Assessing the robustness of raingardens under climate change using SDSM and temporal downscaling

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ABSTRACT

Climate change is expected to lead to higher precipitation amounts and intensities causing an increase of the risk for flooding and combined sewer overflows in urban areas. To cope with these changes, water managers are requesting practical tools that can facilitate adaptive planning. This study was carried out to investigate how recent developments in downscaling techniques can be used to assess the effects of adaptive measures. A combined spatial-temporal downscaling methodology using the Statistical DownScaling Model-Decision Centric (SDSM-DC) and the Generalized Extreme Value distribution was applied to project future precipitation in the city of Bergen, Norway. A raingarden was considered a potential adaptive measure, and its performance was assessed using the RECARGA simulation tool. The benefits and limitations of using the proposed method have been demonstrated and compared to current design practices in Norway. Large differences in the raingarden's performance with respect to percentage overflow and lag-time reduction were found for varying projections. This highlights the need for working with a range of possible futures. Further, it was found that K_{sat} was the determining factor for peak-flow reduction and that different values of K_{sat} had different benefits. Engineering flexible solutions by combining measures holding different characteristics will induce robust adaptation.

Key words | climate change adaptation, hydraulic conductivity, raingarden, SDSM-DC, temporal downscaling

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INTRODUCTION

The Damsgård area in the city of Bergen, Norway, is prone to high amounts of runoff, coming from the urbanized area itself and the hillsides upstream from the urban development. Damsgård drains to the small fjord Puddefjorden, resulting in combined sewer overflows (CSOs) to the fjord during heavy precipitation events. Bergen is renowned for its plentiful rainfall, with an annual mean of 2,250 mm (Jonassen *et al.* 2013). Climate change is expected to lead to higher precipitation amounts and more frequent storm events with higher intensities in the future (Hanssen-Bauer *et al.* 2015). This can lead to an increased number of CSOs (Nilsen *et al.*

2011). Solutions to reduce the stormwater runoff are therefore needed. Blue green stormwater infrastructure, like raingardens, have been highlighted as beneficial measures for climate change mitigation (e.g. Demuzere *et al.* 2014). This is amongst other factors due to their ability to significantly reduce peak flow runoff (e.g. Hunt *et al.* 2008).

In order to use raingardens as climate adaptation measures, they need to be designed for future rainfall intensities. A common practice for estimating future design storms in Norway today is simply to apply a percentage safety factor (climate factor) to present precipitation. To date, there is no common practice for determining the magnitude of the climate factor. The value applied by end-users across the country may range from 1.2 to 1.5, depending on municipal guidelines. Recently, the Norwegian Centre for Climate Services (NCCS) released a report with regional projections of future

climate in Norway based on a combination of regional model output and statistical downscaling (Hanssen-Bauer *et al.* 2015) along with climate profiles for each county. They emphasize projections of short duration rainfall as work in progress and suggest a temporary climate factor of a minimum 40% for rainfall of duration <3 hours. Thus, frequently asked questions by the designers still concern the magnitude of the climate factor and whether simply multiplying today's design precipitation with a climate factor is sufficient. As the necessity of climate adaptation becomes more and more apparent, the demand for practical design tools is rising.

An alternative approach to the climate factor is applying General Circulation Models (GCMs), which simulate the future climatic response to a set of predefined emissions scenarios (referred to as Representative Concentration Pathways (RCPs)) that represent various levels of change in the energy balance of the atmosphere. The GCMs are, however, too coarse to reproduce detailed climate projections at the temporal and spatial scale necessary for hydrological assessments (Herath *et al.* 2016). To bridge the gap between the large-scale climate (predictor) and the local climate (predictand), downscaling techniques can be applied (Benestad *et al.* 2008). There exist numerous downscaling techniques, often categorized into dynamical and statistical approaches (e.g. Maraun *et al.* 2010), where the statistical approaches are the least costly computationally. Statistical downscaling could be aimed to solve the spatial gaps or temporal gaps between large and local scale, and are, in general, based on either empirical transfer functions, resampling methods (weather typing), or conditional probability (stochastic modeling) (Arnbjerg-Nielsen *et al.* 2013). Over the years, GCMs and downscaling techniques have developed and become more and more available to end-users interested in studying the impacts of climate change.

The motivation of the study presented in this paper is to address the end-users' need for practical design tools by demonstrating and assessing a method for evaluating the robustness of adaptation measures in a future climate. With a focus on common practices in Norway, this study seeks to investigate the added value of performing more comprehensive investigations of local rainfall projections compared to the climate factor approach. The Damsgård area in the city of Bergen is used as a case study, with the implementation of raingardens as a possible measure for climate adaptation. Based on the above, this paper addresses the following research questions:

1. To which extent can a combination of spatial downscaling, bias correction, and temporal downscaling be used to produce intensity–duration–frequency (IDF) curves for future climate in Bergen?

2. How does the applied downscaling method compare to the current practice of multiplying the design precipitation with a climate factor?

3. What is the robustness of raingardens as a stormwater peak flow reduction measure in Bergen for different future climate scenarios?

METHODS

The widely applied Statistical DownScaling Model-Decision Centric (SDSM-DC) (Wilby *et al.* 2014) was used to downscale local climate projections for Bergen. The output from SDSM-DC is limited to one day. However, for the results from the downscaling to be useful for evaluation of raingarden performance and other hydrological assessments in urban watersheds, a higher temporal resolution is necessary (Herath *et al.* 2016). In order to achieve this, SDSM-DC was combined with a temporal downscaling approach using the Generalized Extreme Value (GEV) distribution (Nguyen *et al.* 2002) to obtain IDF curves for future climate change scenarios for Bergen, following the procedure of Nguyen *et al.* (2007). Furthermore, peak flow reduction was assessed using the raingarden modeling tool, RECARGA (Atchison & Sverson 2004). The RECARGA model simulates raingarden performance using the green-ampt infiltration and the van Genuchten model for the shape of the water retention curves. It is an event-based or continuous simulations mode model using precipitation, temperature, and evaporation and input time-series. Software and tools were selected based on their applicability. Both SDSM-DC and RECARGA are open access software with user-friendly interfaces, while the temporal downscaling proposed by Nguyen *et al.* (2007) builds on statistical theory that should be manageable for engineers. Selecting methods that are easy to apply for practitioners ensures that the full procedure is a suitable alternative to the common climate factor approach.

Collection of precipitation data

Observed precipitation data were used for two purposes: (1) calibrating the SDSM-DC and statistically downscaling from global to local climate with SDSM-DC; and (2) developing IDF curves from (i) observed data and (ii) downscaled climate data using temporal downscaling.

The weather stations were chosen on the basis of proximity to the study site. The longest record of daily rainfall in the area was found at the Norwegian Meteorological

Institute's (MET) station at Florida, Bergen (50540). Thirty years of data (1985–2015) from this station was used for calibration and validation of the SDSM-DC model. However, this station has only 4 years of sub-daily rainfall data. A station 70 meters away, Florida UIB (50539), has minute data for 10 years. The two stations are located in a flat area and in equal distance to surrounding mountains influencing the precipitation regime (Figure 2). The latter station was therefore chosen for the sub-daily rainfall. The data have been quality controlled by MET and downloaded from eklima.no.

Downscaling of precipitation

The spatial temporal downscaling is a combination of separate spatial and temporal downscaling techniques (Figure 1). It uses SDSM-DC to link the large-scale climate to the local climate and make future climate estimates. The results are further bias corrected. The temporal downscaling approach uses the scaling concept and the GEV distribution to obtain a relationship between daily and sub-daily rainfall (Nguyen *et al.* 2002). The GEV distribution is also used to derive IDF curves. The SDSM-DC and the GEV have been applied successfully in combination to develop IDF curves (e.g. Nguyen *et al.* 2010; Herath *et al.* 2016).

The methodology for spatial, including bias correction, and temporal downscaling described by Nguyen *et al.* (2007) and Herath *et al.* (2016) formed the basis for the methodology applied below.

Scenario generation

Climate projections are linked to large uncertainties. These uncertainties are mainly related to natural variations of the climate system, level of future emissions, and the climatic response to emissions (see e.g. Ekström *et al.* (2015)'s classification of uncertainty). Thus, many have argued for an ensemble approach, where several RCPs, GCMs and downscaling techniques are considered to allow for uncertainty assessment (e.g. Arnbjerg-Nielsen *et al.* 2013). SDSM-DC does not include GCMs directly, but the user of the model can apply scenarios for the future climate by changing *occurrence*, *mean*, *variance* and *trend* of e.g. the precipitation (Wilby *et al.* 2014). To investigate the effects of higher amounts and intensity of rainfall, changes in the treatments mean and variance were investigated by adding expected (1) *change (%) in total precipitation amounts* and (2) *change (%) in rainfall amounts at days with heavy precipitation* to the SDSM-DC time series respectively (Table 1). In Table 1, (1) MEAN and (2) VARIANCE are projected changes from 1971–2000 to 2071–2100 retrieved from NCCS's regional climate projections for Sunnhordland (region covering Bergen) (Hanssen-Bauer *et al.* 2015).

The climate scenarios 1–5 were based on yearly values. Climate scenario 6 was based on the worst combination of seasonal values. Annual values for RCP4.5 High (12, 12) and RCP 8.5 Med (12, 14) were quite similar. Therefore, only a change corresponding to RCP 8.5 Med was investigated.

Temporal downscaling

There are several ways of estimating the GEV parameters, where non-central moments have been used with this approach before (e.g. Nguyen *et al.* 2010; Herath *et al.* 2016). However, due to the emphasis on applicability in the scope of this study, the commonly used maximum log-likelihood estimation method was used for parameter estimation in this study. The log-likelihood function is as follows:

$$l(\theta) = \sum_{i=1}^{N} \log g \; (x; \theta) \tag{1}$$

where g is the probability density function of the GEV distribution. $\theta = [\xi, \; \mu, \; \sigma]$. ξ, μ and σ are the shape, location, and scale parameter of the GEV distribution.

The scaling factors for the different parameters were found as described by Nguyen *et al.* (2007) and Herath *et al.* (2016). They were further plotted against precipitation duration with the aim of finding one common scaling factor. This was calculated by finding the mean of the derived scaling factors.
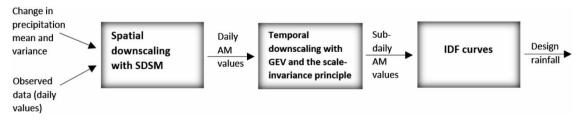

Figure 1 | Flow chart describing the downscaling step in the methodology. AM is an abbreviation for 'annual maximum'.
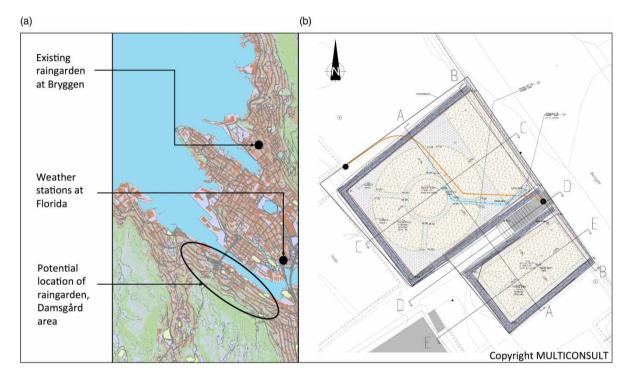
Figure 2 | Overview of the study site, showing the (a) location of existing raingarden at Bryggen, weather stations at Florida and study site Damsgård, and (b) layout of the existing raingarden at Bryggen.

Table 1 | Estimates on how the precipitation mean and variance might change

Climate scenario	0	1	2	3	4	5	6
Changes based on	Observed	RCP 4.5 low	RCP 8.5 low	RCP 4.5 med	RCP 8.5 med	RCP8.5 high	RCP8.5 high autumn/winter
MEAN: Change in total precipitation amounts (%)	0	0	2	6	12	20	30
VARIANCE: Change in precipitation amounts on days with heavy rainfall (%)	0	2	8	7	14	21	30

For constructing depth duration frequency curves, the quantiles (z_p) were calculated:

$$z_p = \mu - \frac{\sigma}{\xi} \left[1 - \{\ln(1-p)\}^{-\xi} \right] \tag{2}$$

where $G(z_p) = 1 - p$ and z_p are associated with the return period ($1/p$). To get IDF curves, the return periods were converted from mm to mm/hr. These intensities were plotted against the precipitation durations.

Construction of IDF curves for historical data

An IDF curve for observed historical precipitation was developed using the GEV distribution. The intensities were multiplied by the climate factors 1.2 (a commonly used climate factor) and 1.4 (Hanssen-Bauer *et al.* 2015). A second IDF curve for observed historical precipitation was constructed using the derived scaling factors for comparing purposes.

Raingarden assessments

Infiltration rate

It was assumed that a possible raingarden at Damsgård will have the same size relative to the watershed (6%) and the same watershed characteristics as an existing raingarden located at the close-by site Bryggen (the city center of Bergen). This raingarden has a facility area of 180.8 m^2 and depression zone of $d_{min} = 12$ cm. The robustness of

the raingarden was assessed by investigating the performance with different infiltration rates, represented by the saturated hydraulic conductivity (K_{sat}). The raingarden was tested with three different K_{sat}: 38 cm/h, 10 cm/h and 3.4 cm/h. The high K_{sat} of 38 cm/h was the value from the existing raingarden at Bryggen, obtained by MPD infiltration tests, as described by Ahmed *et al.* (2014) and Paus *et al.* (2016), which found 10 cm/h to be the minimum recommended K_{sat} in cold climates. It was further found that K_{sat} during autumn/early winter (i.e. September to December) was 25–43% of summer infiltration, with a mean of (34%). Given the recommendation of $K_{sat} = 10$ cm/h, the range 2.5–4.3 cm/h represents the winter infiltration, which naturally will vary based on soil water content at the freezing point and soil and air temperature, and the non-frozen water content of the soil.

Evaluating performance

The performance was evaluated based on (1) overflow (% of runoff into the raingarden), (2) change in lag time (change in minutes from runoff without raingarden), and (3) flow peak reduction in underdrain compared to incoming runoff (%). Lag time is in this study was defined as the time from when the precipitation event starts until flow peak of runoff or flow peak in the underdrain.

Simulation in RECARGA

RECARGA models the performance of a raingarden in 1D vertical flow direction (Dussaillant *et al.* 2005). The model applies Green-Ampts (Mein & Larson 1973) and a surface water balance to model infiltration, runoff and evapotranspiration, and Genuchtens equations (Van Genuchten 1980) to model percolation between the model's three soil layers.

A modified version of RECARGA, allowing for minute resolution for input and output, was used for the simulations (Dalen 2012). Using RECARGA, the performance with the different K_{sat} values was tested for the obtained climate scenarios.

Preparation of RECARGA input

The obtained IDF curves were used to determine the magnitude of the design rainfall to be used in further analyses and to construct symmetrical hyetographs to simulate extreme events. The hyetographs were designed with a duration of 1 hour and varying peak intensities. In order to account

for initial water in soil and for delays in runoff and infiltration, the hyetographs were constructed with a pre-wetting period that corresponded to average daily rainfall.

RESULTS AND DISCUSSION

The accuracy and applicability of the methodology was assessed by investigating the performance of each step separately and combined.

Spatial downscaling

The following predictors were chosen based on assessments of scatter plots, correlation matrices and p-values; Mean sea level pressure (Mslp), Geostrophic airflow velocity at 500 hPa (p5_f), Geostrophic airflow velocity at 850 hPa (p8_f), Zonal velocity component at 850 hPa (p8_u), and 850 hPa geopotential height (p850). The goodness of fit of the model was assessed by the explained variance (R^2). The model had an average $R^2 = 0.22$. This is comparable to previous studies (Mahmood & Babel 2013; Herath *et al.* 2016). Wilby *et al.* (2002) argue that an R^2 under 0.4 is likely for precipitation occurrence and amounts. Further, cross validating the model by a split sample test gave an average R^2 of 0.20. The two R^2 values being close indicates that the model is robust and resilient to data set partitioning. The model performs best in autumn/winter, with the highest R^2 in September (0.26). The poorest performance is found during summer ($R^2 = 0.11$ in July). The climate patterns might explain the difference. The precipitation in Bergen is in general governed by the topography and westerly winds from the North Sea (Jonassen *et al.* 2013). However, the precipitation during summer is typically influenced by convective processes, which are local phenomena.

Bias correction

Figure 3 shows that the SDSM-DC simulated daily annual maximum (AM) rainfall was overestimated for most years, and underestimated for the extreme years. This applies to some extent after bias correction too, though it is highly improved. Further, root-mean-square deviation improved from 8.14 mm to 4.19 mm, and the Nash-Sutcliffe efficiency coefficient (N-S) improved from 0.85 to 0.96 due to bias correction. The percentage bias (p-bias) improved from 7.20% to 0%. Overall, the improvement is most significant for the precipitation amounts with the lowest return period. The precipitation amounts with return periods of 5–20 years
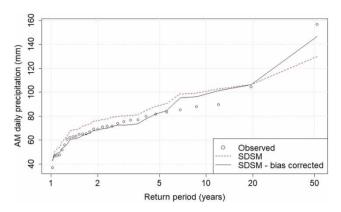
Figure 3 │ Historical AM daily precipitation values based on observed data, SDSM results and bias corrected SDSM results.

are still notably overestimated. A likely reason for this is the lowered amount of data points in this region, caused by too few observational records of extreme daily precipitation.

Temporal downscaling

The scaling factor β was 0.472. When deriving the scaling factors, it was found that the scaling factors for all durations except for 12 hours were similar for all return periods. Therefore, the 12-hour duration was excluded in the calculation of a common scaling factor. The reason for the diverging scaling factor at 12-hour duration is that the

daily data follows MET's definition of a day (7.00 am to 7.00 am). The sub-daily durations were derived from observed minute data. While aggregating these data, a day was considered midnight to midnight. This difference may have influenced the data for the 12-hour durations. However, when comparing the observed IDF curves found directly from the data and by using the scaling factor, it is seen that the longest durations are well represented by the scaling IDF curve (Figure 4(a)).

Figure 4(a) also shows that using the scaling procedure leads to high overestimation of the intensity for the shortest durations (<15 minutes). This implies that the scaling principle should not be used for these intensities. The finding corresponds to Herath *et al.* (2016), who downscaled to 30 minutes at the lowest. Nguyen *et al.* (2010), on the other hand, used a downscaled resolution of five minutes in further hydrological assessments. The temporal scaling procedure represents the durations over 180 minutes well (Figure 4(a)). For durations between 15 and 180 minutes, only the shortest return periods follow the pattern of the observed data. This is not surprising, as one could expect a closer statistical relationship between e.g. AM three-hour duration and AM daily rainfall than AM 15-minute duration and AM daily rainfall. Due to these results, the 15-minute duration was chosen as the lowest duration in the IDF curves in this study. In addition, only intensities over 15 minutes were further used in the RECARGA simulation in
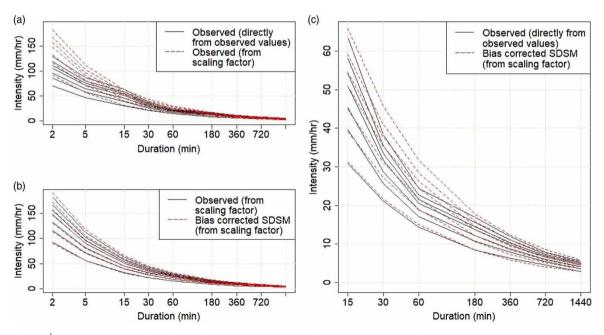

Figure 4 │ IDF curves showing the ability of the applied methodology to represent historical precipitation intensities. (a) observed precipitation, derived directly from the observed values, and by using the scaling factor; (b) observed and bias corrected SDSM precipitation, both developed using the derived scaling factor; (c) observed precipitation found directly from observed values and bias corrected SDSM precipitation found by using the scaling factor. The return periods are 2, 5, 10, 20, 30, 50 and 100 years.

order to avoid propagating the inaccurate results of lower durations in further analyses.

Combination of spatial and temporal

Figure 4(b) shows that the accuracy of the spatial downscaling (after bias correction) applies for sub-daily intensities as well as for daily precipitation. The spatially downscaled IDF curve follows the same pattern as the IDF based on observed data when both curves are constructed using the derived scaling factor. However, the fit is best for the lower return periods.

Figure 4(c) shows that the same patterns as described in the temporal downscaling section apply for the spatially and temporally downscaled IDF curve. The overestimation for larger return periods in the spatial downscaling step (Figure 4(b)) carries over to the spatially and temporally downscaled IDF curves (Figure 4(c)), though the temporal downscaling is the main source of inaccuracy in the results.

In more detail, the model overestimates precipitation intensities for events of durations of 30–180 minutes and for the higher return periods. However, it is evident from Figure 4(c) that bias correction highly improves the performance for events of 15 minute durations for any return period.

Comparison between the downscaled scenarios and climate factors

The IDF curves for the chosen scenarios were compared to the climate factor 1.4, which is the recommended climate factor for durations of less than three hours for the Bergen area (Hanssen-Bauer *et al.* 2015), and to the commonly used climate factor of 1.2. The comparison is shown for the 20-year return period (Figure 5), which is the design criteria for stormwater pipes in the city of Bergen (Bergen
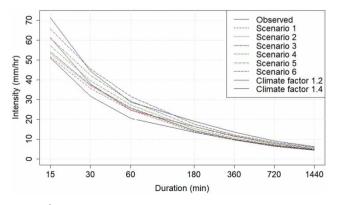
kommune 2005). Applying the climate factor of 1.4 results in intensities higher than all the investigated climate scenarios for all durations, except for the durations from 30 to 120 minutes. Knowing that the spatially and temporally downscaled intensities are overestimated for these same durations, the 1.4 climate factor gives the highest safety margin amongst the investigated cases. The intensities given by the commonly applied climate factor of 1.2, on the other hand, are exceeded by several of the climate scenarios.

It is, however, important to notice that this does not mean that applying a 1.4 climate factor is always sufficient. The investigated scenarios do not by any means constitute an upper limit for climate change. The uncertainties of future emission scenarios, the GCMs and the spatial and temporal downscaling procedure make it crucial to use the results cautiously. This is the motivation behind the SDSM-DC. The GCMs should be used to inform the analysis, but they are not driving them (Wilby *et al.* 2014). This is done by selecting treatments to apply to the current climate situation. In this study, the GCM output was used to inform the choice of treatments, as recommended by Brown & Wilby (2012). The annual and seasonal change estimates for the Sunnhordland region represented the climate changes and are, along with the 1.4 climate factor, from Hanssen-Bauer *et al.* (2015). Thus, the climate factor and the applied treatments are based on the same GCM output. One could therefore expect that multiplying with the 1.4 climate factor would give similar intensities as the worst climate scenario. This was indeed the case, which indicates that there is agreement between the downscaling approach used in this study and the downscaling methods used by Hanssen-Bauer *et al.* (2015).

The raingarden as peak flow reduction measure

The performance was assessed for precipitation events (expressed as symmetrical hyetographs of 1-hour duration) with peak intensity corresponding to 15 min duration and a return period of 20 years following municipal guidelines for stormwater pipes in Bergen (Bergen kommune 2005). However, it can be argued that it is not reasonable to design raingardens for capturing all the runoff from such a rather large event. Raingardens are recommended to be designed to capture the 'everyday' runoff, and to be combined with safe flood ways for larger events (Paus & Braskerud 2014). Therefore, infiltrating 80% of the incoming runoff is considered a successful performance. With concern to Puddefjorden, the risk of a CSO every 20th year

Figure 5 │ IDF curve for all investigated cases for return period of 20 years.

caused by 20% of the runoff from Damsgård is well within acceptable risk levels.

$K_{sat} = 38$ cm/h was the only investigated infiltration rate that gave under 20% overflow for all climate scenarios (Figure 6(c)). It was further found that the K_{sat} should be above 17 cm/h to infiltrate 80% of the runoff for today's condition. However, to meet the criteria for all the investigated climate scenarios, it should be at least 33 cm/h. In addition, winter conditions should also be accounted for. A reduction of K_{sat} 33 cm/h to e.g. 11.2 cm/h (34% reduction, see Paus *et al.* 2016), would neither today nor in the future give adequate infiltration all year round.

For all investigated K_{sat} values, the peak flow in the underdrain was reached before the peak runoff from the event. Hence the lag time was reduced for the flow in the underdrain compared to the lag time without a raingarden. However, an increase in lag time for overflow from the raingarden compared to the pre-raingarden conditions was observed. The largest increase was found for a $K_{sat} = 38$ cm/h, ranging from nine minutes for climate scenario 6 to 14 minutes for climate scenario 1 (Figure 6(c)). A $K_{sat} = 3.4$ cm/h gave the lowest increase in lag time, ranging

from one to three minutes for the different climate scenarios and five minutes for today's situation.

The peak flow reduction was only dependent on K_{sat}, and was independent of the climate scenarios (Figure 6(b)). The highest peak flow reduction was found for $K_{sat} = 3.4$ cm/h (96.3%), while the lowest was found for $K_{sat} = 38$ cm/h (56.7%).

Thus, it is seen that a higher K_{sat} results in less overflow and an increase in overflow lag time, whereas a lower K_{sat} is the most efficient for reducing the peak flow. This shows that the choice of filter medium (and ultimately K_{sat}) should be based on whether peak flow reduction or detention is the most important objective. Alternatively, a combination of different solutions might be beneficial. One could for example have a series with a high-infiltration rate raingarden first, draining into another raingarden or infiltration-based solution with lower infiltration capacity. Or, the raingardens could be placed in opposite order, with a low-infiltration rate raingarden first, infiltrating the small events and overflowing to a second raingarden/infiltration-based solution with higher infiltration rate for the larger events. The above are two possible solutions,
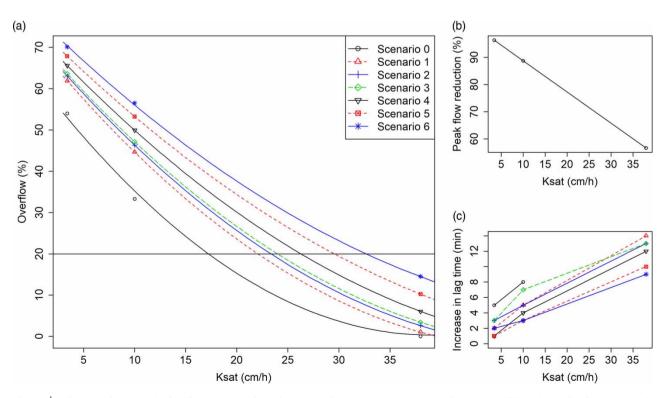

Figure 6 │ Performance of the raingarden for different K_{sat} values for the investigated climate scenarios. (a) Percentage of incoming runoff becoming overflow from the raingarden (%); (b) peak flow reduction compared to peak flow without raingarden (%); (c) lag time reduction for peak overflow from the raingarden compared to peak runoff without raingarden (min).

illustrating that the key to increased robustness is a combination of solutions.

Practical implications of the study

The combination of spatial downscaling, bias correcting and temporal downscaling resulted in refined local climate projections for Bergen. The resulting IDF curves containing the climate signal of various scenarios has a high practical value to end-users, as they are easy to transfer to existing design practices. However, the projections are highly uncertain both due to model uncertainty introduced in climate modeling and downscaling, but also due to the fact that the future course of our society is unknown. This highlights the need for practitioners to assess a range of different scenarios when decisions about climate adaptation are to be reached.

IDFs resulting from the presented analyses were compared to the current design practice in Norway, referred to as the climate factor approach. The investigated scenarios were shown to be more conservative than applying a climate factor of 1.2 and less/or equally as extreme as applying a climate factor of 1.4, both factors commonly used in Norway. The practical implication of this is that implementing the full downscaling procedure as proposed in this study could help inform the choice of a suitable magnitude of the climate factor for different locations in Norway – a highly debated topic within the water sector. However, considering the varying model performance for different event durations and return periods (Figure 4), attention to model confidence at the different levels should be given in doing so.

The applied downscaling methodology is also a good tool for showing the range of possible outcomes of climate change. Generally, it can be used to stress test systems for possible climate change scenarios, and to evaluate the response of an investigated system, as suggested by Wilby *et al.* (2014). Specifically, it was shown, by assessing the performance of a raingarden (as an adaptive measure) to various scenarios, that the more conservative the scenario, the less satisfying the performance. In a design perspective, one should always consider the risk associated with failure of the system (Hanssen-Bauer *et al.* 2015). Thus, the analyses of raingarden performance could be combined with vulnerability analyses. In a highly vulnerable area, little risk might be accepted and the adaptive measure should be designed for a more conservative scenario. On the contrary, in a less vulnerable part of the urban area, one might be less risk aversive. As seen from Figure 6, the criterion of 80% infiltration is fulfilled at $K_{sat} \approx 17$ cm/h for the least

conservative scenario and at 33 cm/h for the most conservative scenarios. Thus, choosing a scenario based on vulnerability analyses would highly influence the requirements to the raingarden and thus other aspects outside the scope of this study, such as costs.

Further, it was shown that different K_{sat} values had different benefits: high K_{sat} values resulted in increased lag time, and lower K_{sat} values improved peak flow reduction. It was further demonstrated that a possible solution to this could be to connect components with different characteristics (e.g. raingardens with different K_{sat} values) in order to add flexibility. This idea may be elaborated in studies investigating a coupling of raingardens with other measures that are less demanding in terms of costs and area. Considering seasonal variations and deterioration of K_{sat} value with time could help inform the selection of suitable co-measures. To exemplify, it was discussed how K_{sat} is reduced during winter in Norway. The implication for the raingarden performance is that lag time is reduced while peak flow reduction would be improved. Thus, a suitable co-measure should compensate for the reduced K_{sat} and lag time. Adding this flexibility ensures that the uncertainty in the scenarios are accounted for and that the measure performs well under a range of scenarios, not a specific one. This, ultimately, results in a robust adaptive measure.

CONCLUSIONS

This study demonstrates how recent developments in downscaling techniques can be used to support end-users and designers in assessing climate change impacts and effects of adaptation measures; specifically, the robustness of raingardens under climate change. A combination of spatial and temporal downscaling was applied to make IDF curves for Florida (Bergen, Norway), and assess the robustness of raingardens as peak flow reduction measures under climate change. The climate change scenarios were generated by manipulating the mean precipitation and precipitation variance. It was found that the largest inaccuracy in the downscaling procedure was in the temporal downscaling step. The IDF curves developed by using the methodology represent the lowest return periods well, but are inaccurate for the highest return periods and more research should be done on improving the temporal downscaling step. However, despite the large uncertainties, it has been demonstrated how the climate forced IDFs could be of practical value to end-users.

The robustness of raingardens as a peak flow reduction measure is highly dependent on the K_{sat} value. The higher the K_{sat} value, the more robust as a peak flow reduction measure the raingarden will be, both in terms of overflow and lag time. Based on overflow and lag time, the recommended minimum K_{sat} value for a cold climate of 10 cm/h is insufficient. However, the peak flow reduction is highest for the lower K_{sat} values. It is therefore concluded that the raingarden media (and ultimately the K_{sat}) must be decided based on which feature of the raingarden is most important. A solution combining different features, e.g. by having several raingardens/infiltration-based solutions with different infiltration rates in series will add robustness and flexibility.

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