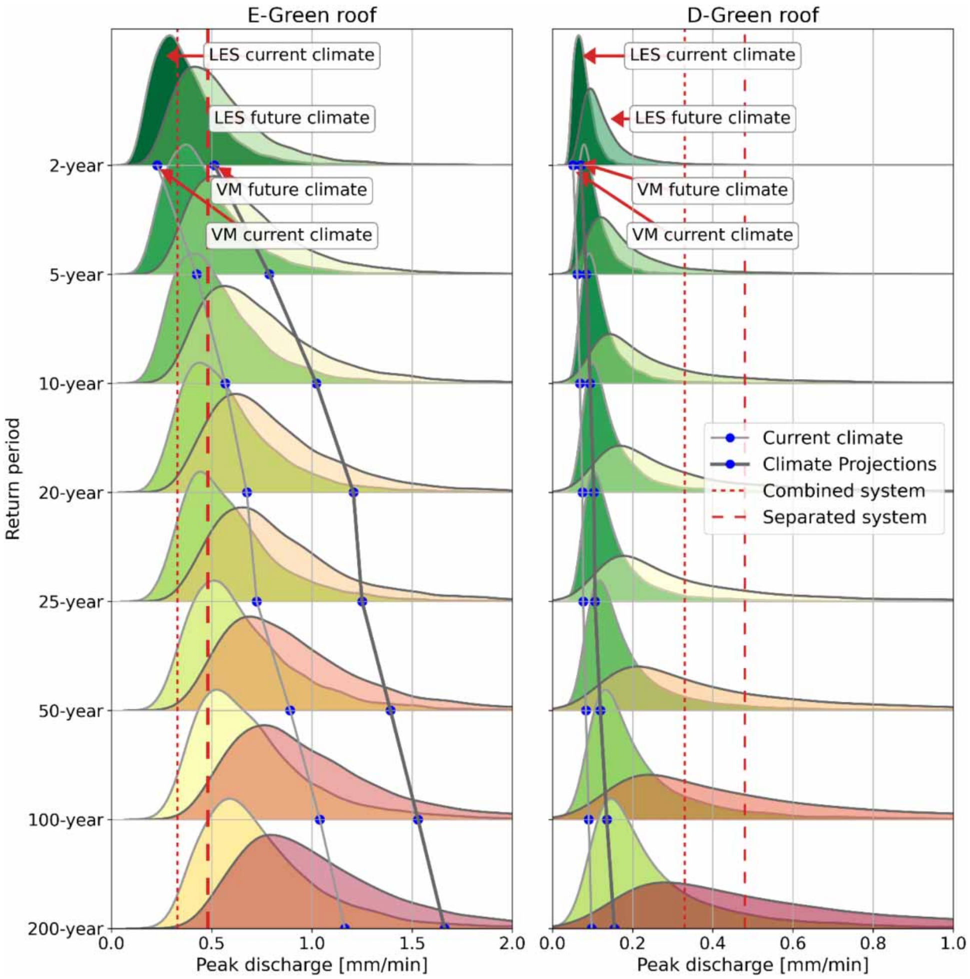

Figure 2 | Predicted peak runoff of the E-green roof (left) and D-green roof (right) using variational method (thick grey line with blue dot markers) and local event sampling (distributions) under current climate (light grey) and projected climate RCP 8.5 (dark grey). The colour of distribution is conditioned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

than 50% of the events up to a 200-year RP with a climate factor, but not reliable as the order of magnitude of its standard deviation change from 0.02 to 0.5 with larger return periods.

Return periods larger than 20-year RP can be considered as the failure domain of the roofs in the 2nd step of the 3-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, it can result in wrong decision or missed opportunities.

Table 2 shows the probability to reach the target depending on the green roof type, return period and method used. For example, considering the D-green roof, the probability to reach the target under and 200-year RP with 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. Moreover, it should be pointed out that the estimate with the VM hyetograph's shaped does not depend on the location. On the other hand, the LES method provides more robust estimates of the performance because a larger variety of events likely to occur in the specific location, like in this case Trondheim are sampled, 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 less representativeness of the estimates. For comparison, a continuous simulation (CS) allows to estimate mean annual runoff duration above threshold which would be less 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 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. This scenario 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 are 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 increased rapidly.

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.

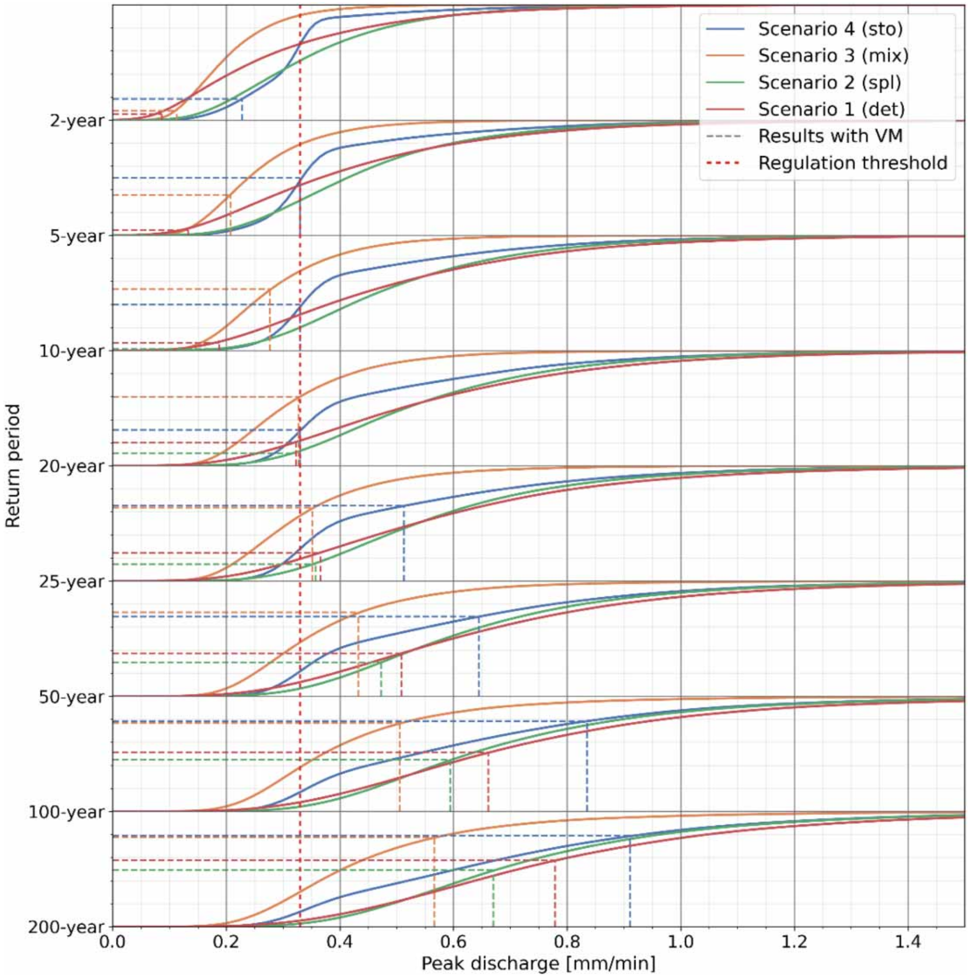

Figure 3 | Cumulative distribution function for the 4 scenarios with the proportion of events below the estimate based on the variational method for different return periods.

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 range of time above threshold (ATT) in minutes calculated from the CS on an annual basis. For scenario 1 the ATT was found to be between 4 and 104 minutes indicating a regular exceedance of the threshold value. On the other hand, the annual times above threshold value for the other scenarios are all below 10 minutes. The use of a continuous simulation shows the capacity of the roof in operating mode where the D-green roof has a long detention time and therefore a higher risks of not being drained before the next event occur (Hamouz *et al.* 2020). Table 3(b) shows the 95% shortest coverage interval (i.e. the shortest interval including 95% of the value, similar to a deviation-based confidence interval but more appropriate for skewed distribution). According to the coverage intervals, Scenario 3 is the most robust and the most reliable. The scenario 2 was the less robust and scenario 1 is the less reliable.

Figure 4 shows the results of the different scenario based on continuous simulations. Continuous simulation allowed to estimate both retention metrics (e.g. retention fraction) and detention metrics (e.g. extreme values of discharge). The left plot with survival distribution can be used in a similar manner to flow duration curves, allowing for estimating 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 ATT). It can be explained by the property of the D-green roof. The water is detained in the roof for a longer time which make this roof more sensitive to antecedent rain events. Which also demonstrates the necessity of CS: the event-based methods used in this study does not take into account antecedent rain.

Table 3 | (a) Probability to reach the threshold depending on the return period according to the LES method: Annual Time above Threshold (ATT) 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	ATT (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	

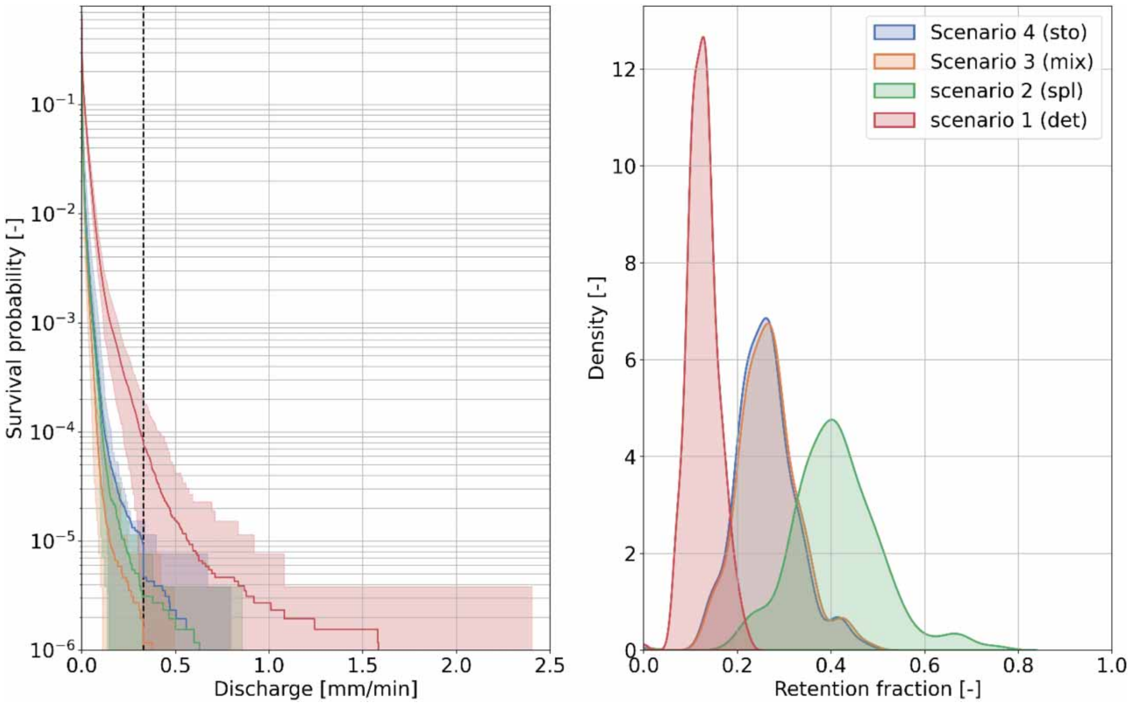

Figure 4 | Comparison of scenario using continuous simulation (CS). Survival distribution of discharge 5th and 95th percentile distribution using a 3-year moving window (shaded area) and 29-years long time series (full line) (left). Distribution of Retention fraction (right).

In the context of CS, a solution is more reliable than another if the standard deviation is smaller. 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 solution 1 was lower, with a smaller deviation than the one of the other scenarios. It is the less robust scenario but the more reliable. The roof covers only 29% of the area which directly affect the retention fraction. On the opposite the scenario 2 with an E-green roof and extra storage layer result in a higher retention fraction, however the deviation of this retention fraction is higher than the other scenario (ranging from 0.2 to 0.6 with a mode at 0.4) which indicate a lower reliability.

Design application potential

The proposed HIDES framework for green roof design is depicted in Figure 1. The framework includes continuous simulation (CS) and local event sampling (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 basis decisions related to step 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 6 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 achieve through VM.

CONCLUSIONS

The VM was compared to the 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 4 designed solution were evaluate using a CS approach (for step 1) and the LES approach (for step 2 and 3). The different solution can be ranked according to different criteria and be used as 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 the more robust in terms of extreme events. The LES method demonstrated the robustness of solution 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.

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A CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

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

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