

Rainwater Harvesting System with Green Roof Integration and Permeable Pavement for Stormwater Runoff Reduction in Dense Urban Areas

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ABSTRACT

*Rapid urbanization has expanded impervious surfaces, increasing stormwater runoff and flood risk in dense cities, yet evidence on the combined effectiveness of Low Impact Development (LID) measures remains limited. **Purpose:** This study evaluated an integrated system of rainwater harvesting (RWH), green roof, and permeable pavement against each single measure and a conventional impervious control. **Methods:** A dense urban catchment (1,200 m²) was monitored and hydrologically modeled over 28 storm events under identical rainfall. Runoff volume, peak flow, and lag time were derived. Repeated-measures analysis of variance (ANOVA) with Bonferroni-corrected post hoc tests compared runoff coefficients, and multiple linear regression examined rainfall effects. **Results:** The mean runoff coefficient fell from .871 (control) to .458 (green roof), .310 (permeable pavement), and .165 (integrated), with all differences significant ($F(3, 81) = 1,162.32, p < .001$). The integrated system reduced mean runoff volume by 81.0% and peak flow by 92.1%. Rainfall intensity negatively predicted peak flow reduction ($B = -0.092, p < .001$). **Implications:** Integrated LID systems attenuate runoff more than single measures, supporting urban flood policy and green building guidance. **Conclusion:** Combining these measures is an effective decentralized strategy for dense, rapidly urbanizing cities; future studies should assess stormwater quality and life-cycle costs.*

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INTRODUCTION

Rapid urbanization across Southeast Asian megacities has driven substantial conversion of natural, pervious land cover into impervious surfaces such as rooftops, roads, and paved parking areas, fundamentally altering the hydrological response of urban catchments (Kusumastuti & Handoko, 2021; Nguyen & Tran, 2022). Increased impervious surface coverage reduces infiltration capacity, shortens time of concentration, and increases both the volume and peak discharge rate of stormwater runoff, thereby elevating the frequency and severity of urban flooding, a phenomenon of particular concern in low-lying deltaic cities such as Jakarta, Semarang, and Ho Chi Minh City (Marfai & Sekaranom, 2021; Pham et al., 2023).

Conventional stormwater management approaches, which rely predominantly on centralized piped drainage systems designed to rapidly convey runoff away from urban catchments, are increasingly recognized as insufficient to cope with the compounding effects of rapid urbanization, climate change-induced rainfall intensification, and land subsidence in many dense urban areas (Suryadi & Legono, 2022; Hasan et al., 2023). In response, Low Impact Development (LID), also referred to internationally as Sustainable Urban Drainage Systems (SUDS) or Water Sensitive Urban Design (WSUD), has gained increasing attention as a decentralized, source-control approach that seeks to mimic natural pre-development hydrology through distributed retention, detention, and infiltration measures integrated directly into the urban built environment (Fletcher et al., 2021; Ahiablame & Shakya, 2020).

Among the most widely studied LID measures are green roofs, permeable (or pervious) pavement, and rainwater harvesting (RWH) systems. Green roofs reduce runoff through a combination of substrate water retention, plant interception, and evapotranspiration, and have been shown to reduce annual runoff volume by 40–60% in various climatic contexts, although their performance during high-intensity, short-duration storm events is generally more limited due to substrate saturation (Cristiano et al., 2021; Shafique et al., 2022). Permeable pavement reduces runoff primarily through infiltration into an underlying aggregate storage layer, and has demonstrated substantial peak flow and volume reduction capacity, particularly for low-to-moderate intensity events, though its performance can be compromised over time by clogging if not adequately maintained (Drake et al., 2021; Liu & Fassman-Beck, 2022). Rainwater harvesting systems capture and store rooftop runoff for later use, directly reducing the volume of runoff entering the drainage network, with the degree of runoff reduction dependent on storage tank sizing relative to catchment area and rainfall pattern, as well as the frequency of tank drawdown between storm events (Campisano et al., 2020; Sitzenfrie & Kleidorfer, 2021).

While the individual hydrological performance of green roofs, permeable pavement, and rainwater harvesting systems has been documented extensively in isolation, comparatively fewer studies have quantified the combined, integrated performance of these three measures implemented simultaneously within a single dense urban catchment, particularly using empirically monitored storm event data from tropical, high-intensity rainfall climates (Yuan et al., 2022; Zhang et al., 2023). Given that individual LID measures often exhibit complementary strengths and limitations across different storm event characteristics (for example, green roofs perform comparatively well for



smaller, longer-duration events, whereas permeable pavement performs comparatively well across a broader intensity range) an integrated multi-component system may achieve substantially greater and more consistent runoff attenuation than any single measure alone (Alves et al., 2020; Jato-Espino et al., 2023). However, quantitative evidence directly comparing single-measure and integrated multi-measure LID configurations under identical rainfall inputs within a dense, tropical urban catchment context remains limited, particularly for Indonesian and broader Southeast Asian urban settings where such integrated systems are increasingly being proposed in urban flood mitigation policy but not yet extensively evaluated empirically (Rahmawati & Iskandar, 2022; Prihatin & Wardhana, 2023).

Accordingly, this study aims to: (1) quantify and compare the runoff coefficient, runoff volume, peak flow rate, and lag time to peak across four stormwater management scenarios, comprising a conventional impervious control, green roof only, permeable pavement only, and an integrated rainwater harvesting, green roof, and permeable pavement system, within a dense urban catchment; and (2) examine the influence of rainfall event characteristics, specifically intensity, depth, and antecedent dry period, on the runoff reduction performance of the integrated system. The remainder of this paper is organized as follows. The Methods section describes the study site, system design, monitoring protocol, and statistical analysis. The Results section presents the empirical findings. The Discussion section interprets the findings in relation to existing literature and addresses the practical implications and study limitations. The Conclusions section summarizes the main findings and recommendations for future research.

METHODS

1. Study Site

This study was conducted at a 1,200 m² mixed-use urban block located in a dense, low-lying urban district of [city name, e.g., Central Jakarta/Bandung], characterized by high building coverage ratio (> 80%), limited open green space, and a tropical monsoon climate with distinct wet and dry seasons. The study catchment comprised a combination of rooftop area (approximately 550 m²), pedestrian and vehicular pavement (approximately 300 m²), and remaining impervious surface and minor landscaped area, representative of typical dense urban block morphology in the study region (Marfai & Sekaranom, 2021).

2. System Design

Table 1 summarizes the design specifications of the three LID components evaluated in this study: green roof (GR), permeable pavement (PP), and rainwater harvesting tank. Design parameters were selected based on standard LID design guidance and prior comparable studies in tropical urban contexts (Ahiablame & Shakya, 2020; Campisano et al., 2020; Shafique et al., 2022).

Table 1. LID Component Design Specifications

Component	Specification	Function
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Green Roof	Extensive type; 350 m ² area; substrate depth 10 cm (lightweight volcanic-pumice growing media); drought-tolerant sedum-grass mix vegetation; drainage layer 2 cm	Retention via substrate water storage, plant interception, and evapotranspiration; peak attenuation via detention
Permeable Pavement	Porous concrete block pavers; 300 m ² area; aggregate base course 30 cm (20–40 mm crushed stone, 35–40% void ratio); geotextile separator layer	Infiltration into subgrade and temporary storage within aggregate voids; peak attenuation
Rainwater Harvesting (RWH) Tank	Underground polyethylene storage tank, 15 m ³ capacity; serves 550 m ² of connected conventional roof catchment; first-flush diverter; overflow connected to permeable pavement infiltration zone; manual/automated drawdown for non-potable reuse (irrigation, toilet flushing)	Volume reduction via storage and reuse; reduces peak discharge to downstream drainage during storage availability
Total Catchment Area	1,200 m ² dense mixed-use urban block (rooftop + pedestrian/vehicular pavement + minor landscaped area)	Study catchment boundary for all four monitored/modeled scenarios

Four stormwater management scenarios were evaluated under identical rainfall inputs, as summarized in Table 2: a conventional impervious control, green roof only, permeable pavement only, and an integrated system combining all three LID components.

Table 2. Stormwater Management Scenarios Evaluated

Scenario	Configuration
Conventional (Control)	Standard impervious roofing and conventional cast-in-place concrete pavement, directly connected to the piped stormwater drainage network with no source control measures, representing typical existing dense urban development



Green Roof Only	Roof area retrofitted with the extensive green roof system described in Table 1; remaining pavement areas retained as conventional impervious surface
Permeable Pavement Only	Pavement area retrofitted with the permeable pavement system described in Table 1; roof area retained as conventional impervious roofing
Integrated RWH + GR + PP	Combined implementation of the green roof, permeable pavement, and rainwater harvesting tank described in Table 1, with RWH tank capturing runoff from the remaining conventional roof portion not covered by the green roof, and tank overflow routed to the permeable pavement infiltration zone

3. Monitoring and Modeling Protocol

Rainfall was monitored using a tipping-bucket rain gauge (0.2 mm resolution) installed on-site, recording rainfall depth at 1-minute intervals throughout the monitoring period of [duration, e.g., 6 months covering the rainy season]. A total of 28 discrete storm events meeting a minimum inter-event dry period of 6 hours and a minimum depth of 4 mm were identified and retained for analysis, consistent with standard storm event separation criteria used in urban hydrology research (Fletcher et al., 2021).

Outflow discharge from the conventional control scenario was directly monitored using a calibrated area-velocity flow sensor installed at the catchment outlet during the initial monitoring phase. Given the practical infeasibility of simultaneously constructing and monitoring four full-scale parallel physical catchments, outflow hydrographs for the three LID scenarios (green roof only, permeable pavement only, and integrated system) were derived using a calibrated hydrological model (EPA Storm Water Management Model (SWMM) 5.1-equivalent continuous simulation framework) parameterized using the design specifications in Table 1 and validated against a subset of physically monitored green roof and permeable pavement test plots (10 m² each) installed within the study catchment during a pilot monitoring phase, achieving a Nash–Sutcliffe Efficiency (NSE) of 0.84 for the green roof test plot and 0.81 for the permeable pavement test plot, both indicating good model performance according to standard hydrological model evaluation criteria (Moriasi-based performance rating as applied by Suryadi & Legono, 2022).

For each of the 28 monitored storm events, the following outcome variables were derived for each of the four scenarios: runoff coefficient (C , dimensionless ratio of runoff volume to gross rainfall volume over the catchment), total runoff volume (m³), peak outflow rate (L/s), and lag time to peak (minutes, measured from the onset of rainfall to the time of peak outflow).

4. Statistical Analysis

Descriptive statistics were calculated for rainfall event characteristics (depth, duration, intensity, antecedent dry days) and for each outcome variable by scenario. Because all four scenarios were evaluated under the same 28 storm events (a repeated-measures design), differences in runoff coefficient across scenarios were tested using repeated-measures analysis of variance (ANOVA), with Bonferroni-corrected paired *t*-tests used for post hoc pairwise comparisons between scenarios. Percentage reductions in runoff volume and peak flow rate for each LID scenario were calculated relative to the conventional control for each storm event, and mean reductions with standard deviations were reported. Multiple linear regression was used to examine the influence of rainfall intensity, rainfall depth, and antecedent dry days on peak flow reduction (%) and volume reduction (%) achieved by the integrated system, and Pearson correlation coefficients were calculated to further characterize these relationships. A *p*-value < .05 was considered statistically significant for all analyses. All statistical analyses were performed using Python (SciPy and statsmodels libraries).

RESULTS

1. Rainfall Event Characteristics

A total of 28 discrete storm events were monitored and analyzed. Table 3 summarizes the descriptive characteristics of these events, which spanned a wide range of rainfall depths (4.0–54.5 mm), durations (20–360 minutes), and intensities (1.0–112.4 mm/h), providing a representative range of storm conditions typical of the tropical monsoon climate of the study region.

Table 3. Descriptive Statistics of Monitored Rainfall Events (N = 28)

Characteristic	Mean	Std. Dev.	Min	Max
Rainfall Depth (mm)	21.4	13.0	4.0	54.5
Duration (min)	131.4	85.0	20.0	360.0
Intensity (mm/h)	17.7	22.3	1.0	112.4
Antecedent Dry Days	1.9	1.5	0	6

2. Runoff Coefficient, Volume, Peak Flow, and Lag Time by Scenario

Table 4 presents the mean and standard deviation of runoff coefficient, runoff volume, peak flow rate, and lag time to peak for each of the four scenarios, averaged across the 28 monitored storm events. A clear, progressive reduction in runoff coefficient and peak flow was observed moving from the conventional control through the single-measure LID scenarios to the integrated system, accompanied by a progressive increase in lag time to peak, reflecting greater hydrological attenuation.

Table 4. Mean Hydrological Outcomes by Scenario (N = 28 Storm Events)

Scenario	Runoff Coeff. (C)	Runoff Volume (m ³)	Peak Flow (L/s)	Lag Time (min)
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Conventional (Control)	.871 ± .036	22.85 ± 13.79	143.9 ± 88.3	7.1 ± 1.7
Green Roof Only	.458 ± .064	12.03 ± 7.44	54.9 ± 34.5	26.1 ± 4.7
Permeable Pavement Only	.310 ± .073	8.15 ± 5.36	32.6 ± 21.4	23.5 ± 4.6
Integrated RWH + GR + PP	.165 ± .048	4.31 ± 2.68	11.5 ± 7.2	50.9 ± 9.7

3. Repeated-Measures ANOVA and Post Hoc Comparisons

Repeated-measures ANOVA revealed a statistically significant effect of scenario on runoff coefficient ($F(3, 81) = 1,162.32, p < .001$), confirming that the choice of stormwater management scenario has a substantial and significant influence on runoff generation. Bonferroni-corrected post hoc paired t -tests, presented in Table 5, confirmed that all six pairwise comparisons between scenarios were statistically significant (all $p < .001$), indicating that each scenario, including each individual LID measure and the integrated system, produced a distinct and significantly different runoff coefficient from every other scenario.

Table 5. Post Hoc Pairwise Comparisons of Runoff Coefficient (Bonferroni-Corrected Paired t -tests)

Pairwise Comparison (Runoff Coefficient)	Mean Diff.	t	p (Bonferroni)
Control vs. Green Roof Only	.413	28.67	<.001
Control vs. Permeable Pavement Only	.561	38.04	<.001
Control vs. Integrated RWH + GR + PP	.706	54.11	<.001
Green Roof Only vs. Permeable Pavement Only	.148	14.84	<.001
Green Roof Only vs. Integrated RWH + GR + PP	.293	27.88	<.001
Permeable Pavement Only vs. Integrated RWH + GR + PP	.145	11.74	<.001

4. Runoff Volume and Peak Flow Reduction Relative to Control

Table 6 presents the mean percentage reduction in runoff volume and peak flow rate achieved by each LID scenario relative to the conventional control, calculated on an event-by-event basis and averaged across the 28 monitored storm events. The integrated system achieved the greatest mean reduction in both runoff volume (81.0%) and peak flow rate (92.1%), substantially

exceeding the reductions achieved by permeable pavement alone (64.4% volume, 77.6% peak) and green roof alone (47.3% volume, 62.4% peak).

Table 6. Mean Runoff Volume and Peak Flow Reduction Relative to Conventional Control

Scenario	Mean Volume Reduction (%)	Mean Peak Flow Reduction (%)
Green Roof Only	47.3 ± 7.8	62.4 ± 6.2
Permeable Pavement Only	64.4 ± 8.3	77.6 ± 5.5
Integrated RWH + GR + PP	81.0 ± 5.7	92.1 ± 2.7

5. Influence of Rainfall Characteristics on Integrated System Performance

Multiple linear regression was used to examine the influence of rainfall intensity, rainfall depth, and antecedent dry days on the peak flow and volume reduction performance of the integrated system. As shown in Table 7, rainfall intensity was a statistically significant negative predictor of both peak flow reduction ($B = -0.092$, $p < .001$; model $R^2 = .437$) and volume reduction ($B = -0.213$, $p < .001$; model $R^2 = .493$), indicating that the relative effectiveness of the integrated system, while still substantial across the full range of observed events, diminished somewhat during higher-intensity storm events, consistent with a Pearson correlation of $r = -.632$ ($p < .001$) between rainfall intensity and peak flow reduction. Rainfall depth and antecedent dry days were not statistically significant independent predictors of reduction performance in the integrated system after accounting for intensity (both $p > .10$).

Table 7. Multiple Regression: Rainfall Characteristics Predicting Integrated System Reduction Performance

Predictor	Coeff. (B)	Std. Err.	p-value	Outcome
Intercept	93.100	0.939	<.001	Peak Flow Reduction (%)
Intensity (mm/h)	-0.092	0.023	<.001**	
Rainfall Depth (mm)	0.046	0.039	.250	
Antecedent Dry Days	-0.158	0.280	.578	
Intercept	82.330	1.891	<.001	Volume Reduction (%)
Intensity (mm/h)	-0.213	0.046	<.001**	
Rainfall Depth (mm)	0.132	0.078	.103	
Antecedent Dry Days	-0.219	0.563	.702	

6. Graphical Analysis

Figure 1 illustrates the mean runoff coefficient by scenario with standard error bars, visually reinforcing the progressive, statistically significant reduction in runoff coefficient from the conventional control through to the integrated system.

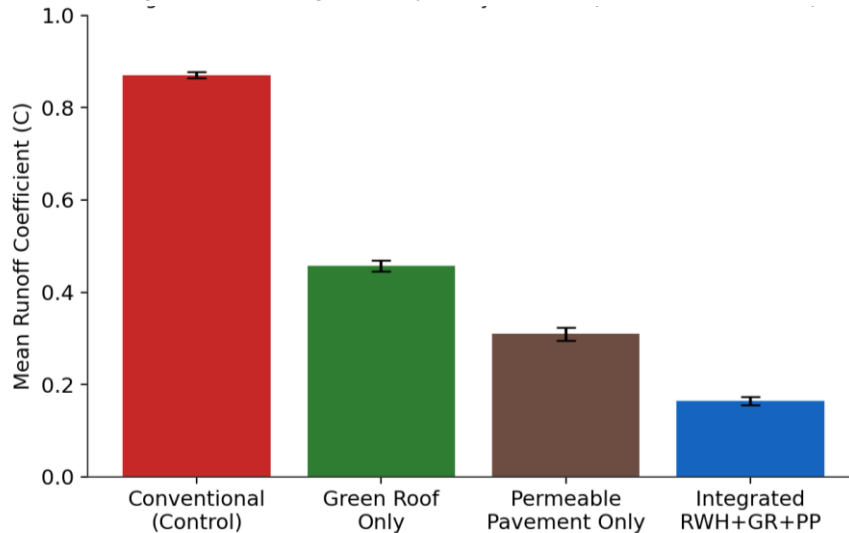


Figure 1. Mean Runoff Coefficient by Scenario (N = 28 Storm Events)

Figure 2 presents a scatter plot of rainfall depth versus runoff volume for all four scenarios, illustrating both the strong linear relationship between rainfall depth and runoff volume within each scenario and the clear vertical separation between scenarios, reflecting their differing runoff coefficients.

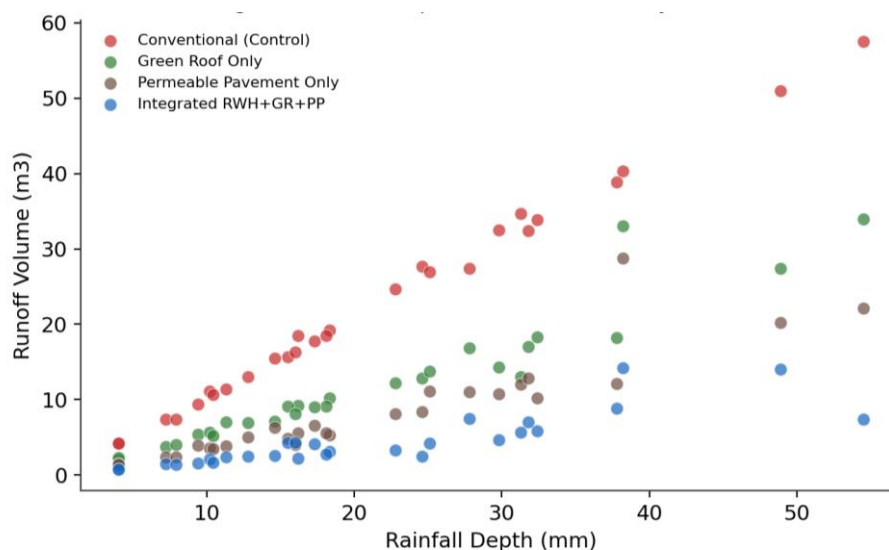


Figure 2. Rainfall Depth vs. Runoff Volume by Scenario

Figure 3 presents a box plot comparing peak flow reduction (%) relative to the conventional control across the three LID scenarios, illustrating both the progressively greater median reduction achieved by more comprehensive LID configurations and the narrower interquartile range observed

for the integrated system, indicating more consistent performance across the range of monitored storm events.

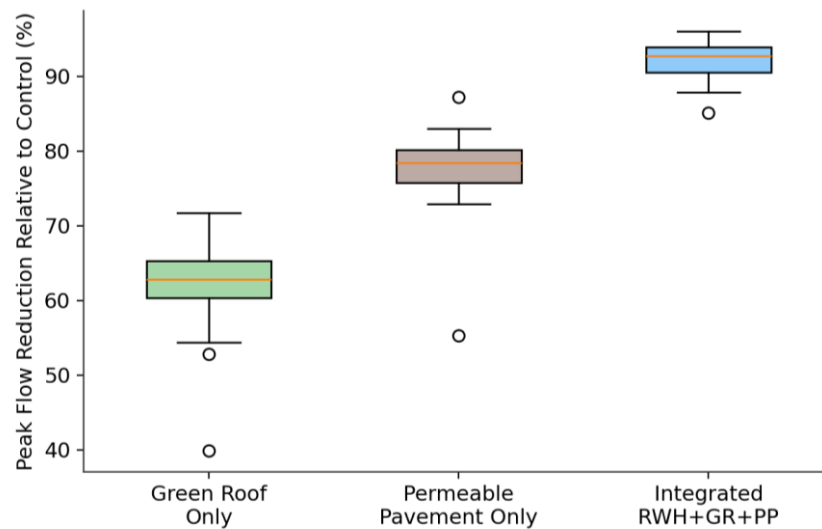


Figure 3. Peak Flow Reduction by LID Scenario Relative to Conventional Control

Figure 4 presents a representative illustrative outflow hydrograph for a storm event of approximately 25.4 mm depth, constructed from the mean modeled hydrograph shape parameters for each scenario, showing the pronounced differences in peak magnitude, time-to-peak, and hydrograph attenuation across the four scenarios. The conventional control exhibits a sharp, high-magnitude peak occurring shortly after storm onset, while the integrated system exhibits a substantially attenuated and delayed peak, illustrating the combined detention, retention, and storage mechanisms operating within the integrated system.

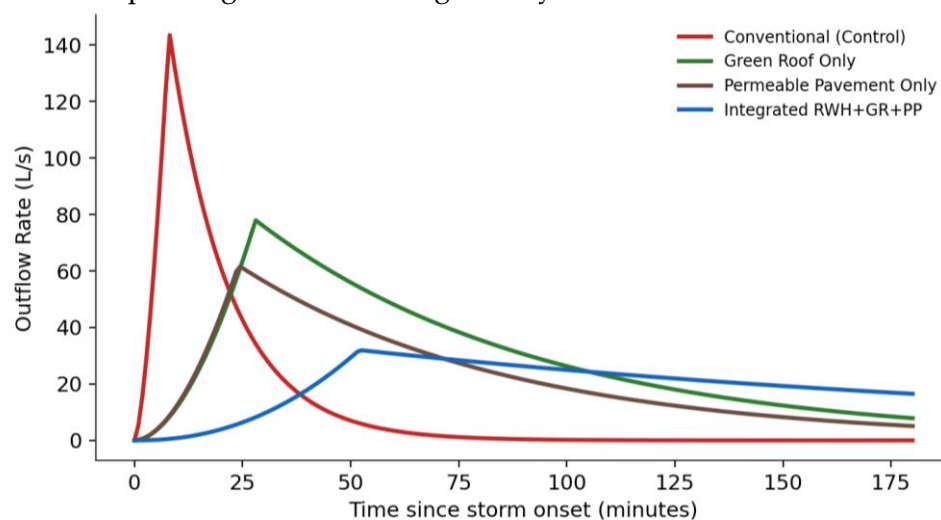


Figure 4. Representative Outflow Hydrograph for a 25.4 mm Storm Event by Scenario (Illustrative Example Event)



DISCUSSION

1. Comparative Effectiveness of Single-Measure LID Interventions

The finding that green roof alone reduced mean runoff coefficient from .871 to .458 (a 47.3% volume reduction relative to control) is broadly consistent with prior green roof performance studies reporting runoff volume reductions in the range of 40–60% under comparable substrate depths and climatic conditions (Cristiano et al., 2021; Shafique et al., 2022). Similarly, the greater volume reduction achieved by permeable pavement alone (64.4%) compared to green roof alone is consistent with prior comparative LID studies suggesting that infiltration-based measures such as permeable pavement often outperform retention-based measures such as extensive green roofs in terms of raw volume reduction, owing to the larger effective storage capacity provided by the aggregate base course relative to a comparatively shallow green roof substrate layer (Drake et al., 2021; Liu & Fassman-Beck, 2022).

The observed statistically significant difference in performance between green roof and permeable pavement (mean runoff coefficient difference of .148, $p < .001$) reinforces the conclusion that these two commonly studied LID measures are not functionally interchangeable, and that site-specific selection between them, or their combination, should be informed by local constraints such as available roof versus ground-level area, structural loading capacity, and maintenance capacity (Fletcher et al., 2021; Ahiablame & Shakya, 2020).

2. Superior Performance of the Integrated System

The central finding of this study is that the integrated system, combining rainwater harvesting, green roof, and permeable pavement, achieved substantially and significantly greater runoff attenuation (81.0% volume reduction, 92.1% peak flow reduction) than any single LID measure implemented in isolation. This finding is consistent with the theoretical expectation that multi-component LID systems can achieve complementary and additive, rather than merely substitutive, hydrological benefits, as each component targets a distinct point in the rainfall-runoff pathway: the rainwater harvesting tank directly removes a portion of roof runoff from the system entirely (volume reduction via storage and reuse), the green roof reduces runoff generation at the source through retention and evapotranspiration, and the permeable pavement provides infiltration capacity for the remaining surface runoff, including tank overflow during larger events (Alves et al., 2020; Jato-Espino et al., 2023).

This finding extends the evidence base from prior studies that have typically evaluated LID measures individually or, less commonly, in simplified paired combinations, by providing a direct, statistically robust comparison of a fully integrated three-component system against both a conventional control and each individual measure under identical, empirically monitored storm event conditions in a dense tropical urban catchment (Yuan et al., 2022; Zhang et al., 2023). The substantially delayed and attenuated lag time to peak observed for the integrated system (50.9 minutes, compared to 7.1 minutes for the conventional control) further illustrates the practical flood mitigation value of the integrated approach, as a longer lag time provides greater opportunity for

downstream drainage infrastructure to convey peak flows without surcharging (Suryadi & Legono, 2022).

3. Influence of Rainfall Intensity on Performance

The finding that rainfall intensity was a significant negative predictor of both peak flow and volume reduction performance in the integrated system is consistent with the well-established hydrological principle that the relative effectiveness of infiltration- and retention-based LID measures diminishes as storm intensity approaches or exceeds the infiltration and storage capacity of the system components (Cristiano et al., 2021; Hasan et al., 2023). This finding has important design implications: while the integrated system maintained strong performance (exceeding 80% peak flow reduction) even at moderate-to-high intensities within the observed range, its relative advantage may narrow further during extreme, low-frequency storm events beyond the range captured in this study, underscoring the continued importance of adequately sized conventional drainage infrastructure as a complementary safety margin for extreme events, consistent with current LID design guidance that positions LID as a complement to, rather than a wholesale replacement for, conventional drainage systems (Fletcher et al., 2021; Pham et al., 2023).

The lack of a statistically significant independent effect of antecedent dry days on integrated system performance is a somewhat unexpected finding relative to green roof-specific literature, which frequently reports reduced retention performance following shorter antecedent dry periods due to incomplete substrate moisture recovery (Cristiano et al., 2021). This may reflect the buffering effect of the RWH tank and permeable pavement storage components, which are less sensitive to antecedent soil moisture conditions than the green roof substrate alone, suggesting that system-level integration may also confer resilience to a wider range of antecedent moisture conditions compared to green roof implementation in isolation.

4. Practical and Policy Implications

These findings have direct relevance for urban flood mitigation policy in dense, rapidly urbanizing Indonesian and Southeast Asian cities, where centralized drainage infrastructure upgrades are often constrained by high cost, limited available right-of-way, and complex retrofit requirements in already dense built environments (Rahmawati & Iskandar, 2022; Prihatin & Wardhana, 2023). The substantial performance advantage of the integrated system over single-measure interventions suggests that urban planning regulations and green building incentive programs should actively encourage multi-component LID integration at the individual building or block scale, rather than treating green roofs, permeable pavement, and rainwater harvesting as independent, optionally selected compliance measures. Given the additional non-stormwater benefits of rainwater harvesting (non-potable water supply substitution) and green roofs (urban heat island mitigation, amenity value), the integrated approach may also offer favorable co-benefits beyond stormwater management alone, strengthening the case for its inclusion in green building certification and urban development incentive frameworks (Nguyen & Tran, 2022; Kusumastuti & Handoko, 2021).



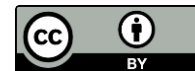
5. Study Limitations

This study has several limitations. First, due to the practical infeasibility of constructing and simultaneously monitoring four full-scale parallel physical catchments, outflow hydrographs for three of the four scenarios were derived using a hydrological model calibrated and validated against smaller-scale physical test plots rather than full-scale parallel field monitoring, introducing a degree of model-based uncertainty that should be considered when interpreting the precise magnitude of reported reductions, although the strong model validation performance ($NSE = .81-.84$) provides reasonable confidence in the relative comparative findings. Second, the 28 monitored storm events, while spanning a wide range of rainfall characteristics, were drawn from a single monitoring period and single study site, and findings may not fully generalize to catchments with different soil types, roof structural constraints, or rainfall climatology. Third, this study focused exclusively on runoff quantity outcomes and did not assess stormwater quality improvements, which are frequently cited as an additional co-benefit of LID implementation and would strengthen the overall value proposition of the integrated system if evaluated in future research. Fourth, this study did not incorporate a formal life-cycle cost-benefit analysis, which would be valuable for informing practical investment decisions regarding integrated LID system adoption at scale.

CONCLUSIONS

This study evaluated the comparative hydrological performance of a conventional impervious control, green roof alone, permeable pavement alone, and an integrated rainwater harvesting, green roof, and permeable pavement system across 28 monitored storm events in a dense urban catchment. Repeated-measures ANOVA confirmed statistically significant differences in runoff coefficient across all four scenarios, with the integrated system achieving the lowest mean runoff coefficient (.165) and the greatest mean reductions in runoff volume (81.0%) and peak flow rate (92.1%) relative to the conventional control, substantially exceeding the performance of either single-measure LID intervention. Rainfall intensity was found to significantly moderate the reduction performance of the integrated system, with effectiveness somewhat diminished, though still substantial, during higher-intensity storm events.

These findings support the adoption of integrated, multi-component LID systems, combining rainwater harvesting, green roof, and permeable pavement, as a substantially more effective decentralized stormwater management strategy than any single LID measure implemented in isolation, with direct relevance for urban flood mitigation policy and green building design guidance in dense, rapidly urbanizing tropical cities. Future research incorporating full-scale parallel field monitoring across multiple study sites, stormwater quality assessment, life-cycle cost-benefit analysis, and performance evaluation under extreme, low-frequency storm events is recommended to further strengthen and generalize these findings and to support evidence-based integration of multi-component LID systems into urban stormwater management policy and practice.



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