Evaluating green roof hydrological performance on varying slopes using EPA SWMM

Janice Lynn Ayog#, Venus Tan
Civil Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, MALAYSIA.
#Corresponding author. E-Mail: jay@ums.edu.my; Tel: +6088-320000.

ABSTRACT Urbanization and climate change have increased the frequency and intensity of urban flooding, particularly in tropical cities such as those in Malaysia. Green roofs offer a promising low-impact development (LID) strategy for stormwater management by reducing runoff volume and peak discharge; however, there remains limited understanding of how roof slope influences green roof hydrological performance under tropical rainfall conditions. This study evaluates the effectiveness of green roofs with different slopes in reducing peak runoff and assesses the capability of the EPA Storm Water Management Model (SWMM) to simulate slope-dependent runoff responses. Experimental runoff data were obtained from a laboratory-scale green roof model with slopes of 2% and 6%, subjected to controlled simulated rainfall events, and were used for calibration and validation of EPA SWMM, focusing on key indicators including peak discharge and time to peak. Results show that green roofs significantly reduced peak discharge compared to conventional roofs, with reductions of 97.2% at 2% slope and 95.4% at 6% slope, with the shallower slope exhibiting greater runoff attenuation associated with delayed runoff response. SWMM simulations demonstrated satisfactory agreement with observed data, with Nash–Sutcliffe Efficiency (NSE) values between 0.50 and 0.65 and RMSE–observations standard deviation ratio (RSR) values between 0.58 and 0.68. Overall, the findings indicate that green roofs, including those on steeper slopes, are effective in attenuating stormwater runoff, and that EPA SWMM is a suitable tool for comparative modelling of green roof hydrology under tropical conditions. These insights support the integration of green roofs into urban stormwater planning in Malaysia and similar environments.

KEYWORDS: Green roof; EPA SWMM; hydrological modelling; Low impact development; Model performance
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INTRODUCTION

Rapid urbanization has profoundly altered the hydrological cycle, as the spread of impervious surfaces accelerates stormwater runoff, increases peak discharges, and reduces infiltration (Landon *et al.*, 2025; Shuster *et al.*, 2005). These changes place growing pressure on conventional drainage infrastructure, particularly in tropical cities such as those in Malaysia, where flash floods are becoming increasingly frequent (Mohamed *et al.*, 2024; Shamsuri *et al.*, 2018). The situation is further exacerbated by climate variability, which intensifies the occurrence of extreme rainfall events and raises concerns about the adequacy of existing flood mitigation measures. Since conventional upgrades often demand high costs and additional space, there is a pressing need for sustainable and space-efficient stormwater management strategies that can effectively reduce peak flows while enhancing urban resilience (Burns *et al.*, 2012).

Green roofs have emerged as a widely promoted nature-based solution for stormwater control (Asman *et al.*, 2017). By incorporating vegetation and a substrate layer, they provide interception, storage, infiltration, and evapotranspiration functions that can reduce runoff volumes, lower peak discharges, and delay the timing of runoff generation (Getter & Rowe, 2006; Berndtsson, 2010). International studies report reductions in peak flow ranging from 50–90%, depending on substrate depth, rainfall intensity, and roof slope (Stovin *et al.*, 2012; Mentens *et al.*, 2006). However, green roof performance is highly context dependent. In Malaysia, empirical data remain scarce (Hamid *et al.*, 2023), particularly with respect to how slope influences hydrological behavior under local rainfall regimes.

Beyond experimental approaches, computational hydrological modelling offers a powerful means of extending understanding and application of green roof performance. Physically based models such as the U.S. Environmental Protection Agency's Storm Water Management Model (EPA SWMM) are widely used to simulate stormwater systems, evaluate design alternatives, and assess performance under different rainfall scenarios (Rossman, 2010). Importantly, hydrological models provide a cost-effective and flexible approach for exploring system behavior beyond laboratory or field limitations. Recent applications of SWMM to green roof studies have shown that, with appropriate calibration and validation, the model can reliably represent rainfall–runoff processes, including peak discharge and time-to-peak dynamics (Weggemans *et al*., 2023).

Despite the growing body of literature demonstrating the hydrological benefits of green roofs, the mechanistic influence of roof slope on runoff attenuation remains insufficiently understood, particularly under tropical rainfall conditions. Short-duration, high-intensity storms typical of tropical climates may alter the balance between substrate storage, detention time, and gravitational drainage as roof slope increases (Mendes *et al*., 2025; Qin, 2020). Most existing studies conducted in the tropical regions have focused primarily on thermal or energy performance (e.g. Pragati *et al*., 2023; Jamei *et al*., 2023; Kaewpraek *et al*., 2021) or on runoff peak and volume reduction rather than runoff timing (e.g. Wong & Jim, 2014; Patel *et al.*, 2021; Ferreira & da Rocha, 2023). Consequently, there is limited understanding of how green roof slope affects peak flow attenuation and time-to-peak under tropical rainfall regimes. This study addresses this gap by analyzing laboratory-scale experimental runoff data and applying the EPA Storm Water Management Model (SWMM) to evaluate slope-dependent green roof hydrological responses under rainfall conditions representative of tropical climates.

METHODOLOGY

Experimental Data Source

The experimental runoff data analysed in this study were obtained from previously published laboratory-scale green roof experiments reported by Asman *et al.* (2019). The experiments were conducted using a controlled indoor rainfall simulator and a physical roof test bed designed to capture detailed runoff responses under specified slope and rainfall conditions. The test bed had a total surface area of 1.287 m^2 and a flow width of 1.17 m, allowing for the generation of complete runoff hydrographs suitable for experimental analysis and numerical modelling. Two roof slope configurations were investigated in the original experiments, namely 2% and 6%, representing typical low- and moderate-slope roof conditions. These slope configurations were selected to examine the influence of roof inclination on runoff generation, peak discharge, and runoff timing from green roof systems. Rainfall was applied as a controlled, uniform event with an intensity of 200 mm h^{-1} over a duration of 1 hour, producing runoff hydrographs that captured the rising limb, peak flow, and recession phase. The rainfall characteristics correspond to short-duration, high-intensity storm events commonly observed in tropical climates and were adopted directly from the experimental protocol described by Asman *et al.* (2019). No modification of the rainfall input was undertaken in this study.

Model Development in EPA SWMM

In the EPA SWMM framework, the green roof was represented using the Low Impact Development (LID) module as a conceptual system comprising a substrate layer overlying a drainage layer, consistent with the experimental configuration reported by Asman *et al.* (2019). While the experimental study clearly defined the test bed geometry and slope conditions, detailed information on substrate composition, vegetation species, and certain hydraulic properties was not fully reported. Accordingly, parameters governing substrate hydraulic behaviour, including saturated hydraulic conductivity, porosity, suction head, and field capacity, were specified using standard SWMM LID module defaults and subsequently refined through calibration against observed runoff hydrographs.

Calibration and Validation Approach

Calibration and validation of the SWMM model were performed using the observed hydrographs from the physical roof experiments. The calibration was based on the 2% slope dataset, while the 6% slope dataset was reserved for validation. Model performance was assessed by comparing simulated and observed hydrographs, with particular emphasis on peak discharge and time to peak, as these indicators directly influence urban stormwater management outcomes.

Performance Evaluation Criteria

The goodness-of-fit between observed and simulated hydrographs was quantified using two widely adopted statistical indices: the Nash–Sutcliffe Efficiency (NSE) and the Root Mean Square Error–observations standard deviation ratio (RSR). The NSE evaluates how closely the simulated runoff matches the observed data which is expressed as

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \bar{Q}_{obs}\right)^2} \tag{1}$$

where n is the number of time steps in the hydrograph, i is the index of each time step, $Q_{obs,i}$ is the observed discharge at time step i, $Q_{sim,i}$ is the simulated discharge at time step i and $\bar{Q}_{obs}$ is the mean of the observed discharge. An NSE value closer to 1 indicates higher model efficiency.

The RSR is defined as the Root Mean Square Error (RMSE) divided by the standard deviation of the observed data and expressed as

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Q_{obs,i} - \bar{Q}_{obs}\right)^2}} \tag{2}$$

where RSR values closer to 0 indicate better model performance. Model performance was classified according to the thresholds proposed by Moriasi *et al.* (2007) as summarized in Table 1.

Table 1. Model evaluation performance ratings based on NSE and RSR (Moriasi *et al.*, 2007)

Performance Rating (%)	NSE	RSR
Very Good	$0.75 \leq NSE \leq 1.00$	$0.00 \leq RSR \leq 0.50$
Good	$0.65 \leq NSE \leq 0.75$	$0.50 \leq RSR \leq 0.60$
Satisfactory	$0.50 \leq NSE \leq 0.65$	$0.60 \leq RSR \leq 0.70$
Unsatisfactory	$NSE \leq 0.50$	$RSR > 0.50$

RESULT AND DISCUSSION

Model Calibration and Validation

The EPA SWMM model was calibrated and validated using observed flow discharges from the physical roof model at 2% and 6% slopes, with the final calibrated parameter values shown in Table 2. The statistical evaluation produced Nash–Sutcliffe Efficiency (NSE) values between 0.50 and 0.65 and RMSE-observations standard deviation ratio (RSR) values ranging from 0.58 to 0.68. According to the performance criteria established by Moriasi *et al.* (2007), these results fall within the "satisfactory" category, indicating that the model reproduced the observed runoff flow response with acceptable accuracy under local rainfall conditions. However, comparison of simulated and observed hydrographs indicates that peak flow responses were attenuated in the simulations, particularly for the steeper slope configuration. This behavior is attributed to the conceptual structure of the SWMM LID module, which represents green roof processes using simplified vertical storage representations that do not explicitly resolve rapid lateral drainage, particularly under steeper slope conditions.

Table 2. Final EPA SWMM parameter values used for roof simulations.

Parameter	Unit	Green roof	Conventional roof
Catchment area	m²	12.9	
Flow width	m	1.17	
Imperviousness	%	0	100
Manning's roughness, *n*	-	0.50	0.01
Depression storage	mm	2.0	
Infiltration method	-	Modified Green-Ampt	
Suction head	mm	300	3.5
Saturated hydraulic conductivity	mm h⁻¹	0.5	
Initial moisture deficit	-	0.015	0.25

Hydrograph comparisons further support these findings. For the 2% slope roof, the simulated outflow closely matched the observed hydrograph, with only minor deviations during peak discharge (Figure 1). Validation with independent rainfall events (Figure 2) revealed that the model slightly underestimated the rising limb, yet it successfully captured both peak discharge and the recession limb within acceptable limits. In contrast, the 6% slope roof exhibited somewhat larger discrepancies between observed and simulated peaks, which can be attributed to the shorter concentration time and more rapid drainage behaviour associated with steeper slopes.

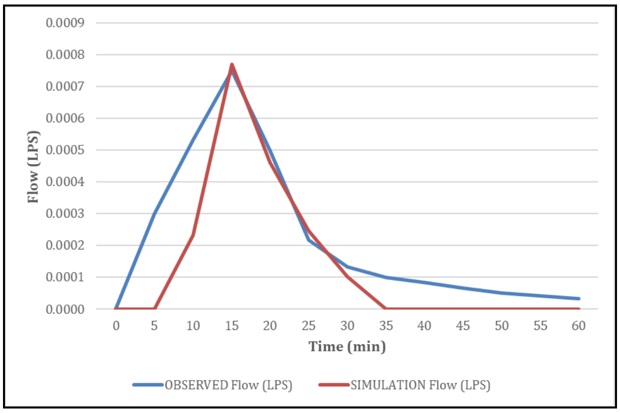

Figure 1. Observed *vs.* simulated flow hydrograph for calibration (2% slope).

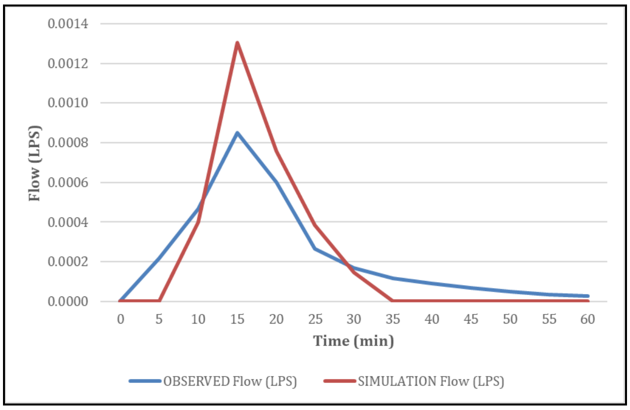

Figure 2. Observed *vs.* simulated flow hydrograph for calibration (6% slope).

Overall, these outcomes suggest that while EPA SWMM tends to produce attenuated peak runoff responses, it remains a reliable tool for representing the hydrological behavior of both roof types. The performance metrics confirm that the model adequately reproduces the timing and magnitude of runoff peaks, which are critical for stormwater management assessments. Consequently, the calibration and validation results provide sufficient confidence for using SWMM in the comparative analysis of green and conventional roof systems.

Comparative Peak Discharge Reduction of Green and Conventional Roofs

The validated EPA SWMM model was applied to evaluate the hydrological benefits of green roof systems under roof slopes of 2% and 6%. Table 3 presents the simulated peak flow discharges for green roofs compared with conventional roofs. At both slopes, the introduction of a green roof substantially reduced peak flows, with the reduction being more pronounced for the 2% slope configuration (i.e. by 97.2%). The gentler slope allowed more time for rainfall to infiltrate and be retained by the substrate, whereas the steeper slope promoted faster drainage, leading to relatively higher runoff volumes.

Table 3. Simulated peak flow and percentage differences for green roofs *vs.* conventional roofs.

Roof Slope (%)	Roof Type	Peak Flow (L/s)	Peak Flow Differences
2%	Conventional	0.0282	97.2%
	Green	0.0008	
6%	Conventional	0.0282	95.4%
	Green	0.0013	

The flow hydrographs in Figure 3 and Figure 4 further illustrate the contrasting responses between green roofs (WGR) and conventional roofs (WoGR) under different slopes. For the 2% slope (Figure 3), the green roof substantially attenuated the peak flow discharge, lowering both the magnitude and steepness of the hydrograph. The delayed time to peak indicates that the green roof provided additional detention and enhanced retention capacity, allowing rainfall to be temporarily stored and released more gradually. This behaviour suggests that a shallower slope promotes higher water residence time within the substrate, maximising infiltration and evapotranspiration. By contrast, at the 6% slope (Figure 4), the green roof still achieved reductions in peak flow relative to the conventional roof, but the attenuation effect was less pronounced. The peak occurred earlier, with only a modest delay compared to the control, and the peak flow remained relatively higher. These differences are consistent with the findings of Chow *et al.* (2018), which indicate that steeper surfaces, due to reduced storage potential and faster drainage pathways, have a limited capacity to retain water because of stronger gravitational forces.

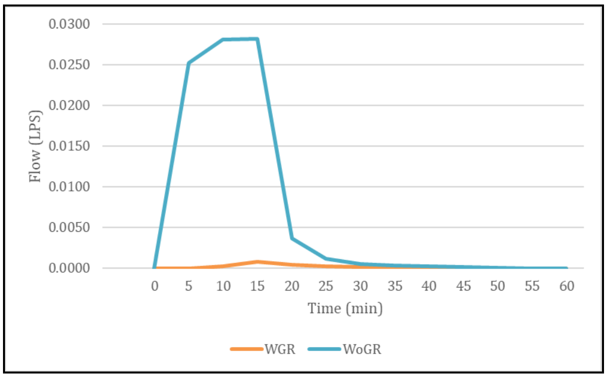

Figure 3. Hydrograph comparison for green roof (WGR) *vs.* conventional roof (WoGR): 2% slope.

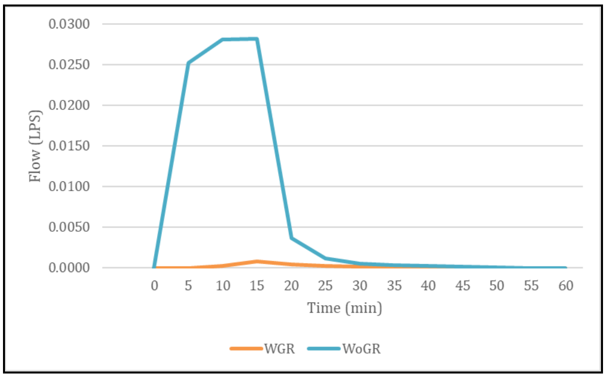

Figure 4. Hydrograph comparison for green roof (WGR) *vs.* conventional roof (WoGR): 6% slope.

CONCLUSION

This study examined the influence of roof slope on green roof runoff behavior under rainfall conditions representative of tropical climates, using laboratory-scale experimental data and numerical simulations with the EPA Storm Water Management Model (SWMM). The results indicate that roof slope affects runoff generation characteristics, particularly peak flow attenuation, highlighting the importance of slope considerations in green roof hydrological performance. The SWMM LID module reproduced the overall runoff response with satisfactory performance for both slope configurations, supporting its suitability for comparative assessment of slope-dependent effects. While differences in peak response between simulated and observed hydrographs reflect the simplified conceptual representation of green roof processes within the model, such limitations are consistent with its intended application for screening-level analysis. Future studies could extend this work by examining a wider range of roof slopes and rainfall characteristics and by incorporating more detailed experimental information on substrate and vegetation properties to support enhanced model parameterization. Overall, the findings provide quantitative support for the consideration of green roofs as a stormwater management measure in urban areas of Malaysia and other regions with tropical climatic conditions.

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