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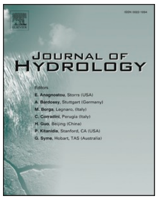

Research papers

Impacts of slope and length on the hydrological performance of green roof drainage mats

Elhadi Mohsen Hassan Abdalla *, Knut Alfredsen, Tone Merete Muthanna

Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Andersens vei 5, Trondelag 7031, Norway

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ABSTRACT

This study evaluated the impact of the roof slope and length on the retention and detention performance of the drainage mats of green roofs. Artificial rainfall events were applied to a test bed at two different lengths (1 m and 4.5 m), three slopes (2 %, 5 %, and 20 %), two drainage mats: retention mat (RM) and hard plastic egg-shape mat (ES), and a standard black roof as a reference. Retention and detention indicators were determined for each rainfall-runoff experiment. In addition, the study developed and calibrated a reservoir routing model to predict the outflows of the drainage mats at different slope and length values. The slope was found to influence both the retention and detention performance of drainage mats for low and high-intensity rainfall events while the length was found to affect the detention performance for low-intensity rainfall events. In addition, the RM and ES mats were found to retain up to 8 and 6 mm, respectively, of rainwater and to delay drainage mat runoff by 25 mins and 15 mins, respectively, demonstrating the significant role of drainage mats in the performance of green roofs. The reservoir model accurately simulated the outflow from the drainage mats (Kling-Gupta Efficiency > 0.75), while the parameters of the model were found to be influenced primarily by the slope of the roof.

1. Introduction

In the last few decades, there has been an increasing interest in green roofs as robust stormwater measures for mitigating the impact of climate change and rapid urbanization (Stovin, 2010). Green roofs provide many environmental (Susca et al., 2011; Wooster et al., 2022), economic (Bevilacqua, 2021; Bevilacqua et al., 2020), and social benefits (Jungels et al., 2013) for urban catchments. The hydrological benefits of green roofs for stormwater management are quantified by retention and detention processes. The former is the measure of permanent reduction of stormwater via evapotranspiration of the green roof (Stovin et al., 2013). The detention refers to flow attenuation and delays as a result of the temporal storage of water in the green roof layers (Stovin et al., 2017). Several studies quantified the retention and detention processes of green roofs in the literature (Johannessen and Braskerud, 2018; Liu and Chui, 2019; Stovin et al., 2012; Voyde et al., 2010).

The retention and detention of agreen roof are affected by its structural properties including the roof geometries (i.e. dimension and slope) and the physical properties (i.e. material type, thickness, etc.) of the green roof layers. Green roof layers consist of a vegetation layer for plant growth, a substrate layer that provides nutrients and support for plants, and a drainage layer to facilitate water movement and outflow. Much of the literature has focused on the impact of the physical properties of the green roof layers on its performance (Li et al., 2018; Liu et al., 2019; Poë et al., 2015; VanWoert et al., 2005; Yio et al., 2013; Zheng et al., 2021). VanWoert et al. (2005) found the retention of green roofs to increase by increasing the depth of the substrate layer. Yio et al. (2013) examined the detention performance of green roof substrates. They found the detention of the substrate layer to increase by increasing its depth and the content of organic materials. Stovin et al. (2015) compared the hydrological performance of vegetated and unvegetated green roofs and found the vegetation layer to enhance both detention and retention performances. Liu et al. (2019) examined the effect of several structural properties on green roof retention. They found the material type of the substrate layer to have the highest impact on the retention of green roofs followed by the substrate depth and the roof slope, while the vegetation layer was found to have the least impact on the retention. Zheng et al. (2021) performed a meta-analysis of green roof retention across 21 countries, identifying factors significantly influencing green roof retention, including rainfall intensity, substrate depth, green roof coverage area, vegetation type, and climate class. They found green roof retention to correlate positively with substrate depth and negatively

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* Corresponding author.
E-mail address: elhadi.m.h.abdalla@ntnu.no (E.M.H. Abdalla).

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Fig. 1. The test bed used in the study. Left: the hard plastic egg-shape drain mat (ES). Right: the retention mat (RM).

with rainfall intensity.

Many studies have investigated the impacts of the roof slope on green roof performance (Bengtsson, 2005; Förster et al., 2021; Getter et al., 2007; Kim et al., 2021; Villarreal and Bengtsson, 2005). However, the findings of these studies are conflicting; some found the slope to have little to no impact on the retention and detention of green roofs while others concluded the opposite.

Regarding green roof detention, Villarreal and Bengtsson (2005) examined factors influencing the green roof performance at different values of slope (2,8 and 14°). They found the slope to not affect peak outflow values. Likewise, Bengtsson (2005) analysed data from a laboratory green roof tilted at different slope values between 2.6 % and 23 % and two lengths (1 m and 2 m). The author found both roof slope and horizontal length to have no impact on the hydrograph of green roof outflow. Thus, the author argued that the process of water percolation through the vegetation and substrate layers dominates the rainfall-runoff process of green roofs. Using a numerical model, Kim et al. (2021) analysed factors influencing the performance of green roofs. They found slope to have little effect on the peak attenuation of green roofs (i.e. detention). In contrast, Getter et al. (2007) found significant differences in the detention of sloped green roofs (2 %, 7 %, 15 %, 26 %); roofs with milder slopes were found to cause higher peak reduction and longer flow delay than steeper roofs. Their finding was confirmed in the study of Förster et al. (2021) in which they examined the effect of varying the slope within a small range (0 %, 2 %). They observed a significant difference in flow reduction between 0 % and 2 % slopes.

The effect of roof slope on the retention of green roofs also brings conflicting findings. Some researchers found the slope to have little or no

Table 1
Variables tested in the experiments.

Variable	Values tested
Slope	2 %, 5 %, and 20 %
Roof material	Black roof (BR), Egg-shape (ES) and Retention mat (RM)
Rainfall intensity	Low rainfall: – Intensity: 0.17–0.25 mm/min – Duration: 10 mins for BR, 60 mins for RM and ES – Time after rainfall: 10 mins for BR, 15 mins for RM and ES High rainfall: – Intensity: 1 mm/min – Duration: 5 mins for BR, 10 mins for RM and ES – Time after rainfall: 5 mins for BR and ES and 10 mins for RM
Length	1 m and 4.5 m

significant impact on green roof retention (Bengtsson, 2005; Wen Liu et al., 2019; Mentens et al., 2006). On the other hand, a group of studies found the slope to be an important factor in green roof retention (Chow et al., 2018; Förster et al., 2021; Getter et al., 2007; VanWoert et al., 2005; Villarreal and Bengtsson, 2005). For instance, Getter et al. (2007) quantified the retention of green roofs at different slope values. They reported a mean event retention of 85.6 % at a 2 % slope compared to only 76.4 % at a 20 % slope. Likewise, Villarreal and Bengtsson (2005) reported retention values of 62 %, 43 %, and 39 % at slopes of 2°, 8°, and 14° respectively for a rainfall event of 0.4 mm/min.

The impacts of the roof length on green roof performance have received scant attention in the research literature. Bengtsson (2005) found changing the length from 2 m to 1 m to have little impact on the outflow hydrograph. In contrast, Sims et al. (2019) observed a 77 % peak reduction from a small laboratory green roof (0.2 m^2) compared to 88 % from a full-sized green roof (200 m^2) from the same rainfall event. The authors attributed this difference to the horizontal flow routing due to the different lengths. Likewise, maximizing flow length was found to significantly attenuate extreme rainfall events in the study of Förster et al. (2021).

The different findings regarding slope and length highlighted the need for more studies investigating their effect on roof performance. Such studies are needed to quantify the effect of the implementation of green roofs at catchment scales where roof buildings would have different geometries (i.e., slope and length). By quantifying those effects, it is possible to make informed decisions on retrofitting existing buildings in the catchment with green roofs, based on their geometry. Moreover, studies that aim to find the optimal spatial locations of green roofs and other green infrastructure measures using hydrological models (Giacomoni and Joseph, 2017; Le Floch et al., 2022; Liang et al., 2020; Yao et al., 2020) could benefit from incorporating the impact of different roof geometries to the hydrological performance of green roofs, which is often neglected in these studies.

The present study attempted to quantify the combined impact of slope and length on the detention and retention of the drainage layer of green roofs. In addition, the study evaluated the suitability of a simple reservoir routing model in simulating the outflow of the drainage mats at different slopes and lengths.

2. Methods

2.1. The laboratory experiments

A test bed was built at the hydraulic laboratory of the Norwegian University of Science and Technology (NTNU) located in Trondheim, Norway. The bed has an area of 5 m^2, 5 m (length) * 1 m (width). The slope of the bed can be modified by raising or lowering one side of the bed. Artificial rainfall events were generated using a set of 1 m soaker hoses, a hose with tiny pores commonly used for drip irrigation,

Table 2
Layers and parameters of the three LID modules of the SWMM model.

Parameter	Symbol	Lower limit*	Upper limit*	Unit
Flow coefficient of the upper tank	ks	*0*	*1*	–
Flow coefficient of the upper tank	kd	*0*	*1*	–
Permanent storage of the drainage mat	S	*0*	*10*	mm
Infiltration capacity	Ic	*0.3*	*1*	mm/min

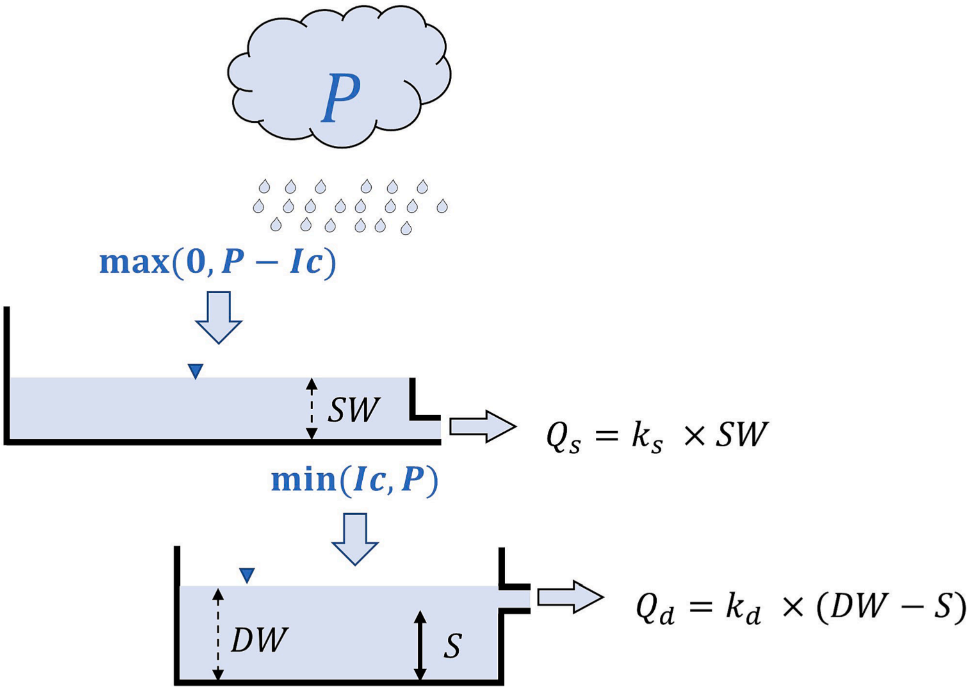

Fig. 2. The reservoir model used in the study.

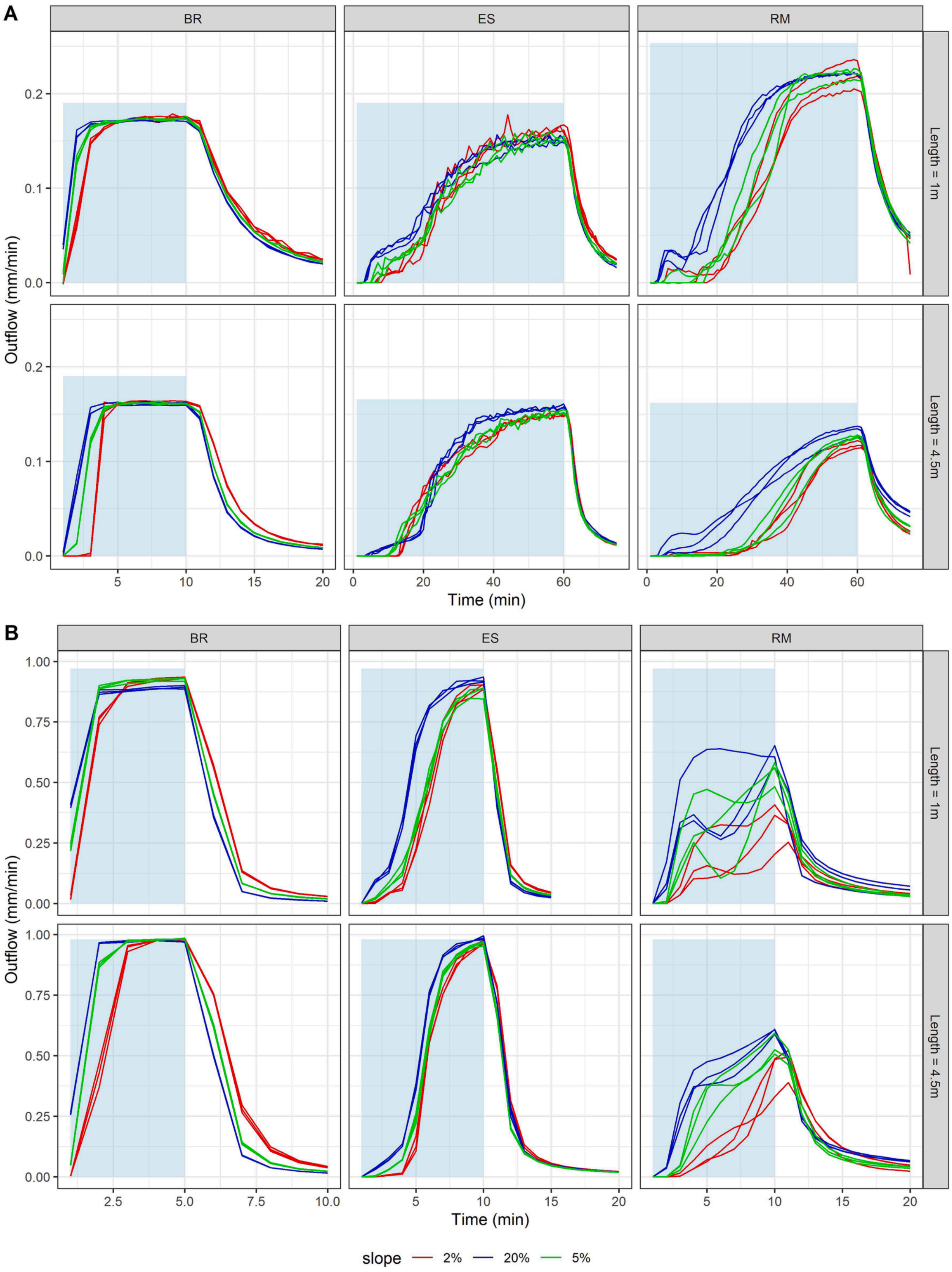

Fig. 3. Outflow hydrographs of the three roofs at (A) low rainfall events and (B) high rainfall events. The light blue area represents the rainfall intensity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Linear regression models for predicting retention and centroid delay from slope and length (Eq. (1)).

Indicator	Rainfall	Roof	Coefficients	value	Std. Error	t value	Pr(>|t|)	R^2
Retention (mm)	Low	BR	c	−0.359	0.010	−34.450	**<0.001**	0.99
			a	−0.003	0.001	−5.318	**<0.001**	
			b	0.133	0.003	49.028	**<0.001**	
		ES	c	5.336	0.109	49.064	**<0.001**	0.88
			a	−0.022	0.006	−3.431	**0.004**	
			b	−0.284	0.028	−9.977	**<0.001**	
		RM	c	7.798	0.171	45.550	**<0.001**	0.91
			a	−0.116	0.010	−11.668	**<0.001**	
			b	−0.205	0.045	−4.576	**<0.001**	
	High	BR	c	0.614	0.159	3.858	**0.002**	0.27
			a	0.002	0.009	0.173	0.865	
			b	−0.097	0.042	−2.341	**0.033**	
		ES	c	5.031	0.218	23.109	**<0.001**	0.66
			a	−0.057	0.013	−4.513	**<0.001**	
			b	−0.171	0.057	−3.001	**0.009**	
		RM	c	6.737	0.290	23.243	**<0.001**	0.76
			a	−0.116	0.017	−6.884	**<0.001**	
			b	0.002	0.076	0.021	0.984	
Centroid delay (min)	Low	BR	c	3.910	0.119	32.785	**<0.001**	0.75
			a	−0.046	0.007	−6.606	**<0.001**	
			b	−0.048	0.031	−1.546	0.143	
		ES	c	14.443	0.391	36.895	**<0.001**	0.49
			a	−0.084	0.023	−3.696	**0.002**	
			b	0.070	0.102	0.688	0.502	
		RM	c	18.946	0.531	35.701	**<0.001**	0.93
			a	−0.319	0.031	−10.333	**<0.001**	
			b	1.228	0.139	8.850	**<0.001**	
	High	BR	c	1.534	0.081	19.007	**<0.001**	0.80
			a	−0.031	0.005	−6.551	**<0.001**	
			b	0.083	0.021	3.916	**0.001**	
		ES	c	3.344	0.079	42.357	**<0.001**	0.90
			a	−0.036	0.005	−7.411	**<0.001**	
			b	0.196	0.021	9.250	**<0.001**	
		RM	c	4.603	0.404	11.389	**<0.001**	0.43
			a	−0.070	0.023	−2.978	**0.009**	
			b	0.161	0.106	1.523	0.149	

distributed at equal distances (≈12 cm) at the top of the bed frame (Fig. 1). Every four hoses were connected to a 4-way flow connector and the water flows to these connectors were controlled by a set of valves fixed at the side of the frame (Fig. 1). All experiments were performed using uniform rainfall intensities. The amount of rainfall was measured by an ultrasonic water meter, MULTICAL® 21, with an accuracy of ± 5 % at minimum flow (2 l/hour) and an accuracy of 2 % at nominal flow values (1.6 m^3/ hour). The outflow from the test bed was collected in a bucket and weighted using a Mettler Toledo® ICS435 balance, with an accuracy of ±1 g. During rainfall-runoff experiments, time series of weight readings from the balance was collected using the Smartlux data logger software (https://www.smartlux.com/sdl/).

Rainfall-runoff experiments were done using two rainfall intensities and by varying three variables: slope, roof material, and length, as shown in Table 1. All combinations of the variables in Table 1 were tested and each experiment was repeated three times, totaling 108 rainfall-runoff experiments. To select the rainfall intensities, we analysed 30 years of rainfall time series of the city of Trondheim with a 1 min time step. 99 % of the non-zero values were found to have an intensity of 0.2 mm or below. On the other hand, a value of 1 mm/min represents an extreme rainfall intensity that has been exceeded only 15 times during the 30 years. The duration of rainfall events was selected so that the outflow rate is equal to rainfall intensity. However, after running initial experiments, it was decided to fix the duration of both drainage mats to allow for direct comparisons.

Two commonly used drainage mats were tested: retention mat (RM) and hard plastic Egg-shape mat (ES). Fig. 1 shows the test bed with the two drainage mats. In addition, the test bed was tested without a drainage mat, for simulating a black roof (BR). Valves controlling the artificial rainfall were opened/closed for testing the change in roof length. For instance, all valves were closed except for the two downstream ones when testing the roof length of 1 m (i.e. each valve controls the rainfall of 0.5 m of the roof). Rainfall-runoff experiments were done at dry initial conditions. Before each experiment, the test bed was drained of any stored water. For ES, the mat was removed from the bed after each experiment and emptied from the water before running a new experiment. After each experiment of the RM, the wet mat was removed from the bed and dried while a new dry mat was used for running the next experiment.

2.2. *Analysis of rainfall-runoff experiments*

Rainfall-runoff experiments were analysed to predict detention and retention performances. Retention was measured as the difference between the cumulative rainfall and cumulative runoff at the end of the experiment. On the other hand, centroid delay, the time between the centroid of the rainfall hyetograph and the centroid of the outflow hydrograph, was selected as a measure of detention of the drainage layers. In addition, linear regression models (Eq. (1)) were built to assess the relationship between the slope and length of the roof and the retention and detention indicators.

$$\text{Indicator} = a \times slope + b \times length + c \tag{1}$$

2.3. *The reservoir model*

The study used a reservoir model consisting of two tanks to simulate the outflow of drainage mats. In this model, the upper tank receives rainfall (P), which then either infiltrates into the lower tank or accumulates in the upper tank based on the rainfall intensity and the

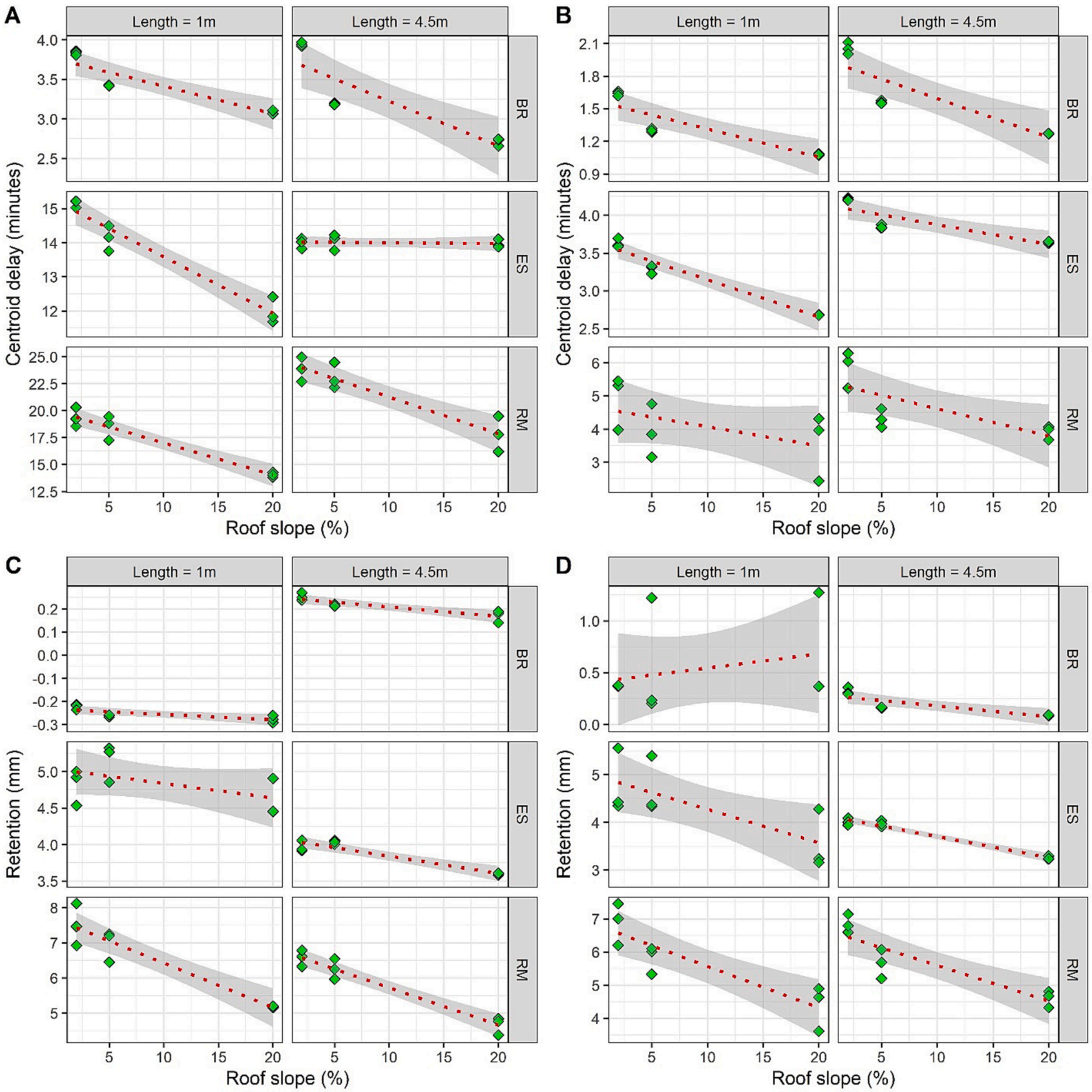

Fig. 4. Effect of slope and length on detention performance measured by centroid delay for (A) low rainfall and (B) High rainfall events. Effect of slope and length on retention performance for (C) low rainfall and (D) High rainfall events. The light grey area represents the confidence intervals of the regression equations.

infiltration capacity (Ic) of the upper tank, as shown in Fig. 2. Specifically, when the rainfall intensity is smaller than the infiltration capacity (Ic) of the upper tank, the rainfall enters the upper tank and subsequently infiltrates into the lower tank. However, if the rainfall intensity exceeds the Ic value, the excess rainfall (P-Ic) is stored in the upper tank, representing the volume that cannot infiltrate, and will contribute to the surface outflow (Qs). This was done to separate two types of runoff occurring in green roofs that is referred to by Yang et al. (2015); "saturation-excess" runoff (i.e., runoff occurring after the storage is full) and "infiltration-excess" (i.e., runoff occurring when rainfall intensity exceed the infiltration capacity).

The infiltrated water in the lower tank fills the permanent storage of the drainage mat (S). The outflow of the lower tank (Qd) is determined from the surplus storage (DW-S), where DW represents the drainage water level in the lower tank. The total outflow of the drainage mat is then calculated as the sum of the outflow from the two tanks (i.e., Qs + Qd).

The Model has four parameters that require calibration (ks, kd, Ic, and S). The differential evolution (DE) algorithm (Storn and Price, 1997) was used to find the optimal parameters of the model for each experiment. DE is a population-based algorithm that searches for optimal model parameters within the parameter ranges provided by the user (Table 2 in this study). The limits of ks and kd were set between 0 and 1 representing the ratio of available storage that is converted to runoff. The upper limit parameter S, which represents the retention storage of the mat, was selected to be larger than the maximum retention value

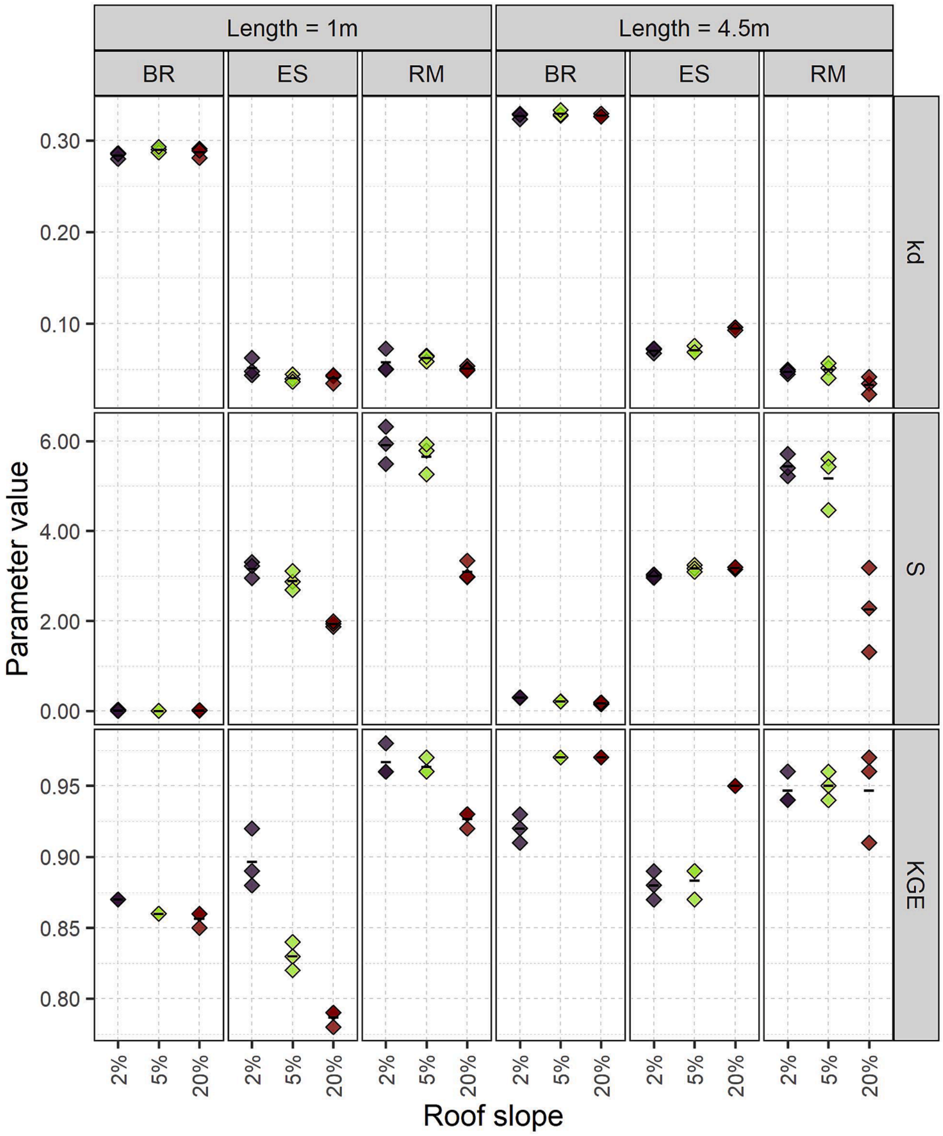

Fig. 5. Calibration results of the reservoir model (Low intensity rainfall events).

observed in the experiments. For the parameter Ic, the results of the experiments suggested that infiltration-excess runoff only occurred at high rainfall intensity events (1 mm/min). Therefore, to eliminate the occurrence of the surface runoff at low rainfall intensity events (0.1 mm/min), the lower limit of the parameter Ic was selected as 0.3 mm/min.

The DE algorithm select an initial population of parameter sets and evaluates their goodness of fit using an objective function. Then, each population evolves to the next one in such a way that each parameter set is either improved or kept the same (based on its objective function value) until the total number of populations is reached (100 in this study). The best parameter set in the final population is selected as the optimal one. The Kling Gupta efficiency (KGE) (Gupta et al., 2009) was selected as the objective function in this study. KGE was selected because it balances residual and volumetric errors. The former is relevant for matching outflow hydrographs, especially at high values and hence is important for detention metrics. On the other hand, reducing volumetric errors is more relevant for estimating retention.

3. Results

3.1. *Effect of slope and length on the green roof drainage layer*

Outflow hydrographs of all experiments are shown in Fig. 2. The results illustrate the effect of roof materials, slope, and length on the resulting hydrograph for low and high rainfall events. For instance, the outflow of the BR was almost instant in comparison to any of the drainage mats. Additionally, increasing the slope led to faster outflow in all rainfall-runoff experiments even for high rainfall intensities. The length of the roof was found to influence the delay of runoff outflow, especially for rainfall events with low intensities. The RM produced less outflow when compared with the ES mat at the same rainfall intensity.

Retention and centroid delay indicators were calculated for all experiments and plotted as shown in Fig. 3. Increasing the slope was found to decrease the performance of drainage mats as measured by the retention and centroid delay indicators. For instance, the RM with a 2 % slope yielded a centroid delay of 20 mins compared to 14 mins yielded by the RM with 20 %. Even for the BR, changing the slope from 20 % to 2 % increased the centroid delay by one minute. Increasing the slope led to decreasing the retention of the RM mat from 7 mm to 5 mm.

It should be noted that the low rainfall events for 1 m length were

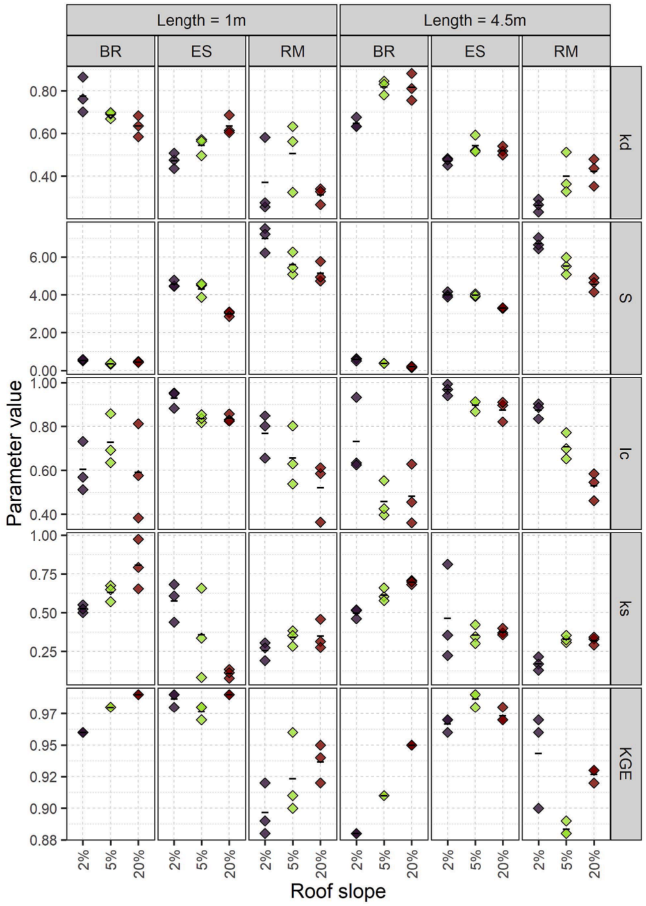

Fig. 6. Calibration results of the reservoir model (*high* intensity rainfall *events*).

higher for the RM mat due to issues in setting the inflow rates close to the minimum rate that can be measured by the flowmeter. Nevertheless, when comparing the outflow rates of low-intensity rainfall events at the length of 4.5 m, the outflows from the RM mat were lower, particularly the rising limb of the hydrograph, which can be attributed to the higher retention capacity of the RM compared to the ES mat. However, at high rainfall intensity, the RM mats release outflow slightly faster than the ES mat particularly at high slopes, even before reaching saturation. This can be explained by the high rainfall intensity exceeding the infiltration rate of RM leading to outflow at the surface of the mat, as conceptually explained in Fig. 2.

In addition, it can be noted in Fig. 3, that the flow rates of the RM declined after a short time before increasing again at high and low rainfall intensities. A possible explanation for this might be because all experiments were done with dry RM mats which could repel water infiltration when their moisture content is close to zero, leading to decreased infiltration rate and increased surface outflow at the start. The water repellency of porous media has been investigated by previous studies (Najm et al., 2021; Wang and Wallach, 2022 and references therein). As discussed by Dekker et al. (2001), the water repellency of soils often diminishes in the presence of liquid water, which could explain the decreasing flow rate as a result of increasing infiltration and storage after some time (Fig. 3).

Linear regression models were built for each roof and rainfall intensity, comprising a total of 18 observations for each model, to assess the relationship between the indicators with the slope and length (Eq. (1)). Most of these models showed to predict the performance well, based on the high values of R^2. The results in Table 3 show the effect of slope to be significant for all experiments. Regarding the RM, the impact of roof length on retention and centroid delay was only found to be significant for low-intensity rainfall events. However, it is important to note that the low-intensity rainfall events for the 1 m length were higher for the RM mat due to challenges in precisely setting the inflow rates close to the flowmeter's minimum measurable rate. Hence, the impact of roof length on the retention of the RM can be attributed to the difference in rainfall amount between the two roof lengths.

On the other hand, the roof length was found to have a significant influence on the centroid delay for low-intensity rainfall events, with a coefficient (b) of 1.228, suggesting that the centroid delay increases with an increase in roof length. Therefore, it is possible that the actual impact of roof length on centroid delay for the RM mat may be slightly larger than what was measured in this study.

3.2. *Calibration results of the reservoir model*

The calibration results of the reservoir model are presented in Fig. 5 and Fig. 6 for low and high-intensity rainfall events, respectively. The calibration yielded results with KGE values higher than 0.75 for all experiments, which are considered "good" modelling results as classified by Thiemig et al. (2013). Fig. 7 illustrates the simulated outflows by the reservoir model, which confirms the ability of the calibrated models to reproduce the observed outflows at different lengths and slope values.

The calibrated parameters of the reservoir model were found to vary depending primarily on the slope. For instance, the storage parameter S decreased by increasing the slope for the drainage mats. Interestingly, the values of the parameter S were close to the retention values shown in Fig. 4. On the other hand, the flow coefficients (kd and ks) were found to increase by increasing the slope, particularly for high-intensity rainfall events for the RM mats (Fig. 6), meaning that increasing slope leads to higher flow peaks (i.e., reduced detention).

Increasing the roof's slope resulted in reducing the value of the parameter Ic, particularly for the RM mat (Fig. 6). This indicates the infiltration capacity of the mat is reduced by increasing the slope leading to faster outflow as a result of the surface runoff. parameter Ic was also found to be affected by the roof's slope. Morbidelli et al. (2015) observed a significant reduction of infiltration in sloped soils in a laboratory experiment which resulted in the occurrence of surface runoff for high slopes even for rainfall events with low intensity.

4. Discussion

4.1 Effects of slope and length on drain mats

This study is perhaps the first study to evaluate the impact of roof slope and length on the performance of the drain mats alone without vegetation and substrate layers. The RM and ES mats were found to retain up to 8 and 6 mm of rainwater, respectively. In addition, the RM and ES mats could delay outflows by 25 mins and 15 mins, respectively. This demonstrates the significant role of drainage mats in the performance of green roofs.

The results of this study found the slope to influence both the retention and detention performance of drainage layers for low and high-intensity rainfall events. On the other hand, the effect of the length can influence the detention performance for low-intensity rainfall events but less for high intensity rainfall. Thus, the findings agree with many studies that found the slope to influence green roof performance (Förster et al., 2021; Getter et al., 2007; Villarreal and Bengtsson, 2005) while contradicting other studies that found the slope to have insignificant impacts (Bengtsson, 2005; Kim et al., 2021; Liesecke, 1998; Schade, 2000). Getter et al. (2007) attributed the disagreement between the studies regarding the effect of the slope to the degree of saturation of the green roofs before the experiment. They argue that studies testing the effect of slope on wet initial conditions, such as the study of Liesecke (1998) and Schade (2000), concluded the insignificant of slope on green roof performance. This is supported by the results of this study as all experiments were done at dry initial conditions which supports the argument of Getter et al. (2007).

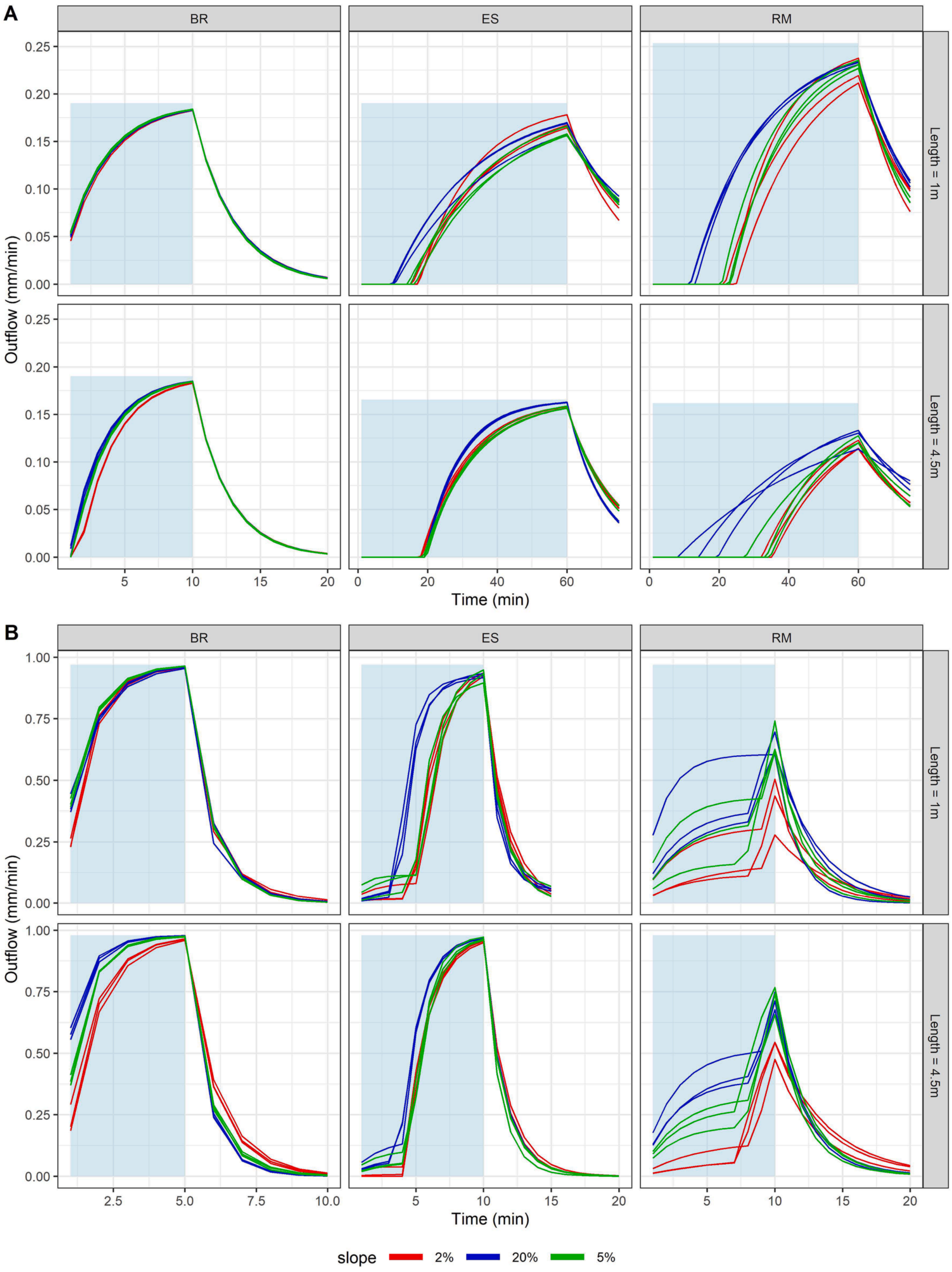

Fig. 7. Simulated hydrographs of the three roofs by the reservoir model at (A) low rainfall events and (B) high rainfall events. The light blue area represents the rainfall intensity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Only Bengtsson (2005) was found to investigate the effect of length on green roof performance in the literature. The author concluded that length had an insignificant impact on the performance of the green roof. In this study, however, the length was found to have an impact on detention at low rainfall intensity. In the study of Bengtsson (2005), artificial rainfall with higher intensities (0.4–1 mm/min) were used to investigate the effect of the length. In addition, the values of length tested (1 m and 2 m) were smaller than the ones used in this study.

It should be noted that the retention values obtained by the drainage mats represent the maximum possible values since all experiments were done at dry initial conditions. Initial saturation of drainage layers is affected by many factors including properties of precipitation events at the green roof location (i.e., amount, intensity, duration, inter-events dry weather periods, etc.) and the ability of the drainage layer to restore retention capacity, either by evaporation or plant transpiration. The latter relies on the vegetation types, potential evapotranspiration, and accessibility of drainage storage water by plants roots. Qin et al. (2016) evaluated the effect of evaporation from both substrate and drainage layers using an experimental setup. Moreover, they developed a hydrological model based on plant water uptake from the drainage layer. They found increasing the storage of the drainage layer to reduce water stress and irrigation requirement of the green roofs.

In this study, the dry mats were found to repel the infiltration of water at the start. This repellency decreased with time as the moisture contents of the mat increased. This invites further studies in the matter, particularly for other green roof layers. For instance, one could investigate the water repellency of dry substrates and evaluate the consequence on green roof performance and possible hydrological models. It should be noted that the Water Repellency of soil and porous media was investigated by numerous studies in the literature (Najm et al., 2021; Wang and Wallach, 2022 and references therein). However, to the knowledge of the authors, no studies were conducted in the context of green infrastructure.

4.1. *Implications for conceptual models*

Conceptual models of green roofs, such as the reservoir model, are powerful tools for evaluating the hydrological performance of green roofs with low computational costs. The accuracy of conceptual models was found by previous studies to be comparable to more complex physically-based models (Palla et al., 2012; Peng and Stovin, 2019). The accuracy of such model, however, rely on calibration with observed data limiting the application of these models in cases when measurements are not available. In such cases, inferring model parameters from roof properties based on the calibrated parameters of similar green roofs can be used (Abdalla et al., 2022; Vesuviano and Stovin, 2014; Yio et al., 2013) after addressing issues related to the transferability of model parameters as discussed by previous studies (Abdalla et al., 2022, 2023; Johannessen et al., 2019).

In the study, the parameters of the reservoir model are highly influenced by the slope of the roof. For the same drainage mat, the storage parameter (S) decreases with the increasing slope while the flow coefficients increase with the slope for high rainfall intensity. Therefore, when transferring model parameters of a green roof, the effect of slope, and to a lesser extent the length, should be considered. Specifically, parameters of the storage and flow coefficient should be adjusted to represent the difference in geometries between the calibrated and new green roofs.

4.2. *Implications for stormwater management*

The results of this study have important practical implications for stormwater management. When designing a green roof, it is possible to modify the roof geometry, particularly the roof length, by changing the location of the outlet to the roof gutter. Hence, prolonging or shortening the length of the flow within the green roof. Since the length of the roof was found to enhance the detention of the drainage layer, the location of the outlet can be optimized to maximize the flow length with the green roof.

In addition, the results of this study can be used to investigate the impact of implementing green roofs at the catchment scale. Specifically, the optimal location of green roofs in urban catchments to maximize hydrological benefits. As mentioned before, many studies attempted to optimize the spatial location of green infrastructure using hydrological models of urban catchments (Hou et al., 2020; Le Floch et al., 2022; Liang et al., 2020; Yao et al., 2020). For instance, Yao et al. (2020) found retrofitting buildings that are directly connected to the drainage network with green roofs to be the most cost-effective implementation strategy at the catchment scale. According to Le Floch et al. (2022), retrofitting downstream areas with green roofs reduces the drainage peak flow at the catchment outlet while targeting roof areas upstream reduces flooding of manholes of the urban catchments. However, in these studies, the impact of different roof geometries on the hydrological performance of green roofs was not considered, which could influence the findings on the optimal locations of green roofs. Hence, future studies on the optimal spatial locations of green infrastructure should consider the impact of roof geometries on the hydrological performance of green.

5. Summary and conclusion

The impacts of the roof slope and length on the retention and detention of the drainage mats of green roofs were evaluated in this study. Additionally, the study calibrated a reservoir model to simulate the outflow of the drainage mat at different slope and length values. Based on the findings of this study, the following conclusions can be drawn:

- The RM and ES mats were found to retain up to 8 mm and 6 mm of rainwater and to delay the drainage flow by up to 25 min and 15 min, respectively, which indicates the important role of drainage mats in green roof performance.
- The slope influences both the retention and detention performance of drainage layers for low and high-intensity rainfall events while the length affects the detention performance for low-intensity rainfall events.
- The reservoir model simulated the outflow of the drainage mat with good accuracy ($KGE > 0.75$). The parameters of the reservoir model should be adjusted to simulate the outflow at different slope and length values.

CRediT authorship contribution statement

Elhadi Mohsen Hassan Abdalla: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Knut Alfredsen:** Conceptualization, Methodology, Supervision, Writing – review & editing, Formal analysis. **Tone Merete Muthanna:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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