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From rooftop pilots to campus-scale stormwater modelling: assessing green roof performance for urban flood mitigation in Hanoi

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ABSTRACT

Urban flooding is an increasing challenge in dense cities where impervious surfaces accelerate runoff and overload drainage systems. This study evaluates green roofs as a distributed source-control measure for stormwater management at Hanoi University of Civil Engineering (HUCE), Vietnam, using an integrated experimental–modelling framework that combines pilot-scale roof observations with SewerGEMS-based campus-scale drainage simulations. Green roof scenarios were assessed by varying antecedent moisture conditions, planting soil thickness, rainfall magnitude, and rooftop coverage. The results showed that antecedent soil moisture strongly controlled green roof performance. The non-irrigated green roof achieved the highest runoff reduction, peak attenuation, and peak delay, while irrigated systems performed less effectively due to reduced available storage. Increasing planting soil thickness from 80 to 250 mm improved runoff retention, with the 250-mm configuration providing the greatest hydrological benefit. At the campus scale, green roof implementation reduced runoff volume and peak discharge, with a maximum runoff reduction of 84.55% under full rooftop coverage. Water-level analysis at MH09, the most flood-prone drainage manhole in the campus stormwater network, showed that green roofs mitigated drainage stress under moderate rainfall but were insufficient as a standalone solution under extreme storms. The findings supported integrating green roofs into multi-layered urban stormwater strategies.

Key words: green roof, low impact development, nature-based solutions, runoff retention, urban drainage, stormwater management

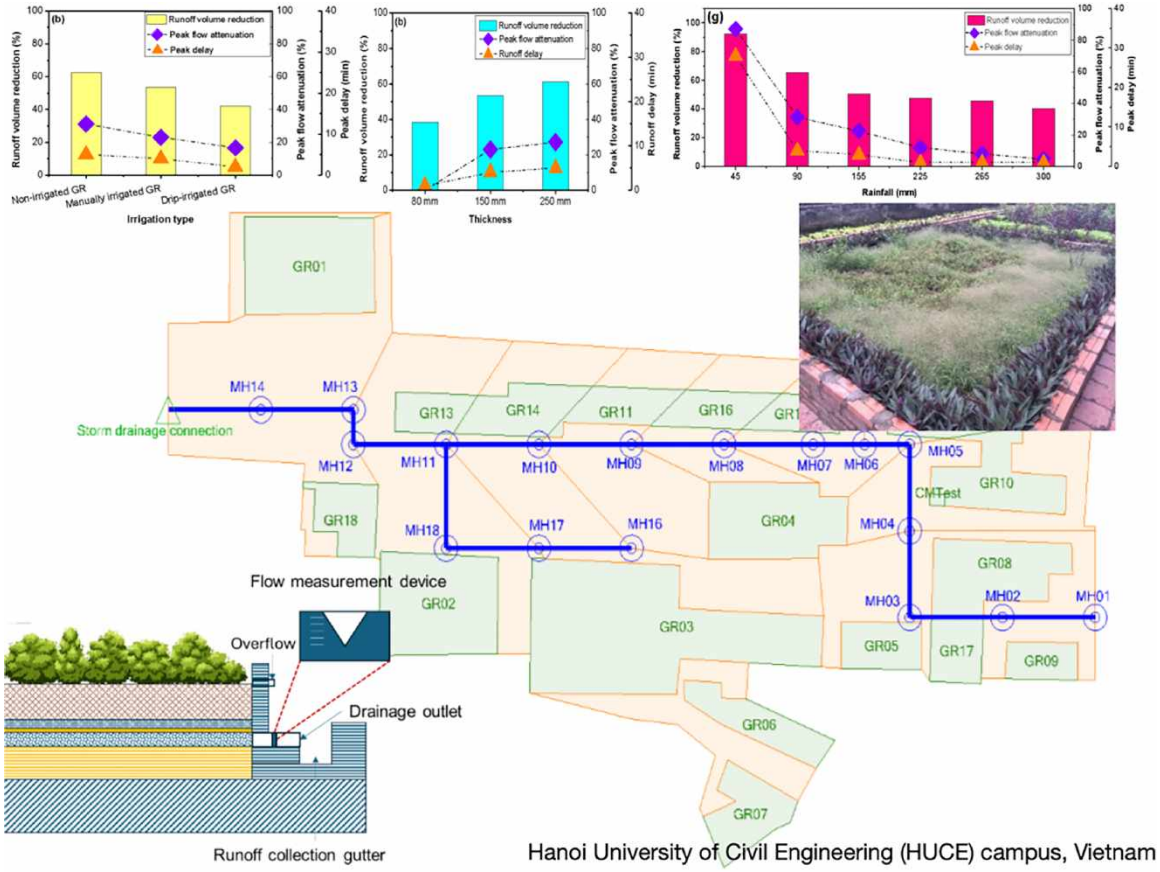
HIGHLIGHTS

- Non-irrigated green roofs showed the most efficient rooftop runoff-control performance.
- A 250-mm soil layer provided the highest rooftop runoff retention.
- Full green roof coverage reduced campus runoff by up to 84.55%.
- Green roofs delayed water-level rise at critical manhole MH09 under P10 rainfall.
- P50–P100 storms require storage and drainage upgrades.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

Urban flooding has become an increasingly critical challenge in rapidly urbanizing cities, where the expansion of impervious surfaces accelerates stormwater runoff and increases pressure on existing drainage systems. Rooftops, roads, parking areas, and paved courtyards reduce infiltration and shorten runoff concentration time, leading to higher peak discharge and more frequent drainage overload during intense rainfall events (Wadhwa & Pavan Kumar 2020; Cao *et al.* 2022; Akter & Rain 2025). This problem is further intensified by climate change, which is increasing the frequency and severity of heavy rainfall events in many urban regions (Legg 2021; Meresa *et al.* 2022). In dense cities, where land for new retention ponds or drainage expansion is limited, distributed source-control measures are increasingly needed to complement conventional pipe-based drainage infrastructure.

Green roofs are a promising nature-based solution for source-control stormwater management because they can be implemented on building rooftops without requiring additional ground-level land while providing rainfall retention, peak attenuation, and runoff-delay benefits (Czemiel Berndtsson 2010; Shafique *et al.* 2018; Pons *et al.* 2022). The concept of nature-based solutions, formally defined by the International Union for Conservation of Nature (IUCN) as actions to protect, sustainably manage, and restore ecosystems in ways that address societal challenges while benefiting human well-being and biodiversity, has been widely adopted as an umbrella framework for green infrastructure approaches (Cohen-Shacham *et al.* 2016). Through the combined functions of vegetation, planting soil, and drainage layers, green roofs retain rainfall, delay runoff generation, attenuate peak discharge, and redistribute stormwater outflow over time (Speak *et al.* 2013; Versini *et al.* 2015; Sims *et al.* 2019). Their performance, however, is highly variable and depends on local design and hydrological conditions, including rooftop structure, planting soil depth, drainage configuration, rainfall intensity and duration, and antecedent moisture condition (Li & Babcock 2014; Mora-Melià *et al.* 2018; Dong *et al.* 2023). In particular, a thicker planting soil layer can increase temporary water storage, while wet antecedent conditions caused by irrigation or preceding rainfall can reduce the available pore volume before a storm event (VanWoert *et al.* 2005; Meng *et al.* 2021).

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Hydrological and hydraulic models have been widely used to assess green roof performance beyond individual test plots. Low Impact Development (LID)-based modelling approaches provide useful tools for estimating runoff reduction, peak attenuation, and drainage-network responses at building, neighbourhood, and urban scales, particularly when green roof processes are represented through storage, infiltration, drainage, and routing parameters (Li & Babcock 2014; Locatelli *et al.* 2014; Versini *et al.* 2015; Dong *et al.* 2023). Nevertheless, a key limitation remains: many studies either focus on small-scale experimental monitoring or rely on idealized modelling scenarios, while fewer studies connect pilot-scale green roof observations with drainage-network simulations to evaluate how rooftop-level performance translates into broader stormwater benefits. In addition, most assessments emphasize runoff volume and peak discharge, whereas fewer explicitly examine water-level response at hydraulically vulnerable drainage nodes, which is critical for practical flood-risk interpretation and stormwater policy.

These knowledge gaps are particularly relevant for Hanoi, Vietnam, where rapid urban development has increased impervious surface coverage and frequent pluvial flooding occurs during heavy rainfall events (Hieu *et al.* 2025; Hoang & Tran 2025). A recent satellite-based assessment of Hanoi found that approximately 80% of newly urbanized land between 2015 and 2024 was located on geomorphologically flood-susceptible units such as floodplains and paleochannels, with the main pressures being increasing impervious surfaces, infilling of lakes and ponds, and reduced drainage capacity (Hieu *et al.* 2025). Although green roofs have been discussed as a potential urban stormwater measure, and preliminary local studies at HUCE have examined rooftop runoff control (Cuong *et al.* 2017) and cost (Dang *et al.* 2016), locally grounded evidence remains limited regarding their performance under monsoon rainfall conditions, their sensitivity to irrigation-related antecedent moisture, and their potential contribution when scaled from rooftop pilots to a campus drainage network. For public spaces in dense urban districts, rooftops represent a practical but underused space for distributed runoff control; however, implementation requires quantitative evidence that links design parameters, rainfall conditions, drainage performance, and policy-relevant flood mitigation outcomes.

To address these gaps, this study develops an integrated pilot-observation and SewerGEMS-based modelling framework to assess green roof performance from rooftop to campus-scale at Hanoi University of Civil Engineering (HUCE), located in the centre of Hanoi city, Vietnam. The objectives were designed to follow the main steps required for translating full-scale green roof performance into drainage system evidence. First, rooftop-scale simulations were used to isolate the effects of key hydrological and design controls, including antecedent moisture condition, planting soil thickness, and rainfall magnitude. Next, field observations from conventional and green roof systems were used to compare and verify whether the simulated responses were consistent with real rooftop behaviour under local rainfall conditions. Subsequently, campus-scale simulations were performed to evaluate whether rooftop-level benefits could translate into measurable runoff reduction, peak attenuation, and peak delay at the drainage-network outlet. Finally, water-level responses at MH09, the most flood-prone and hydraulically unfavourable drainage manhole in the HUCE campus stormwater network, were examined to connect green roof implementation with flood-relevant hydraulic performance, thus informing urban flood mitigation and stormwater policy implications. The novelty of this study lies in linking rooftop pilot observations, SewerGEMS-based LID modelling, campus-scale implementation scenarios, and critical-node water-level assessment within a single framework.

2. MATERIALS AND METHODS

2.1. Overall modelling framework

The methodological framework was designed to link full-scale green roof behaviour with campus drainage performance through a sequence of modelling and observation steps. First, the hydrological behaviour of the green roof was formulated using an event-based water balance approach and represented in SewerGEMS using the LID Green Roof module in SewerGEMS software. Second, key green roof design and hydrological parameters, including planting soil thickness, antecedent soil moisture, rainfall magnitude, and rooftop coverage, were varied to construct a set of scenario-based simulations. Third, rooftop-scale simulations were compared with outdoor roof-cell observations from the Hanoi University of Civil Engineering (HUCE) green roof experiment to examine whether the modelled drainage responses were consistent with observed behaviour (Dang *et al.* 2016; Cuong *et al.* 2017). Fourth, the selected green roof configurations were implemented in the campus-scale SewerGEMS drainage model to evaluate runoff volume reduction, peak flow attenuation, peak delay at

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the campus outlet, and water-level response at MH09, the most flood-prone manhole in the campus stormwater network. Finally, the results were interpreted to identify practical implications for campus-scale stormwater management and potential policy directions for wider green roof implementation in Hanoi. The main steps of the SewerGEMS model setup and scenario development are illustrated in Supplementary Information – Figure S1.

2.2. Study area

This study was conducted at the campus of Hanoi University of Civil Engineering (HUCE), located in a highly urbanized area of Hanoi, Vietnam. The campus contains a large proportion of impervious surfaces, including building rooftops, internal roads, paved courtyards, and parking areas. During intense rainfall events, runoff from these surfaces is rapidly conveyed to the internal stormwater drainage network before discharging to the municipal drainage system, increasing the risk of local drainage stress and surface inundation. The study area, observed flooding context, and SewerGEMS campus drainage model are shown in Figure 1. Building rooftops were selected as the main intervention area because they represent extensive impervious surfaces that can be controlled at source without requiring additional ground-level land. Green roofs were therefore evaluated as a distributed source-control measure to reduce runoff generation, attenuate peak discharge, and delay stormwater delivery to the campus drainage system.

2.3. Pilot green roof system and LID representation

Pilot-scale observations from previous green roof systems installed at HUCE were used as a practical reference for model setup and interpretation. The experimental rooftop was selected based on practical, structural, and hydrological considerations. The site was located within the inner urban area of Hanoi and is connected to the HUCE campus stormwater drainage system, making it suitable for evaluating rooftop source-control measures. It provided sufficient flat reinforced-concrete roof area for comparable roof cells, safe long-term access for installation and monitoring, available water supply for irrigation, and existing drainage outlets for runoff collection. Rooftop runoff is collected in open concrete gutters (the runoff collection gutter shown in Figure 2) and conveyed downward through uPVC vertical downpipes into covered concrete perimeter channels. These channels discharge into the underground stormwater pipe network, which collects runoff from the entire campus and drains toward the municipal stormwater system to the west of the campus (Supplementary Information – Figure S1(a)). This roof-to-network drainage sequence reflects the conventional stormwater design used in reinforced-concrete buildings in Hanoi. The green roof installation was limited to a small pilot area and did not obstruct normal building operation or roof drainage. Therefore, the site was considered appropriate for pilot-scale testing, although detailed structural assessment would be required before wider application to other buildings. The experimental system consisted of one conventional roof used as the control and three green roof cells representing non-irrigated, manually irrigated, and drip-irrigated conditions. Each outdoor roof cell had an effective area of approximately 16 m^2 (4 m × 4 m).

The green roof was constructed as a standard layered system using locally available materials, including natural planting soil rather than a lightweight engineered substrate, reflecting a practical and low-cost configuration suitable for local implementation. The green roof structure consisted of a vegetation layer, a planting soil layer, a sand transition layer, a geotextile membrane, a gravel drainage layer, waterproofing protection, and the reinforced concrete roof slab (Figure 2). The vegetation layer was selected to reflect locally applicable green roof strategies under Hanoi's hot and humid monsoon conditions. The non-irrigated green roof was planted with drought-tolerant ornamental and ground-cover species, while the manually irrigated and drip-irrigated green roofs were planted mainly with edible vegetables and herbs to represent productive green roof options. Representative species and planting strategies are provided in Supplementary Information – Table S1. The selected species were locally available, had shallow or fibrous root systems suitable for the 150-mm planting soil layer, and avoided deep woody roots that could affect the waterproofing layer. Edible vegetable species were mainly established by direct seeding as a low-cost and easily replicable planting method.

Field-based verification was conducted using observed rainfall–runoff data from the outdoor roof-cell experiment. The monitored dataset included measured rainfall events and outflow hydrographs from the conventional roof, non-irrigated green roof, manually irrigated green roof, and drip-irrigated green roof. The observed hydrographs were used to verify whether the simulated green roof responses were consistent with real rooftop behaviour under local rainfall conditions. The comparison focused on the same performance

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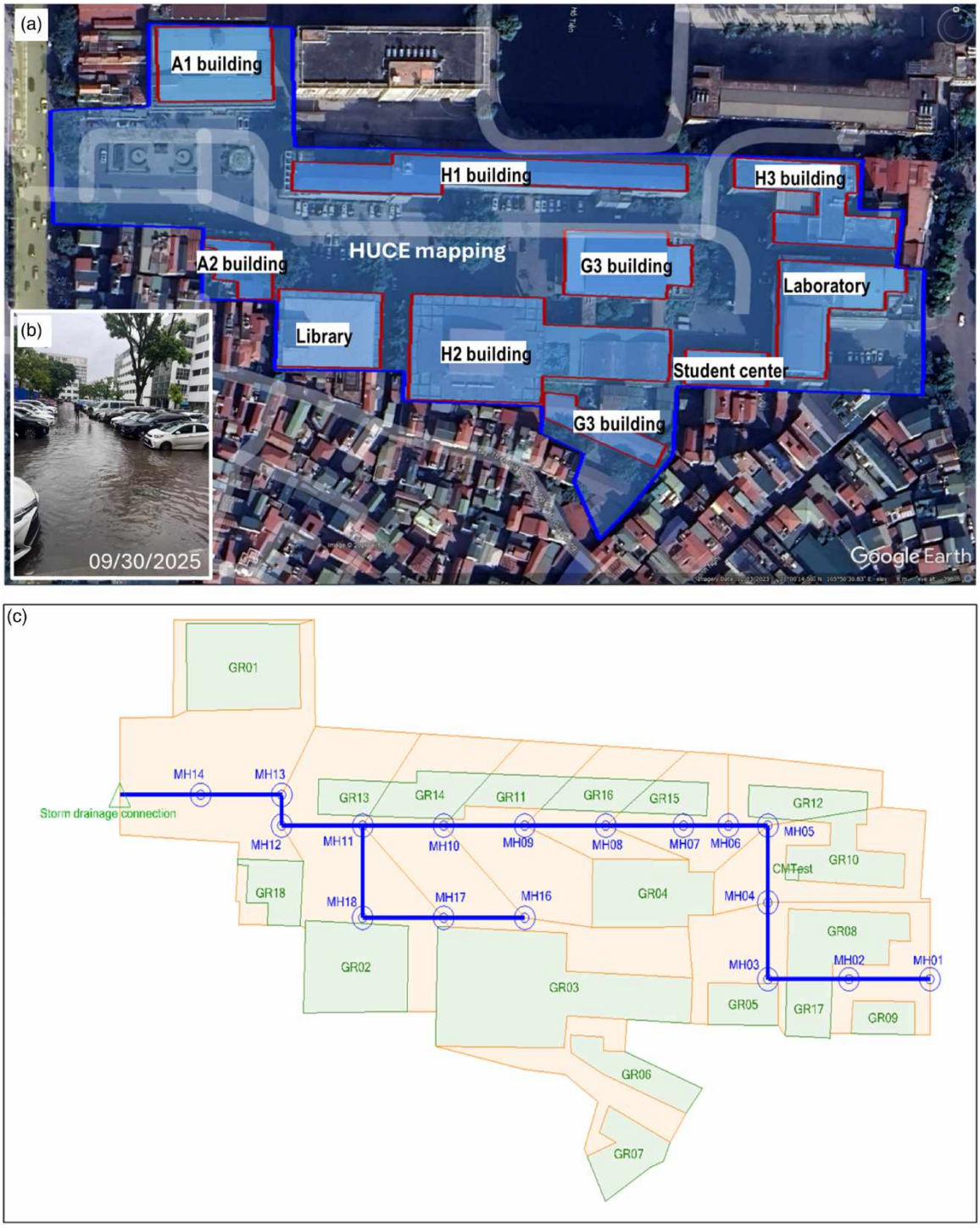


Figure 1 | HUCE campus study area and observed flooding: (a) campus layout and selected building rooftops considered for green roof implementation; (b) observed pluvial flooding within the campus during the heavy rainfall event on 30 September 2025 and (c) SewerGEMS model of the HUCE campus drainage system and rooftop sub-catchments selected for green roof implementation.

indicators used in the modelling analysis, including runoff volume reduction, peak flow attenuation, runoff delay, and peak delay. Because the field dataset was limited to a small number of roof cells and rainfall events, the observations were used as a ground-based consistency check rather than a full statistical calibration of the SewerGEMS model. The observed outflow data for the two consecutive rainfall events are provided in Supplementary Information – Table S2.

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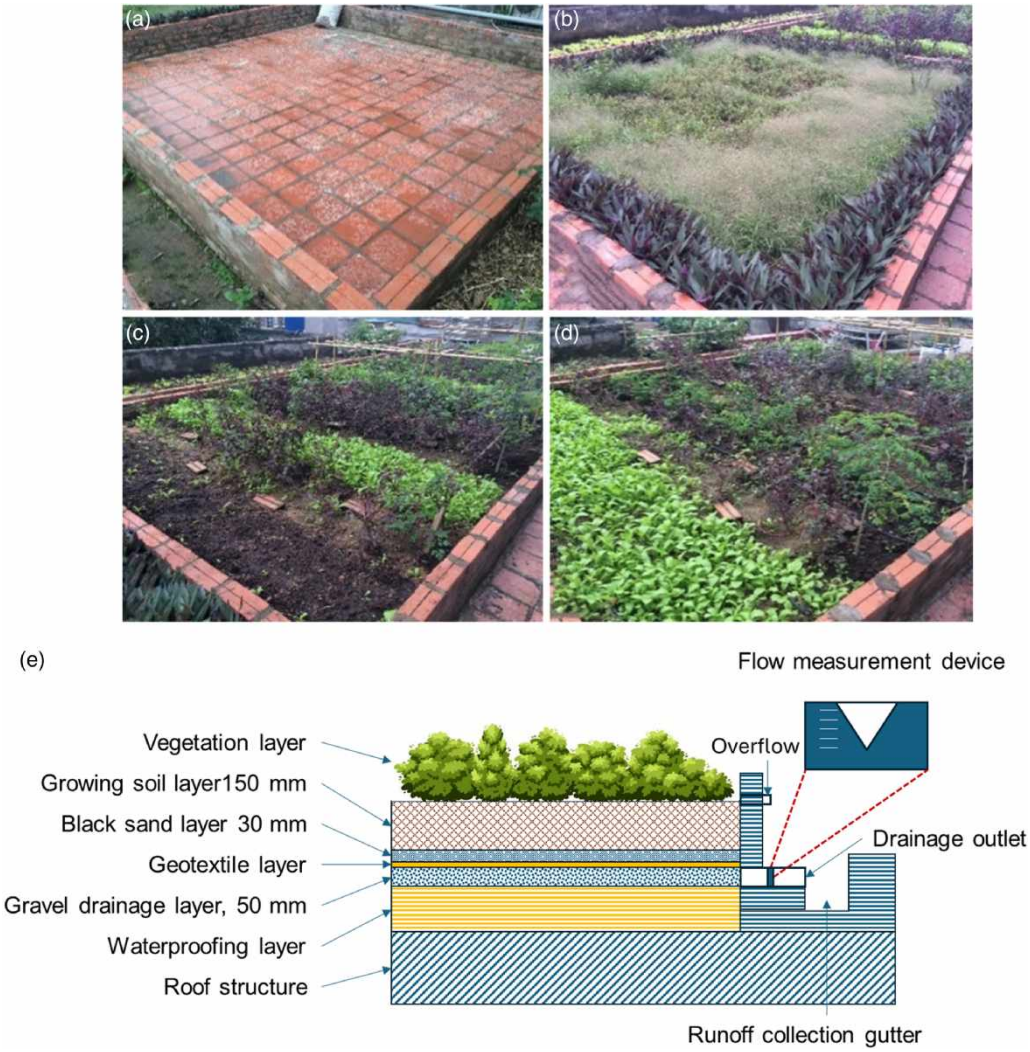


Figure 2 | Pilot-scale 4 m × 4 m green roof system at HUCE: (a) conventional roof; (b) non-irrigated green roof planted with drought-tolerant ornamental and ground-cover species; (c) manually irrigated green roof planted with edible vegetables and herbs; (d) drip-irrigated green roof planted with edible vegetables and herbs; and (e) layer configuration of the pilot green roof system. Rooftop runoff is collected in the open gutter and measured at the drainage outlet before discharge into the closed campus stormwater network.

In SewerGEMS, the green roof was represented using the Low Impact Development (LID) Green Roof module. The LID system was conceptualized as a layered structure consisting of a surface layer, a planting soil layer, and a drainage layer. The surface layer represents shallow depression storage and surface flow resistance, while the planting soil layer accounts for rainfall storage, infiltration, and percolation. The drainage layer represents temporary storage and lateral drainage toward the roof outlet. Because the pilot green roof was constructed with natural planting soil, the LID parameters were selected to reflect the hydraulic behaviour of locally available soil and drainage materials. Three planting soil thickness configurations were considered: 80, 150, and 250 mm. The 150-mm configuration corresponds to the pilot-scale green roof previously tested at HUCE, while the 80- and 250-mm configurations were used to evaluate thinner and thicker planting soil layers. Other surface, soil hydraulic, and drainage-layer parameters were kept constant across the three configurations to isolate the effect of planting soil thickness on runoff generation and drainage response. The LID Green Roof parameters used in SewerGEMS are summarized in Supplementary Information – Table S3.

2.4. Green roof design, irrigation, and rainfall scenarios

To evaluate the effects of green roof design and hydrological conditions, simulation scenarios were developed by varying planting soil thickness, antecedent soil moisture, rainfall magnitude, and rooftop coverage. Three

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planting soil thicknesses were considered: 80, 150, and 250 mm. Irrigation condition was represented through the initial saturation of the planting soil layer rather than by changing the intrinsic soil hydraulic properties. Three antecedent moisture conditions were defined: non-irrigated, low-irrigation, and high-irrigation scenarios, corresponding to initial soil saturation levels of 20, 40, and 60%, respectively (Supplementary Information – Table S4). This approach allowed the effect of irrigation-related antecedent wetness on runoff generation and drainage response to be assessed while keeping the same soil hydraulic parameters.

Seven rainfall scenarios were used to represent a range of storm conditions relevant to Hanoi. Three short-duration rainfall events of 16, 45, and 90 mm over 1.5 h were used to examine rooftop-scale responses under frequent to intense local rainfall conditions. Four design rainfall events of 155, 225, 265, and 300 mm over 6 h, corresponding to P5, P10, P50, and P100 rainfall conditions, respectively, were used for extended rooftop-scale stress testing and campus-scale drainage simulations. The rainfall scenarios were selected as engineering design events grounded in local rainfall statistics and recent extreme rainfall experience in northern Vietnam. For the 6-h events, the 155-, 265-, and 300-mm scenarios are broadly consistent with the 5-year, 50-year, and 100-year rainfall depths derived from IDF curves for the Ha Dong meteorological station in Hanoi, which give approximate 6-h rainfall depths of 155, 262, and 293 mm, respectively (Le 2020; Duong & Tran 2024; Department of Construction of Hanoi city and Vietnam Water and Environment Joint Stock Company (VIWASE) 2026). The 225-mm event was retained as an intermediate severe rainfall scenario between the 5-year and 50-year events. These scenarios were therefore intended to represent a plausible range of rainfall loading conditions rather than a full probabilistic rainfall ensemble. All rainfall inputs were defined in SewerGEMS as 5-min incremental time–depth hyetographs, meaning that each value represents the rainfall depth occurring within the corresponding 5-min interval rather than cumulative rainfall. The incremental rainfall depths used to construct rainfall hyetographs for SewerGEMS simulations are presented in Supplementary Information – Table S5. For the campus-scale analysis, selected green roof configurations were applied to 25, 50, 75, and 100% of suitable rooftop areas. These coverage levels were used to evaluate how the extent of rooftop greening affects runoff volume reduction, peak flow attenuation, peak delay, and water-level response at critical drainage locations.

2.5. Water balance and performance indicators

The hydrological performance of the green roof was evaluated using an event-based water balance approach. For each rainfall event, incoming water was partitioned into surface runoff, drainage outflow, evapotranspiration, and temporary storage within the green roof layers. The total outflow from the green roof was then compared with that from the conventional roof or baseline drainage condition. The selected indicators were chosen to represent the two main hydrological functions of green roofs: retention and detention. Runoff volume reduction was used to quantify rainfall retention, while peak flow attenuation was used to evaluate the reduction of drainage loading during peak response. Runoff delay and peak delay were included to describe the temporal redistribution of stormwater outflow. These indicators have been widely used in green roof hydrological assessment and modelling studies (Czemiel Berndtsson 2010; Locatelli *et al.* 2014; Silva *et al.* 2021; Dong *et al.* 2023). At the campus scale, the simulated water level at MH09 was additionally used to assess local drainage stress and potential surcharge risk at the most flood-prone drainage manhole in the HUCE stormwater network.

$$P + I = R_s + R_d + \mathrm{ET} + \Delta S \tag{1}$$

$$R_{\mathrm{out}} = R_S + R_d \tag{2}$$

$$V_{\mathrm{out}} = \frac{A \times R_{\mathrm{out}}}{1,000} \tag{3}$$

$$V_{\mathrm{red}} = V_{\mathrm{control}} - V_{\mathrm{green}} \tag{4}$$

$$\mathrm{RR} = \left(\frac{V_{\mathrm{control}} - V_{\mathrm{green}}}{V_{\mathrm{control}}}\right) \times 100 \tag{5}$$

$$\mathrm{PA} = q_{p,\mathrm{control}} - q_{p,\mathrm{green}} \tag{6}$$

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$$\mathrm{PR} = \left(\frac{q_{p,\mathrm{control}} - q_{p,\mathrm{green}}}{q_{p,\mathrm{control}}}\right) \times 100 \tag{7}$$

$$\Delta T_r = T_{r,\mathrm{green}} - T_{r,\mathrm{control}} \tag{8}$$

$$\Delta T_p = T_{p,\mathrm{green}} - T_{p,\mathrm{control}} \tag{9}$$

where P is the cumulative rainfall depth during a storm event (mm), I is the irrigation or antecedent water input (mm), R_s is the cumulative surface runoff depth from the green roof (mm), R_d is the cumulative drain outflow depth from the drainage layer (mm), ET is the evapotranspiration depth (mm), and ΔS is the change in water storage within the green roof system (mm). R_{out} is the total outflow depth from the green roof (mm), calculated as the sum of surface runoff and drain outflow. A is the green roof area (m^2), and V_{out} is the corresponding total outflow volume (m^3). Because this study focused on event-based rainfall–runoff response, evapotranspiration was included in the general water balance but was not analysed as a separate performance indicator. The runoff volume reduction, V_{red} (m^3), represents the absolute decrease in runoff volume from the green roof relative to the conventional roof or baseline scenario. The relative runoff reduction, RR (%), was used as the main indicator for comparing green roof performance across scenarios because it normalizes the reduction by the corresponding baseline runoff volume. $V_{control}$ and V_{green} are the total runoff volumes (m^3) from the conventional roof or baseline condition and the green roof scenario, respectively. Peak flow attenuation, PA, represents the absolute reduction in peak outflow rate. The relative peak flow reduction, PR (%), was used as the main indicator for comparing peak attenuation across rooftop and campus-scale scenarios. $q_{p,control}$ and $q_{p,green}$ are the peak outflow rates from the conventional roof or baseline condition and the green roof scenario, respectively. Runoff delay, ΔT_r (min), was defined as the difference between the onset time of outflow from the green roof and that from the conventional roof or baseline condition. Peak delay, ΔT_p (min), was defined as the difference between the time to peak outflow from the green roof and that from the conventional roof or baseline condition. These indicators were used to assess both the retention and detention effects of green roof implementation at rooftop and campus scales. As an illustrative example, for the non-irrigated green roof under the 45 mm rainfall event, the relative runoff reduction was calculated as $\mathrm{RR} = (V_{control} - V_{green})/V_{control} \times 100 = 92.43\%$, indicating that roughly 92% of the incoming rainfall volume was retained relative to the conventional roof baseline. The remaining indicators (PR, ΔT_r, ΔT_p) were computed analogously from the corresponding outflow hydrographs.

2.6. Campus-scale green roof implementation

After the rooftop-scale simulations, the 150- and 250-mm green roof configurations were incorporated into a campus-scale stormwater model developed in SewerGEMS (Bentley Systems, PA, USA). The HUCE campus was represented by rooftop sub-catchments, paved surface sub-catchments, drainage nodes, conduits, manholes, and outlet structures. Building rooftops were defined as candidate areas for green roof implementation, while roads, courtyards, and other paved areas were treated as conventional impervious surfaces. The campus stormwater network, comprising the covered perimeter channels and underground pipelines, was represented in SewerGEMS as closed conduits connected through manholes, consistent with the enclosed drainage that conveys rooftop runoff across the campus. The campus drainage layout and selected rooftop sub-catchments are shown in Figure 1(c). Green roof implementation was evaluated under five scenarios: a baseline case without green roofs and four rooftop coverage levels corresponding to 25, 50, 75, and 100% of suitable rooftop areas. The coverage levels refer to the proportion of suitable rooftop area converted to green roofs, not to the entire HUCE campus area. In the campus-scale model, 18 rooftop sub-catchments were identified as suitable for green roof implementation, with a total suitable rooftop area of approximately 11,440 m^2. Therefore, the 25, 50, 75, and 100% coverage scenarios correspond to approximately 2,860, 5,720, 8,580, and 11,440 m^2 of implemented green roof area, respectively. Roads, courtyards, and other non-rooftop impervious surfaces were kept unchanged in all scenarios. Thus, the 100% coverage scenario represents full conversion of suitable rooftop areas, rather than greening of the entire campus catchment. The rooftop areas assigned to each coverage scenario are summarized in Supplementary Information – Table S6. For full rooftop conversion, the LID element was set to occupy the entire sub-catchment. For partial implementation, the LID area and width were defined based on the implemented green roof area and roof geometry. Campus-scale simulations were conducted under the P5, P10, P50, and P100 rainfall scenarios. The outputs were assessed using runoff volume

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reduction, peak flow attenuation, and peak delay at the campus outlet. In addition, the simulated water level at the critical manhole MH09 was compared with the pipe invert and crown elevations to evaluate local drainage stress and potential surcharge conditions.

The SewerGEMS model was designed as a scenario-based comparison between the baseline drainage condition and green roof implementation scenarios. To ensure consistency among scenarios, rainfall was assumed to be spatially uniform over the pilot roof cells and the HUCE campus, and all rainfall inputs were represented as 5-min incremental time–depth hyetographs. Irrigation effects were represented through the initial saturation of the planting soil layer, while intrinsic soil hydraulic parameters were kept constant among irrigation scenarios. For the soil-thickness analysis, only the planting soil depth was varied, while other LID parameters were unchanged. For campus-scale simulations, selected rooftop sub-catchments were assumed to be technically suitable for green roof implementation, and partial implementation was represented by adjusting the LID area and width according to rooftop coverage. The main model inputs, boundary conditions, assumptions, limitations, and performance indicators are summarized in Supplementary Information – Table S7. To reduce the influence of scaling and absolute-volume uncertainty, green roof performance was evaluated mainly using relative indicators, including runoff volume reduction (%) and peak flow attenuation (%), calculated against the corresponding baseline condition under the same rainfall event. This allowed the comparison to focus on the hydrological effect of green roof implementation rather than on absolute runoff volumes alone. The analysis should therefore be interpreted as a scenario-based modelling assessment rather than a probabilistic uncertainty analysis.

3. RESULTS AND DISCUSSION

3.1. Rooftop-scale hydrological response of green roofs

The rooftop-scale simulations were conducted to clarify how the hydrological performance of the green roof was affected by antecedent soil moisture, planting soil thickness, and rainfall magnitude. These three factors represent the main controls on the available storage capacity and drainage behaviour of the green roof system. The results are presented in Figures 3–5, where the drainage hydrographs and summary indicators were used to evaluate runoff volume reduction, peak flow attenuation, and peak delay.

The effect of irrigation condition is shown in Figure 3. As illustrated by the hydrographs in Figure 3(a), the non-irrigated green roof generated a more delayed and attenuated drainage response than the irrigated cases. This indicates that a relatively dry planting soil layer provided greater available pore space for temporary rainfall storage before drainage occurred. In contrast, the manually irrigated and drip-irrigated green roofs produced earlier outflow and shorter delays because their higher antecedent moisture reduced available storage. The quantitative indicators in Figure 3(b) support this trend: the non-irrigated green roof achieved the highest runoff volume reduction (62.53%), peak flow attenuation (31.25%), and peak delay (5 min). The manually irrigated green roof showed lower performance, with a runoff volume reduction of 53.62%, peak flow attenuation of 22.92%, and peak delay of 4 min. The drip-irrigated green roof showed the lowest performance, with a runoff volume reduction of 42.12%, peak flow attenuation of 16.67%, and peak delay of 2 min. Compared with the non-irrigated case, runoff volume reduction decreased by approximately 14.3% and 32.6% for the manually irrigated and drip-irrigated systems, respectively. These results show that irrigation can weaken the stormwater retention function of green roofs when it increases initial soil wetness before rainfall. This finding is consistent with previous studies indicating that antecedent moisture strongly influences green roof runoff retention and peak attenuation (Chen 2013; Liu *et al.* 2020; Busker *et al.* 2022).

The effect of planting soil thickness is presented in Figure 4. The drainage hydrographs in Figure 4(a) show that the 80-mm green roof responded more rapidly to rainfall, whereas the 150- and 250-mm configurations produced more gradual and delayed drainage responses. This difference reflects the larger water storage capacity provided by thicker planting soil layers. As shown in Figure 4(b), the 80-mm green roof achieved a runoff volume reduction of 38.28%, with no measurable peak flow attenuation and a peak delay of 1 min. Increasing the planting soil thickness to 150 mm increased runoff volume reduction to 53.62%, peak flow attenuation to 22.92%, and peak delay to 4 min. The 250-mm green roof provided the highest retention performance, with a runoff volume reduction of 61.18%, peak flow attenuation of 27.08%, and peak delay of 5 min. These results indicate that increasing planting soil thickness from 80 to 250 mm substantially improved runoff retention, while the additional improvement from 150 to 250 mm was more moderate. The improvement in peak

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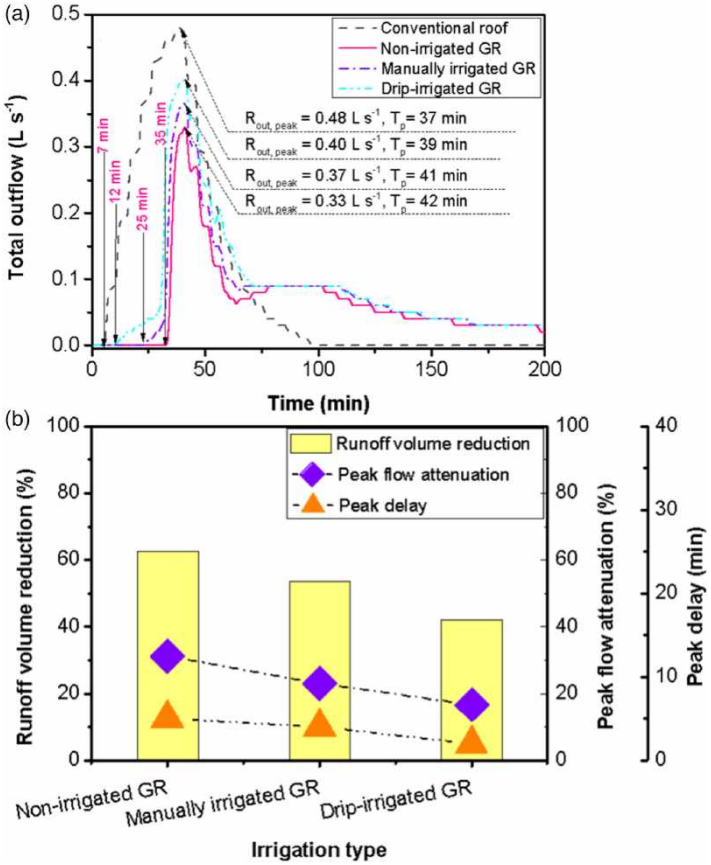


Figure 3 | Effect of irrigation condition on green roof hydrological performance: (a) drain outflow hydrographs under different irrigation conditions; (b) comparison of runoff volume reduction, peak flow attenuation, and peak delay.

attenuation and delay was also relatively small between the 150- and 250-mm configurations, suggesting that increasing soil thickness mainly enhances runoff volume retention, while peak timing and attenuation are also controlled by drainage dynamics. From a practical perspective, the 150-mm configuration may provide a more feasible compromise for existing buildings, whereas the 250-mm configuration offers stronger retention where structural loading constraints can be addressed.

The influence of rainfall magnitude is shown in Figure 5. The hydrographs in Figure 5(a)–5(f) indicate that the green roof response depended strongly on rainfall depth and temporal distribution. Under smaller rainfall events, the green roof retained a large portion of incoming rainfall and substantially delayed drainage generation. This behaviour was most evident under the 45-mm rainfall event, for which the green roof achieved a runoff volume reduction of 92.43%, peak flow attenuation of 87.10%, and a peak delay of 28 min (Figure 5(g)). Under the 90-mm rainfall event, runoff volume reduction decreased to 65.35%, peak flow attenuation decreased to 31.25%, and peak delay dropped to 4 min. For the 155-mm event, runoff volume reduction further decreased to 50.59%, while peak attenuation and peak delay decreased to 22.41% and 3 min, respectively. Under larger design storms of 225, 265, and 300 mm, runoff volume reduction decreased to 47.83, 45.70, and 40.55%, respectively. Peak flow attenuation also declined markedly from 11.90 to 8.08% and 4.50%, while peak delay remained only 1 min for all three events. These results indicate that green roofs still provide partial runoff volume reduction under large events, but their peak-control function becomes limited as soil and drainage storage approach saturation.

Overall, the rooftop-scale simulations indicate that green roof performance is governed by the combined effects of antecedent soil moisture, planting soil thickness, and rainfall magnitude. Antecedent moisture controls the storage capacity available before rainfall, planting soil thickness determines the total water-holding capacity, and rainfall magnitude determines whether the green roof functions mainly as a retention system or as a temporary detention layer. The 80-mm configuration showed limited hydrological benefit and was less suitable for campus-scale application. The 250-mm configuration produced the strongest runoff retention, but its greater

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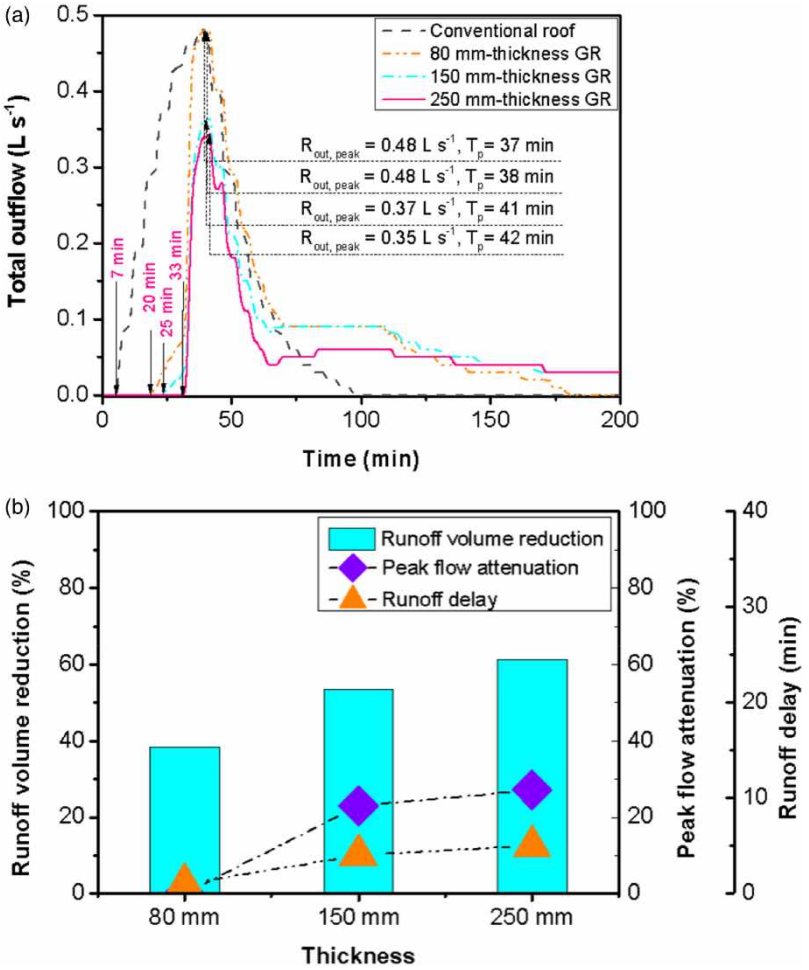


Figure 4 | Effect of planting soil thickness on green roof hydrological performance: (a) drain outflow hydrographs for the 80-, 150-, and 250-mm green roof configurations; (b) comparison of runoff volume reduction, peak flow attenuation, and runoff delay.

soil depth may increase structural loading and limit application to existing buildings. The 150-mm configuration, which corresponds to the pilot-scale green roof previously tested at HUCE, provided a balanced level of runoff reduction and practical feasibility. Therefore, the 150- and 250-mm configurations were selected for the campus-scale simulations.

3.2. Pilot-scale observations of green roof performance under consecutive rainfall events

Pilot-scale observations from the experimental roof models at HUCE were used as a field-based verification of the green roof hydrological response under real rainfall conditions. The experimental system consisted of one conventional roof and three green roof configurations: a non-irrigated green roof, a manually irrigated green roof, and a drip-irrigated green roof. The monitored rainfall sequence included two consecutive rainfall events within the same day, allowing the response of the roof systems to be evaluated not only during an initial rainfall event but also under a subsequent event affected by antecedent wetness.

The observed runoff hydrographs and performance indicators are presented in Figure 6, while the corresponding outflow data are provided in Supplementary Information – Table S2. As shown in Figure 6(a), the conventional roof responded rapidly to rainfall, producing sharp runoff peaks shortly after rainfall onset. This behaviour reflects the very limited storage capacity of the impervious roof surface, where most rainfall is rapidly converted into direct runoff. In contrast, all three green roof configurations produced lower and more delayed outflow hydrographs. The green roof hydrographs were generally smoother than that of the conventional roof, indicating that the planting soil and drainage layers temporarily stored rainfall and released it gradually through

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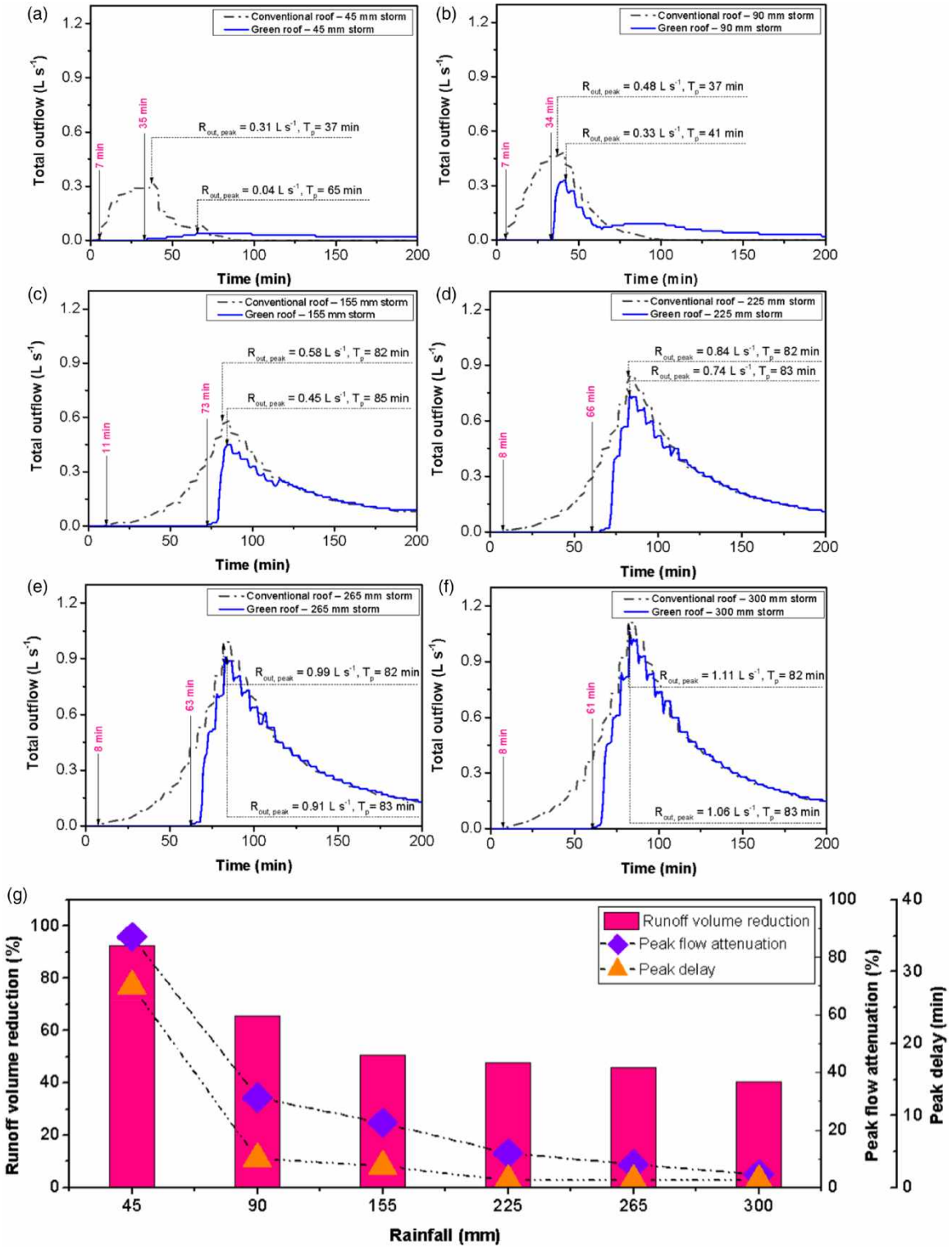


Figure 5 | Effect of rainfall magnitude on green roof hydrological performance under different storm scenarios: (a)–(f) drain outflow responses for selected rainfall events; and (g) summary of runoff volume reduction, peak flow attenuation, and peak delay.

the outlet. This confirms that the green roof system functioned not only as a retention layer but also as a detention layer that redistributed runoff over a longer period.

For the first rainfall event, the quantitative results in Figure 6(b) show that the non-irrigated green roof provided the highest runoff control performance. It achieved a runoff volume reduction of 81.73%, peak flow

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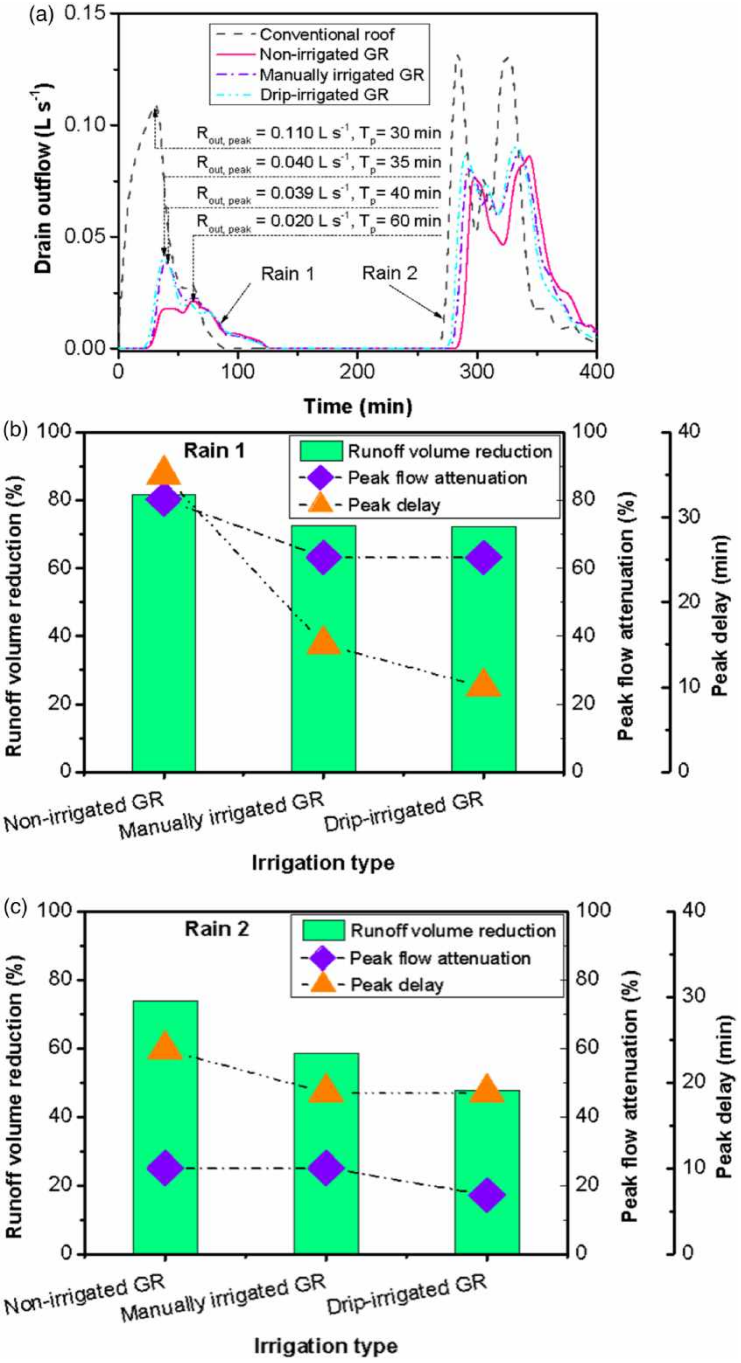


Figure 6 | Pilot-scale hydrological performance of conventional and green roof systems under two consecutive rainfall events at HUCE: (a) observed outflow hydrographs for four roof configurations; (b) runoff reduction, peak attenuation, and peak delay during the first event; and (c) corresponding indicators during the second event.

attenuation of 80.32%, and peak delay of 35 min. The manually irrigated green roof achieved a lower runoff volume reduction of 72.67%, peak flow attenuation of 63.11%, and peak delay of 15 min. The drip-irrigated green roof showed a similar runoff volume reduction of 72.27% and peak flow attenuation of 63.11%, but its peak delay was further reduced to 10 min. The runoff delay was 5 min for all three green roof configurations, indicating that the initial onset of runoff was delayed by a similar amount, while the major difference among the irrigation conditions appeared in the magnitude and timing of the peak outflow. Compared with the non-irrigated green roof, the manually irrigated and drip-irrigated green roofs reduced runoff volume reduction by approximately 11.1 and 11.6%, respectively. The decrease in peak flow attenuation was also evident, declining from 80.32 to 63.11% for both irrigated cases. More importantly, the peak delay decreased substantially from

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35 min for the non-irrigated green roof to 15 and 10 min for the manually irrigated and drip-irrigated green roofs, respectively. This indicates that irrigation had a stronger effect on peak timing than on total runoff volume during the first rainfall event.

The second rainfall event showed a different but hydrologically meaningful response. As presented in Figure 6(c), runoff volume reduction decreased for all green roof configurations compared with the first event. The non-irrigated green roof still showed the highest runoff volume reduction, reaching 73.70%, followed by the manually irrigated green roof with 58.49% and the drip-irrigated green roof with 47.60%. Peak flow attenuation was 25.06% for both the non-irrigated and manually irrigated green roofs, and 17.18% for the drip-irrigated green roof. Peak delay was 24 min for the non-irrigated green roof and 19 min for both irrigated configurations. The lower runoff volume reduction and peak attenuation during the second event suggest that the green roof systems had not fully recovered their storage capacity after the first rainfall event. This effect was most evident for the drip-irrigated green roof, which showed the lowest runoff reduction. Compared with the non-irrigated system, the manually irrigated and drip-irrigated systems showed approximately 20.6 and 35.4% lower runoff volume reduction during the second event, respectively. These observations support the modelling results in Section 3.1, confirming that antecedent wetness and rainfall sequence strongly affect green roof retention and delay under local rainfall conditions.

Overall, the field observations provide ground-based verification of the modelled green roof behaviour. Under the measured rainfall events, all green roof configurations had reduced and delayed outflow compared with the conventional roof. The non-irrigated green roof consistently showed the most significant runoff volume reduction and peak-delay response, which was consistent with the simulated effects of lower antecedent soil moisture in Section 3.1. During the first rainfall event, the non-irrigated green roof achieved 81.73% runoff volume reduction and 80.32% peak flow attenuation, while the manually irrigated and drip-irrigated systems showed lower performance. During the second rainfall event, performance decreased for all green roof configurations, indicating reduced storage recovery between consecutive rainfall events. These results support the use of the SewerGEMS model for scenario-based interpretation, although the limited number of monitored events means that the comparison should be regarded as field-based verification rather than full statistical calibration. This interpretation is consistent with previous green roof studies showing that runoff retention and peak attenuation are affected by antecedent moisture, rainfall sequence, and storage recovery (Jim & Peng 2012; Berretta *et al.* 2014; Cristiano *et al.* 2020).

3.3. Campus-scale hydrological performance under green roof implementation scenarios

The campus-scale hydrological performance of green roof implementation at HUCE is presented in Figure 7 and Supplementary Information – Figure S2. Based on the rooftop areas identified in Table S6 and the SewerGEMS drainage model shown in Figure 1(c), two green roof configurations with planting soil thicknesses of 150 and 250 mm were applied to selected rooftop sub-catchments. Four green roof coverage levels were considered, corresponding to 25, 50, 75, and 100% of suitable rooftop areas. Figure 7(a)–7(d) show the results for the 150-mm green roof configuration under P5, P10, P50, and P100 rainfall events, respectively, while Figure 7(e)–7(h) present the corresponding results for the 250-mm configuration. The performance was evaluated using runoff volume reduction, peak flow attenuation, and peak delay at the campus outlet. For the 150-mm green roof configuration, increasing rooftop coverage consistently improved runoff volume reduction under all rainfall scenarios. Under P5 (Figure 7(a)), runoff volume reduction increased from 17.09% at 25% coverage to 67.83% at 100% coverage. Under P10 (Figure 7(b)), the corresponding increase was from 10.31 to 47.91%. A similar coverage-dependent trend was observed under P50 and P100, with runoff volume reduction increasing from 7.93 to 35.28% and from 7.27 to 30.07%, respectively (Figure 7(c) and 7(d)). These results indicate that the 150-mm configuration could provide meaningful campus-scale runoff volume reduction, although the benefit becomes less under more extreme rainfall events.

The peak flow attenuation of the 150-mm configuration also increased with rooftop coverage, but the magnitude of improvement depended strongly on rainfall severity. Under P5 (Figure 7(a)), peak flow attenuation increased from 11.90% at 25% coverage to 44.86% at full coverage. Under P10 (Figure 7(b)), the increase was from 0.81 to 27.26%. In contrast, under P50 and P100, full rooftop coverage reduced the peak flow by only 5.40 and 2.75%, respectively (Figure 7(c) and 7(d)). This suggests that the 150-mm green roof system attenuates peak discharge more effectively under moderate rainfall events than under extreme storms. The 250-mm configuration generally provided greater runoff volume reduction than the 150-mm configuration, particularly at

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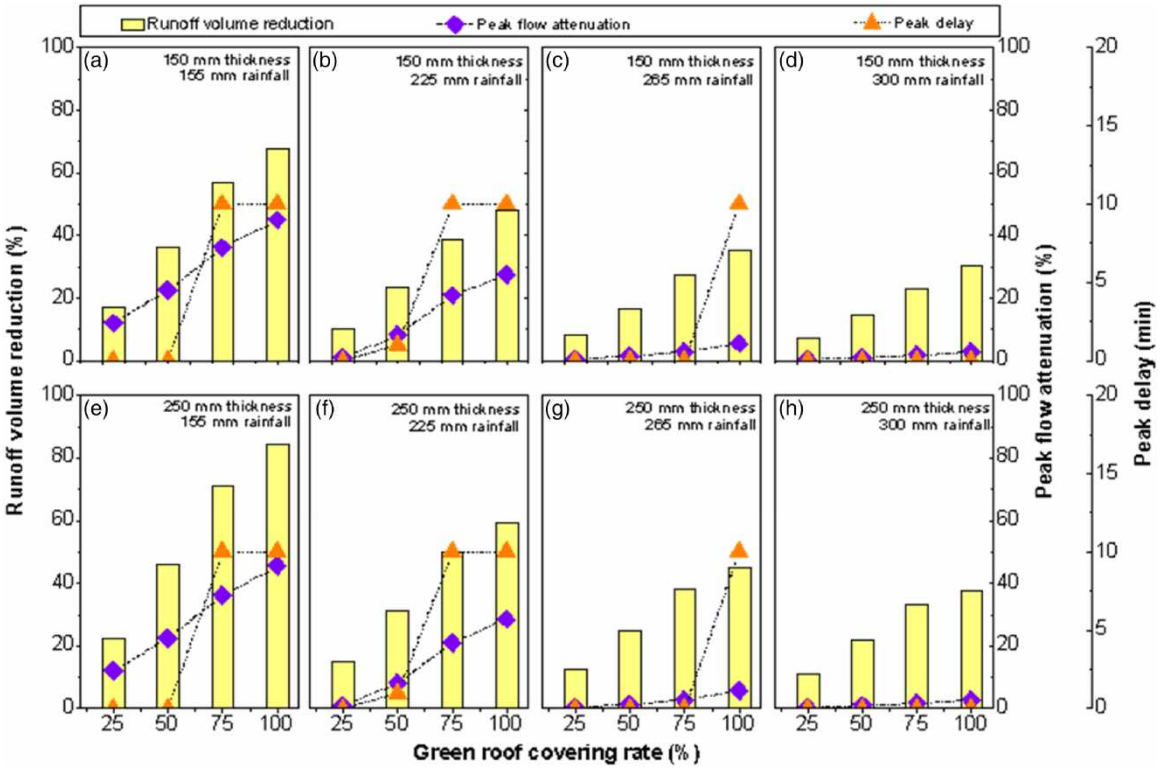


Figure 7 | Campus-scale hydrological performance of green roof implementation under different rooftop coverage levels and rainfall scenarios: (a)–(d) 150-mm green roof configuration under P5, P10, P50, and P100 rainfall events, respectively; (e)–(h) 250-mm green roof configuration under P5, P10, P50, and P100 rainfall events, respectively.

medium and high coverage levels. Under P5 (Figure 7(e)), runoff volume reduction increased from 22.25% at 25% coverage to 84.55% at full coverage. Under P10 (Figure 7(f)), the corresponding increase was from 14.87 to 59.30%, while under P50 and P100 it increased from 12.61 to 44.84% and from 11.06 to 37.42%, respectively (Figure 7(g) and 7(h)). These results confirm that increasing planting soil thickness from 150 to 250 mm markedly enhances the volume-retention capacity of green roofs at the campus scale (Lee *et al.* 2013).

However, the advantage of the 250-mm configuration over the 150-mm configuration was more evident for runoff volume reduction than for peak flow attenuation. For example, under P5 and 100% coverage, increasing the soil thickness from 150 to 250 mm increased runoff volume reduction from 67.83 to 84.55%, whereas peak flow attenuation increased only slightly from 44.86 to 45.42%. Similarly, under P10 and full coverage, runoff volume reduction increased from 47.91% for the 150-mm configuration to 59.30% for the 250-mm configuration, but peak attenuation increased only from 27.26 to 28.48%. Under P50 and P100, both configurations produced similar peak attenuation values, despite the larger runoff volume reduction achieved by the 250-mm green roof. This indicates that increasing planting soil thickness mainly strengthens the retention function of green roofs, while peak discharge at the campus outlet is also controlled by rainfall temporal distribution, flow routing in the drainage network, and the synchronization of runoff from different sub-catchments.

The peak delay results further demonstrate the non-linear behaviour of the campus drainage response. Under P5 (155 mm), both the 150-mm and 250-mm configurations produced a 10-min peak delay at 75 and 100% coverage (Figure 7(a), 7(e), Figure S2(a) and S2(e)). A similar pattern was observed under P10 (225 mm), where peak delay increased to 10 min at 75 and 100% coverage for both configurations (Figure 7(b), 7(f), Figure S2(b) and S2(f)). Under P50 (265 mm), peak delay remained limited and reached 10 min only at full coverage (Figure 7(c), 7(g), Figure S2(c) and S2(g)). In contrast, under P100 (300 mm), no peak delay was observed for either green roof thickness or coverage level (Figure 7(d), (h), Figure S2(d) and S2(h). This result indicates that green roofs can delay the campus outlet peak under moderate rainfall conditions when coverage is sufficiently high, but their ability to shift peak timing becomes limited under extreme rainfall events.

Overall, Figure 7 shows that rooftop coverage and planting soil thickness influence different aspects of campus-scale stormwater performance. Increasing rooftop coverage consistently improved runoff volume

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reduction and peak attenuation, particularly from 25 to 75% coverage. Increasing soil thickness from 150 to 250 mm substantially improved runoff volume reduction but did not proportionally increase peak attenuation or peak delay. Therefore, if the main objective is to reduce total stormwater volume discharged from the campus, the 250-mm configuration provides a clear advantage. If the objective is to reduce peak discharge at the outlet, expanding rooftop coverage may be more important than increasing soil thickness alone. Under P5 and P10 events, high coverage levels of 75–100% produced clear hydrological benefits, whereas under P50 and P100 the green roofs still reduced runoff volume but had limited ability to delay and attenuate the outlet peak. These results support the use of green roofs as a source-control measure for reducing routine stormwater loads and partially mitigating larger rainfall events.

3.4. Implications for urban flood mitigation and stormwater policy

Beyond the outlet-based indicators presented in Figure 7, the simulated water level at MH09 was examined to assess the flood mitigation relevance. MH09 was selected as a critical drainage location for detailed water-level analysis because it represented the most flood-prone and hydraulically unfavourable manhole in the HUCE campus stormwater network (Figure 1(c)). In Figure 8, the simulated water level hydrographs at MH09 were

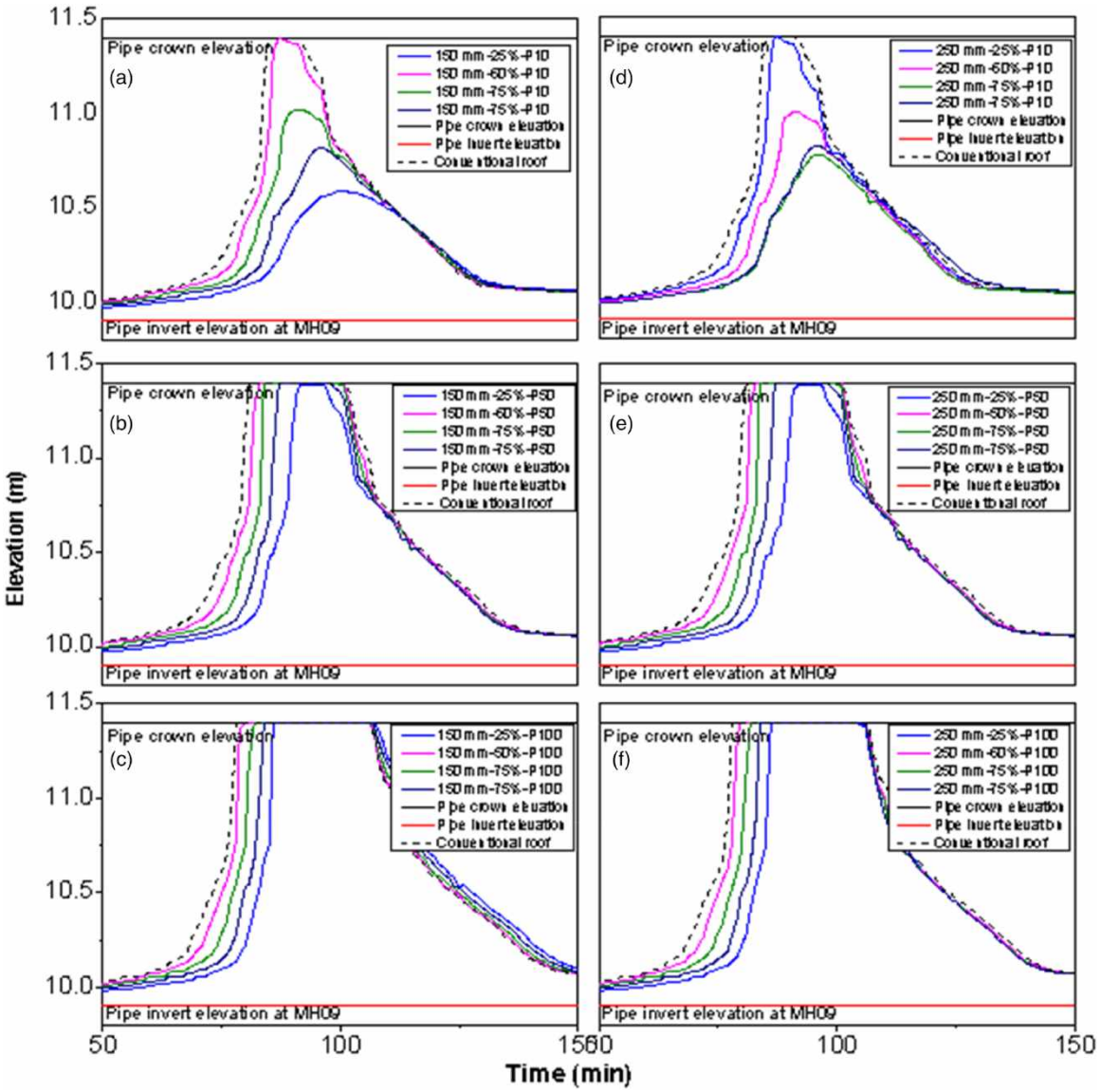


Figure 8 | Simulated water level response at the critical manhole MH09 under campus-scale green roof implementation scenarios for P10, P50, and P100 rainfall events. The pipe invert and pipe crown elevations are shown as reference levels to identify partially full, near full, and surcharge conditions.

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compared with the pipe invert elevation and pipe crown elevation. The pipe invert elevation represented the bottom level of the pipe, while the pipe crown elevation represented the top internal level of the pipe. When the simulated water level remained between these two reference levels, the pipe operated under partially full flow condition. When the water level approached or exceeded the pipe crown elevation, the pipe was likely to operate under nearly full or surcharge conditions, indicating increased flood stress. However, actual surface flooding should only be confirmed when the water level exceeded the manhole rim or ground elevation.

Under the P10 rainfall scenario, green roof implementation produced a clear mitigation effect at MH09. Increasing rooftop coverage delayed the rising limb of the water level hydrograph and reduced the rate at which the water level approached the pipe crown elevation. This indicates that distributed rooftop storage can slow runoff delivery to the drainage network and reduce short-term hydraulic loading at the critical node (Dong *et al.* 2024). The effect was visible for both the 150-mm and 250-mm green roof configurations, although the 250-mm configuration generally produced a smoother response because of its larger storage capacity. These results suggested that, under moderate rainfall conditions, green roofs could help reduce the duration and intensity of near-full pipe flow at vulnerable drainage locations. Under the P50 rainfall scenario, the benefit of green roofs was still observable but became less pronounced. Increasing rooftop coverage delayed the water level rise and slightly moderated the hydrograph response. However, the simulated water level at MH09 still approached or exceeded the pipe crown elevation during the peak period, suggesting that the pipe was likely operating under full-flow or surcharge conditions. Therefore, for large rainfall events, green roofs can provide partial mitigation by reducing and delaying runoff contribution, but they may not be sufficient to completely prevent critical hydraulic conditions. For the P100 rainfall scenario, the simulated water level rose rapidly and remained high across all green roof coverage levels and soil thickness configurations. The differences among the 25, 50, 75, and 100% coverage scenarios became relatively small compared with the P10 event. This indicated that, under extreme rainfall, the hydraulic response at MH09 was dominated by rainfall magnitude and the conveyance capacity of the drainage network. Although green roofs still contribute to distributed storage and runoff redistribution, their effect alone was insufficient to prevent surcharge risk at this critical drainage point under extreme storm conditions.

The comparison between the 150-mm and 250-mm green-roof configurations also provided an important design implication. The 250-mm configuration offered greater runoff storage and generally produced a more moderated water level response, particularly under P10 and P50 events. However, its advantage became less evident under P100, where the drainage system was strongly controlled by extreme rainfall loading. This confirmed that increasing planting soil thickness improved retention capacity but could not fully compensate for insufficient hydraulic capacity in the drainage network during high-return-period storms. These results suggest that green roofs should be regarded as an effective source-control measure, but not as a standalone flood-control solution. For frequent and moderate rainfall events, high rooftop coverage can meaningfully reduce runoff volume, attenuate discharge, and delay water level rise. For large and extreme rainfall events, green roofs still provide partial benefits, but additional measures are required to manage surcharge and inundation risks. These may include detention tanks, surface storage areas, permeable pavements, rain gardens, localized pipe upgrades, and improved drainage routing.

From a policy perspective, the findings support the integration of green roofs into urban stormwater management as part of a broader green infrastructure strategy. Green roof policies should not focus only on rooftop greening area but should also include performance-based indicators such as runoff volume reduction, peak flow attenuation, peak delay, and reduction of surcharge risk at critical drainage nodes. For dense urban areas such as Hanoi, where ground-level space for new drainage infrastructure is limited, rooftops represent an important opportunity for distributed runoff control. Implementation guidelines should therefore translate hydrological screening results into project-specific design and verification requirements. These considerations can be organized into a practical decision pathway for green roof policy. First, surcharge-prone drainage nodes such as MH09 are identified as priority locations. Second, performance targets are set in terms of runoff volume reduction, peak flow attenuation, and peak delay, rather than rooftop greening area alone. Third, a planting soil thickness is selected according to the roof's structural capacity, for example the 150 mm configuration for retrofits with limited load allowance and the 250 mm configuration for new or structurally assessed roofs. Fourth, a coverage level is chosen according to local rainfall risk. Consistent with the MH09 water-level results, this coverage rule should be rainfall-tiered: high rooftop coverage is prioritized for frequent and P10 events, green roofs are combined with local storage under P50 conditions, and they are paired with

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drainage upgrades and detention for P100 events, where rooftop source control alone is insufficient. The recommended policy package therefore spans building regulation (roof suitability and structural loading assessment), performance-based design approval, integration with complementary measures such as detention tanks, permeable pavements, and rain gardens, and operational management to preserve pre-storm storage. These considerations align with existing statutory planning for Hanoi. The Master Plan for the Capital City of Hanoi, approved in 2026 with a long-term development vision, provides a blue and green policy framework into which green roof source control could be incorporated as a performance-based rooftop measure, integrated alongside drainage upgrades and storage provisions in flood-prone districts (Hanoi People's Committee 2026). Green roofs should be integrated with other nature-based and engineered stormwater measures, allowing rooftop source control to work together with additional storage and drainage improvements (Wendling & Holt 2020; Brasil *et al.* 2021).

While the integrated pilot-observation and SewerGEMS modelling framework provides useful evidence on green roof performance from rooftop to campus scale, several limitations should be acknowledged. The simulations assumed spatially uniform rainfall, represented irrigation through initial soil saturation, and treated vegetation effects indirectly through LID parameterization without species-specific growth or evapotranspiration dynamics. The campus-scale scenarios also assumed that selected rooftops were technically suitable for green roof implementation. The model outputs should therefore be interpreted as hydrological screening rather than implementation readiness, because retrofit feasibility may be constrained by compounding building-level factors such as residual structural capacity, saturated load, roof condition, waterproofing/root-barrier integrity, drainage/overflow performance, and maintenance access (Castleton *et al.* 2010; Shafique *et al.* 2018). Detailed structural, ownership, economic, water-quality, thermal, biodiversity, and long-term performance assessments were beyond the study scope. The rainfall scenarios were based on local design rainfall statistics and selected stress-test events, but a full probabilistic uncertainty analysis was outside the scope of this study. Therefore, the results should be interpreted as relative green roof performance under defined rainfall and implementation scenarios, rather than probabilistic estimates for the full range of possible storm events in Hanoi.

Although the present study focused on the HUCE campus, future research should extend the analysis to a city-wide green roof feasibility assessment for Hanoi to quantify both the potential rooftop area suitable for green roof implementation and the corresponding stormwater attenuation benefits during heavy rainfall. Such an assessment should not assume a uniform conversion rate across the city, because roof suitability is likely to vary substantially among different urban morphologies. Hanoi could be classified into representative zones, including the historic Old Quarter, existing high-density inner-city districts, and newly planned urban areas. New urban areas and existing inner-city districts with larger reinforced-concrete flat roofs may offer higher application potential, while the Old Quarter may have lower suitability due to high building density, fragmented ownership, heritage constraints, sloped or tiled roofs, and limited roof accessibility. Future works should combine data of GIS-based mapping, high-resolution satellite or aerial imagery, urban planning information, building features such as footprint, function, ownership, roof features such as slope, material, structural loading capacity, and drainage connectivity, to estimate potential green roof area. These spatial estimates could then be linked with drainage-network modelling to evaluate how much stormwater flooding pressure could be alleviated across different parts of Hanoi, especially during heavy rainfall events (Kolasa-Więcek & Suszanowicz 2021; Busker *et al.* 2022). This information could support a dedicated cost-benefit analysis of multi-purpose green roof systems, building on prior cost assessments in literature (Dang *et al.* 2016), alongside other rainwater harvesting and stormwater management measures, to inform appropriate incentive policies. For Hanoi, such analysis should also be aligned with official urban planning documents, drainage improvement priorities, and future development scenarios for the capital city (Nguyen 2022; Hanoi People's Committee 2026). Furthermore, benefits of storm management solutions could be maximized only when they are properly operated and maintained. In this context, the present campus-scale results provide an initial evidence base for considering green roofs in future technical guidelines for urban stormwater management, particularly as part of a multi-layered strategy that combines rooftop source control with storage, permeable surfaces, and drainage upgrades.

4. CONCLUSIONS

This study evaluated the potential of green roofs for stormwater runoff control and urban flood mitigation in Hanoi by linking rooftop-scale simulations, outdoor roof-cell observations, and campus-scale SewerGEMS

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drainage modelling. The results showed that green roof performance was strongly controlled by antecedent soil moisture, planting soil thickness, rainfall magnitude, and rooftop implementation coverage. At the rooftop scale, drier initial soil conditions provided greater available storage before rainfall, whereas irrigation reduced runoff retention, peak attenuation, and peak delay. Increasing planting soil thickness improved runoff volume reduction, with the 250-mm configuration showing the highest retention capacity. However, the additional improvement in peak attenuation and peak delay was more limited, indicating that soil thickness mainly strengthened the retention function, while detention performance was also controlled by drainage dynamics and rainfall temporal distribution.

Field observations from outdoor roof cells at HUCE supported the modelled green roof behaviour under local rainfall conditions. Compared with the conventional roof, all green roof configurations reduced and delayed outflow during the observed rainfall events. The non-irrigated green roof consistently showed the strongest runoff reduction and peak-delay response, while the reduced performance during the second rainfall event confirmed the importance of antecedent wetness and storage recovery between consecutive storms. These observations provide field-based verification of the scenario-based modelling results, although the limited number of monitored events means that the comparison should be interpreted as a ground-based consistency check rather than full statistical calibration. At the campus scale, applying green roofs to suitable rooftop areas reduced runoff volume and peak discharge at the campus outlet. The highest runoff volume reduction reached 84.55% under the 250-mm configuration with full coverage of suitable rooftop areas. However, the campus-scale results also showed that the effectiveness of green roofs depended strongly on rainfall severity. Under P5 and P10 rainfall scenarios, high rooftop coverage produced clear runoff reduction, peak attenuation, and peak-delay benefits. Under P50 and P100 events, green roofs still reduced runoff volume but had limited ability to attenuate or delay the outlet peak. Water-level analysis at MH09 further showed that green roofs could reduce and delay drainage stress under P10 rainfall, but their effectiveness became limited under P50 and P100 events when the drainage system reached the surcharge conditions.

Overall, green roofs should be considered an effective rooftop source-control measure for reducing routine stormwater loads and partially mitigating urban flooding in dense, land-constrained cities such as Hanoi. However, they should not be treated as a standalone flood-control solution, especially under extreme rainfall. Wider implementation should integrate green roofs with complementary stormwater management measures, including distributed storages, permeable surfaces, rain gardens, localized drainage upgrades, and improved drainage routing. Future studies should extend this campus-scale assessment to city-wide rooftop suitability mapping, structural feasibility assessment, cost-benefit analysis, and drainage-network modelling to support practical blue and green roof policies for Hanoi. Furthermore, benefits of storm management solutions could be maximized only when they are properly operated and maintained.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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