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Integrated Infiltration Runoff Drainage Assessment for Urban Pluvial Flooding at a Campus Scale in a Tropical Environment

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ABSTRACT

Urban pluvial flooding frequently occurs in semi-urban tropical environments where intense rainfall exceeds local infiltration and drainage capacity. This study presents an integrated infiltration runoff drainage assessment at the campus scale to evaluate surface water inundation risk at Politeknik Negeri Semarang, Indonesia. Soil physical and hydraulic properties were characterized through laboratory testing, and infiltration behavior was simulated using the physically based Green–Ampt model under 2, 5, 10, and 20-year return period rainfall. Runoff was estimated using the Rational Method based on rainfall intensity corresponding to the time of concentration, while drainage storage capacity was quantified through field-based geometric measurements. The results indicate that the site is dominated by fine-grained soils (OH/MH; A-7-5) with very low saturated hydraulic conductivity (4.209×10^{-6} mm/s), limiting infiltration effectiveness to the early stage of rainfall. Infiltration rates rapidly decline toward saturated conductivity values, causing increasing rainfall increments to be converted directly into surface runoff. Estimated runoff volumes increase from 341.308 m^3 (2-year) to 527.498 m^3 (20-year return period). Although total drainage storage capacity (1270.38 m^3) exceeds runoff volume, the storage margin decreases significantly under higher return periods, indicating increasing susceptibility to drainage surcharge. The integrated framework provides a process-based explanation of pluvial flooding driven by limited infiltration and drainage capacity utilization in tropical campus environments.

1. Introduction

Urban drainage systems in rapidly developing areas are increasingly challenged by intense rainfall events that generate surface runoff exceeding local storage and conveyance capacity. When rainfall-induced runoff cannot be accommodated by drainage networks and available infiltration capacity, temporary surface water inundation occurs, commonly referred to as urban pluvial flooding. This type of flooding is not associated with river overflow but is instead driven by the interaction between rainfall intensity, soil infiltration behavior, land surface characteristics, and drainage system performance [1][2].

In tropical regions, flooding caused by heavy rainfall is becoming more frequent due to high rainfall intensity combined with progressive land-use changes that reduce effective infiltration areas. Increasing urban development and heavy rainfall contribute to increasing urban flood volume and increasing drainage loads [3]. The expansion of impervious surfaces and the limited capacity of urban drainage systems often result in localized inundation even during relatively short rainfall events. Similar conditions have also been reported in urban areas experiencing rapid land-use change and increasing runoff concentration [4]. Previous studies have shown that such flooding is strongly controlled by the exceedance of drainage storage capacity and transient soil saturation rather than catchment-scale hydrological processes [5][6].

Semarang City, Central Java, Indonesia, represents a typical tropical urban environment where pluvial flooding frequently occurs. The Politeknik Negeri Semarang (Polines) campus, located in the Tembalang area, experiences recurrent surface water inundation during

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heavy rainfall events despite the presence of an established drainage network. Several buildings within the campus are situated in local topographic depressions, which further increase vulnerability to water ponding when drainage capacity is exceeded. Previous investigations in the surrounding Tembalang area have reported similar drainage-related inundation driven by rainfall-induced runoff [7][8].

The generation of surface runoff in such environments is closely linked to soil infiltration characteristics. Infiltration governs the partitioning of rainfall into subsurface flow and surface runoff, particularly during the early stages of rainfall. Fine-grained soils with moderate to high plasticity typically exhibit low permeability and limited infiltration capacity, leading to rapid saturation and increased runoff generation under intense rainfall conditions [9][10]. Numerous studies have shown that infiltration rates are initially high due to matric suction effects but decline rapidly as the soil approaches saturation, highlighting the transient nature of infiltration processes [11][12]. Wei et al. also observed a similar trend, where an increase in soil moisture during rainfall resulted in a reduced infiltration rate [13].

Physically based infiltration models provide a valuable framework for representing these processes. Zhang et al. also reported that rainfall infiltration behavior in unsaturated geomaterials is strongly influenced by transient hydraulic boundary conditions [14]. The Green–Ampt model has been widely applied to simulate infiltration under rainfall conditions because it explicitly accounts for soil hydraulic properties and wetting front advancement [15]. When combined with rainfall frequency analysis and runoff estimation methods, infiltration modeling enables a more realistic assessment of runoff generation and drainage surcharge potential. For small to medium urban catchments such as campus areas, the Rational Method remains a practical approach for estimating peak runoff, particularly when rainfall intensity is derived from the time of concentration [16][17].

In addition to runoff generation, drainage storage capacity plays a critical role in controlling surface water inundation. Drainage channels act as temporary storage that can attenuate runoff peaks; however, when their capacity is exceeded, water is forced onto the surface, resulting in localized flooding. Studies on urban drainage systems emphasize that pluvial flooding often arises not from insufficient total storage volume alone but from the combined effects of limited infiltration, reduced effective drainage capacity, and local hydraulic bottlenecks [1][18].

Despite increasing attention to pluvial flooding, integrated studies that explicitly link soil infiltration behavior, rainfall characteristics, runoff generation, and drainage storage capacity at the campus scale remain limited, particularly in Indonesian contexts. Many existing studies focus on regional flooding or evaluate drainage systems without incorporating detailed soil infiltration analysis [19][20]. Consequently, there is a need for an integrated assessment that captures the coupled hydrological and geotechnical controls governing surface water inundation in semi-urban environments. This evaluation is essential for adapting urban drainage under changing rainfall conditions [21].

This study investigates rainfall infiltration and surface runoff at the Polines campus as an integrated approach to understanding and reducing pluvial flood risk caused by drainage capacity exceedance. The objectives are to (i) characterize soil physical and hydraulic properties, (ii) evaluate infiltration behavior using the Green–Ampt model under different rainfall return periods, (iii) estimate runoff based on rainfall intensity corresponding to the time of concentration, and (iv) assess the adequacy of existing drainage storage capacity. By integrating infiltration analysis with runoff and drainage evaluation, this study provides a scientifically grounded basis for improving stormwater management strategies in campus-scale and similar urban environments.

Unlike many previous studies that evaluate urban flooding mainly through rainfall–runoff relationships or drainage hydraulics alone, this study integrates soil infiltration behavior, runoff generation, and drainage storage capacity within a unified campus-scale framework. The novelty lies in explicitly linking transient infiltration dynamics, represented by the physically based Green–Ampt model, with drainage storage exceedance as the mechanism controlling surface water inundation.

Instead of treating infiltration losses as a lumped parameter, this study demonstrates how limited soil permeability and rapid saturation restrict runoff reduction during intense rainfall, even when total drainage storage appears sufficient. By combining laboratory-based soil characterization, rainfall frequency analysis, time-of-concentration–based runoff estimation, and detailed drainage storage evaluation, the proposed framework provides a process-oriented explanation of pluvial flooding in tropical semi-urban environments.

2. Methods

2.1. Study Area

This study was conducted at the Politeknik Negeri Semarang (Polines) campus, located in the Tembalang area, Semarang City, Central Java, Indonesia. The campus represents a semi-urban catchment characterized by mixed land use, including academic buildings, paved surfaces, and limited green open spaces. Several facilities are situated within shallow topographic depressions, making the area susceptible to surface water inundation during intense rainfall events. Stormwater drainage is provided by an open-channel network that functions both as a conveyance system and temporary storage during rainfall.

2.2. Soil Sampling and Laboratory Testing

Soil samples were collected from representative locations within the campus area. Disturbed samples were used to characterize soil physical and hydraulic properties governing infiltration behavior. Laboratory testing was conducted at the Soil Mechanics Laboratory of Polines following relevant ASTM standards.

The tests included grain size distribution analysis (sieve and hydrometer), Atterberg limits tests, and specific gravity tests. Soil classification was performed using the Unified Soil Classification System (USCS) and the AASHTO classification system. Saturated hydraulic conductivity (Ks) was determined through laboratory permeability tests using constant-head or falling-head methods depending on soil gradation.

2.3 Rainfall Data and Frequency Analysis

Daily maximum rainfall data over a ten-year period were obtained from the nearest rainfall station serving the Tembalang area. The data were screened for consistency and completeness, and annual maximum rainfall values were extracted. Frequency analysis was conducted to estimate design rainfall depths for return periods of 2, 5, 10, and 20 years. The selected return periods represent typical design conditions for evaluating urban drainage performance.

2.4. Infiltration Analysis

Infiltration behavior was evaluated using the physically based Green–Ampt model, which represents infiltration in unsaturated soils as the downward movement of a sharp wetting front. The infiltration rate *f(t)* is expressed as Equation 1.

$$f(t) = K_s\left(1+\frac{\psi_f(\theta_s-\theta_i)}{F(t)}\right) \qquad (1)$$

Where K_s as the saturated hydraulic conductivity, ψ_f as the the wetting front suction head, θ_s *and* θ_i as the saturated and initial volumetric water contents, respectively, and *F(t)* as the cumulative infiltration at time *t*. In addition, Cumulative infiltration is obtained by solving Equation 2.

(a) (b)

Figure 1. Location of the study area (a) and layout of the existing campus drainage network (b)

$$F(t) = K_s t + \psi_f(\theta_s - \theta_i)\ln\left(1+\frac{F(t)}{\psi_f(\theta_s-\theta_i)}\right) \quad (2)$$

Model parameters were derived from laboratory test results and estimated soil water characteristic properties. The analysis focused on the temporal evolution of infiltration capacity and the transition from unsaturated to near-saturated soil conditions during rainfall events.

2.5. Time of Concentration

The time of concentration (T_c) was estimated using the Kirpich (Equation 3) , which is commonly applied to small urban catchments.

$$T_c = 0.0195\, L^{0.77} S^{-0.385} \quad (3)$$

where *L* represent the length of the longest flow path and *S* represent the average slope of the catchment. The calculated T_c was used to determine the critical rainfall duration for runoff estimation.

2.6. Runoff Estimation

Surface runoff was estimated using the Rational Method, which is suitable for small urban catchments such as campus areas. Peak runoff discharge *Q* was calculated as Equation 4.

$$Q = C\, I\, A \quad (4)$$

where *C* represents the runoff coefficient representing land-use and surface characteristics, *I* represents the rainfall intensity corresponding to the time of concentration, and *A* represents the catchment area.

Runoff coefficients were selected based on observed land cover and surface conditions within the campus. Rainfall intensity values were derived from the design rainfall depth divided by the critical rainfall duration equal to T_c.

2.7. Drainage Storage Capacity Assessment

The drainage network was inventoried through field observation and dimensional measurements of channel cross sections and lengths. The storage volume of each drainage segment was calculated geometrically, and the total drainage storage capacity was obtained by summing individual segment volumes.

Drainage performance was evaluated by comparing runoff volumes and peak discharges with the available drainage storage capacity. Conditions where runoff exceeded storage capacity were interpreted as drainage surcharge, leading to surface water inundation.

2.8. Integrated Assessment Framework

An integrated assessment framework was applied to evaluate urban pluvial flooding driven by drainage capacity exceedance. The framework links rainfall characteristics, transient infiltration behavior, runoff generation, and drainage storage capacity within a unified process-based analysis. This approach enables identification of critical conditions under which surface water inundation occurs despite the presence of drainage infrastructure, highlighting the combined influence of limited infiltration and drainage surcharge at the campus scale.

3. Results and Discussion

3.1. Soil Characteristics and Hydraulic Implications

The soil characterization results indicate that the study area is dominated by fine-grained soils with moderate to high plasticity. As summarized in Table 1, the soil is classified as OH/MH according to the Unified Soil Classification System and A-7-5 under the AASHTO classification. The measured saturated hydraulic conductivity is 4.209×10^{-6} mm/s, which falls within the category of very low permeability soil.

Table 1. Physical and hydraulic properties of soil in the study area

Parameter	Unit	Value
Specific Gravity (*Gs*)	–	2,65
Liquid Limit (*LL*)	%	> 50
Plasticity Index (*PI*)	%	19,35
Soil classification (USCS)	–	OH / MH
Soil classification (AASHTO)	–	A-7-5
Saturated hydraulic conductivity (K_s)	mm/s	$4{,}209 \times 10^{-6}$

3.2. Soil Water Retention Characteristics

The unsaturated hydraulic behavior of the soil is further illustrated through the Soil Water Characteristic Curve (SWCC), as presented in Figure 2. The curve represents the relationship between matric suction and volumetric water content and provides quantitative insight into moisture retention and desaturation behavior of the fine-grained soil in the study area.

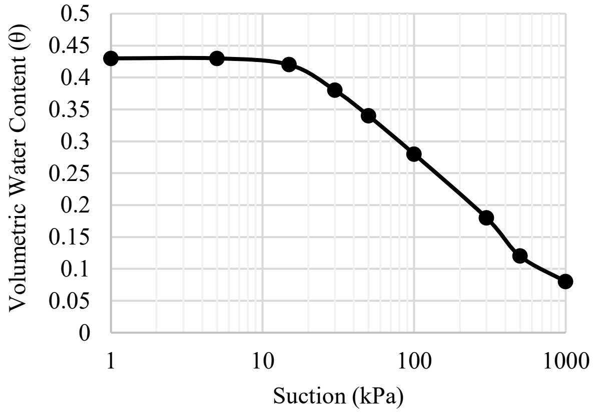


Figure 2. Soil Water Characteristic Curve (SWCC) for the study area

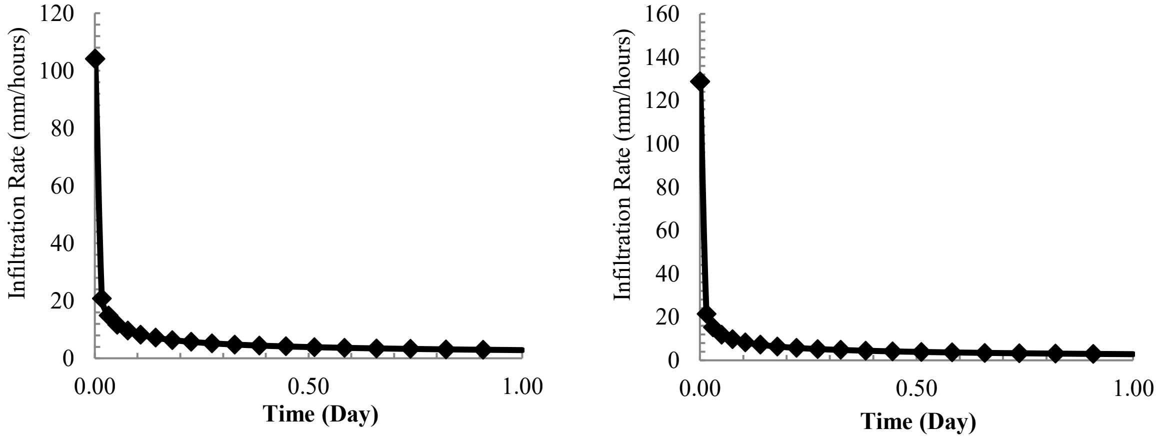
As shown in Figure 2, the saturated volumetric water content (θ_s) is approximately 0.43, while the residual volumetric water content (θ_r) is approximately 0.08. The air entry value (AEV) is approximately 15 kPa, indicating the suction threshold at which desaturation begins. The dominant transition zone extends from approximately 15 kPa to 300 kPa, reflecting gradual moisture redistribution within the soil matrix.

The relatively low air entry value confirms the fine pore structure typical of high-plasticity soils. Once matric suction decreases during rainfall infiltration, hydraulic conductivity rapidly approaches its saturated value, limiting additional increases in infiltration capacity.

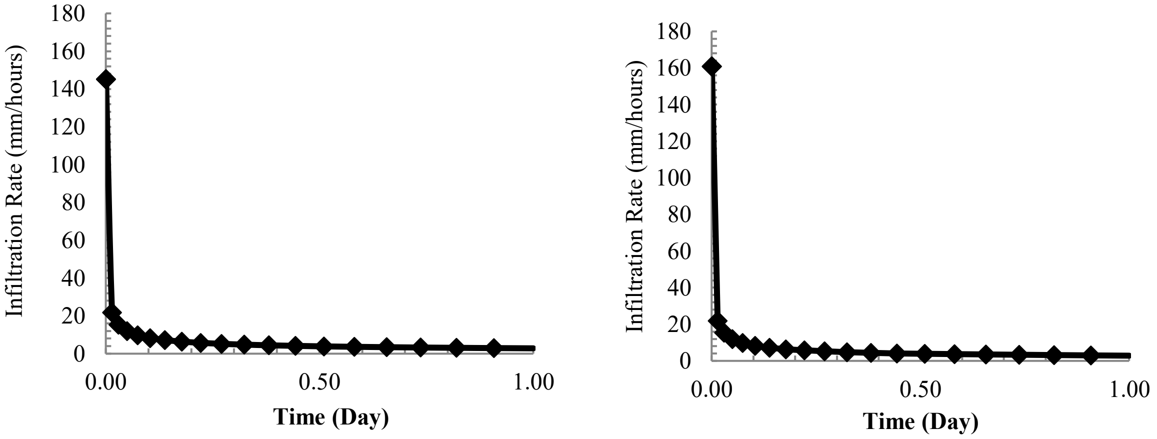
3.3. Infiltration Dynamics under Design Rainfall

The infiltration behavior simulated using the Green–Ampt model exhibits a distinct transient pattern, as illustrated in Figure 3. At the onset of rainfall, infiltration rates are relatively high due to the influence of matric suction in unsaturated soil conditions. However, infiltration rates decline rapidly with time as the soil approaches saturation, eventually converging toward a quasi-steady value close to the saturated hydraulic conductivity.

Differences among return periods are evident during the initial phase of rainfall, where higher rainfall intensity produces higher initial infiltration rates. However, as rainfall continues, the infiltration curves tend to converge, indicating similar infiltration behavior at later stages.

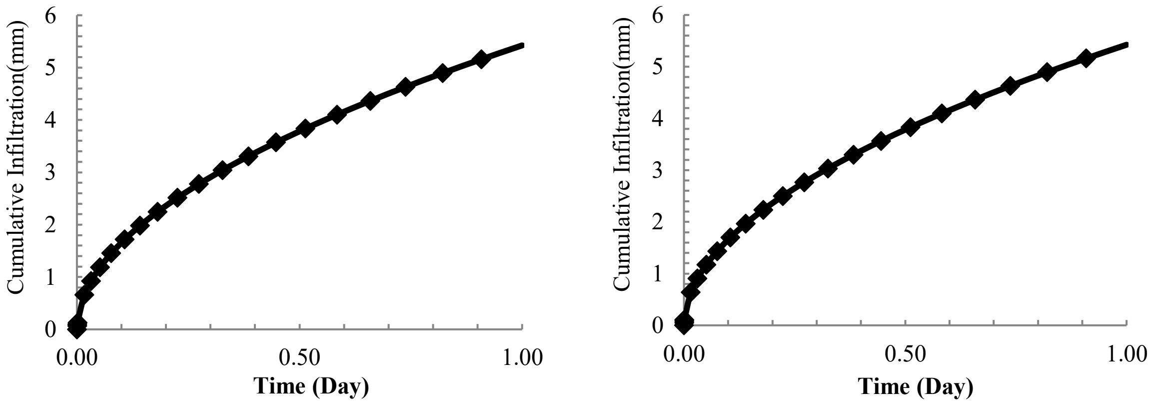


(a) 2-year return period rainfall   (b) 5-year return period rainfall



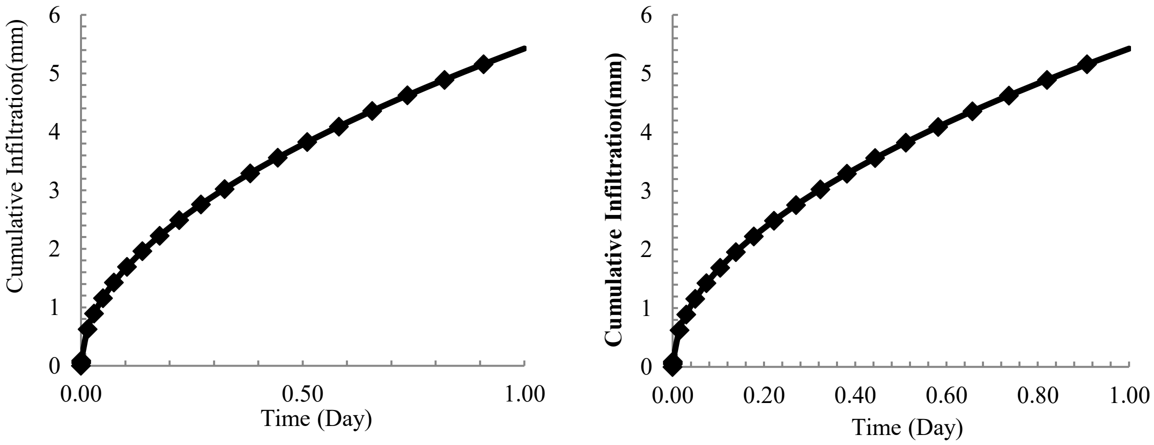
(c) 10-year return period rainfall   (d) 20-year return period rainfall

Figure 3. Temporal variation of infiltration rate simulated using the Green–Ampt model under different rainfall return periods



2-year return period rainfall

5-year return period rainfall



10-year return period rainfall

20-year return period rainfall

Figure 4. Cumulative infiltration as a function of time simulated using the Green–Ampt model for different rainfall return periods.

Table 2. Comparison between runoff volume and drainage storage capacity for different rainfall return periods

Return period (years)	Design rainfall (mm/day)	Estimated runoff volume (m^3)	Drainage storage capacity (m^3)	Storage margin (m^3)
2	104.123	341.308	1270.38	928.692
5	128.767	422.090	1270.38	847.910
10	145.125	475.710	1270.38	794.290
20	160.924	527.498	1270.38	742.502

Cumulative infiltration (Figure 4) increases nonlinearly with time. Higher return periods produce larger cumulative infiltration values during early and intermediate rainfall durations. At longer durations, the cumulative infiltration curves evolve with similar slopes, indicating that infiltration increments become relatively uniform across return periods.

3.4. Rainfall Characteristics and Runoff Response

Rainfall frequency analysis using the Log-Pearson Type III distribution produced design rainfall depths ranging from 104,123 mm (2-year return period) to 160,924 mm (20-year return period). This increase in rainfall depth directly translates into higher runoff volumes and peak discharges, as estimated using the Rational Method. Runoff volumes were calculated using the Rational Method based on rainfall intensity corresponding to the time of concentration. The results are summarized in Table 2.

The results indicate a progressive increase in runoff volume with increasing rainfall return period. The estimated runoff volume increases from 341.308 m^3 for the 2-year return period to 527.498 m^3 for the 20-year return period.

3.5. Hydrological Partitioning and Rainfall Excess Transformation

To provide a clearer interpretation of rainfall–runoff behavior at the campus scale, the design rainfall input was conceptually partitioned into infiltration and rainfall excess components. At the beginning of rainfall events, water is partially absorbed into the soil profile under unsaturated conditions, driven by matric suction and surface hydraulic gradients. However, as infiltration capacity progressively declines toward the saturated hydraulic conductivity (K_s), the proportion of rainfall converted into surface runoff increases.

The results indicate that infiltration effectiveness is temporally constrained. During the early stage of rainfall, a portion of rainfall is accommodated within the soil matrix. As the soil approaches near-saturation conditions, additional rainfall increments exceed infiltration capacity and are transformed into rainfall excess. This transition occurs more rapidly under higher return period rainfall, where rainfall intensity surpasses the declining infiltration rate at an earlier stage.

The increase in runoff volume from 341.308 m^3 (2-year return period) to 527.498 m^3 (20-year return period) reflects this progressive shift in rainfall partitioning. Rather than demonstrating enhanced infiltration under higher rainfall intensity, the system exhibits increasing dominance of rainfall excess generation. Consequently, runoff response becomes primarily governed by surface hydrological processes once soil storage potential is exhausted.

This rainfall partitioning mechanism confirms that hydrological response in the study area is controlled by intrinsic hydraulic limitations rather than by total rainfall volume alone.

3.6. Discussions

Role of Soil Water Retention Behavior in Infiltration Limitation

The Soil Water Characteristic Curve (SWCC) provides a fundamental explanation of the transient infiltration behavior observed in this study. The identified air entry value of approximately 15 kPa indicates that desaturation begins at relatively low suction levels, which is characteristic of fine-grained soils with small pore throats and high plasticity. Such soils initially retain water effectively under moderate suction; however, capillary resistance diminishes rapidly as wetting progresses.

During the early stage of rainfall, matric suction enhances the hydraulic gradient between the soil surface and the advancing wetting front. This suction-controlled regime explains the elevated initial infiltration rates simulated using the Green–Ampt model. Classical infiltration theory has long established that early infiltration is dominated by suction effects before gradually transitioning to a conductivity-controlled regime [10][11]. Recent experimental investigations on unsaturated soils further confirm that matric suction significantly influences early infiltration but becomes progressively less dominant as the soil approaches saturation [12].

As suction decreases, hydraulic conductivity converges toward the saturated value (K_s). In the present study, the measured K_s (4.209×10^{-6} mm/s) is extremely low, indicating severe limitations in vertical percolation once near-saturation is reached. Although the SWCC shows a relatively wide suction transition zone (15–300 kPa), moisture redistribution within this range does not substantially increase infiltration capacity under sustained rainfall. Similar findings have been reported where infiltration under design storm conditions becomes strongly bounded by intrinsic soil hydraulic parameters rather than rainfall intensity alone [9].

The SWCC therefore clarifies why infiltration in the study area functions only as a short-duration buffer. Once suction effects are exhausted, additional rainfall increments are converted predominantly into surface runoff. This transition from suction-controlled to conductivity-limited flow represents a critical mechanism governing pluvial flood susceptibility at the campus scale.

Influence of Soil Hydraulic Properties on Infiltration Limitation

The results demonstrate that the study area is dominated by fine-grained soils (OH/MH; A-7-5) with very low saturated hydraulic conductivity (4.209×10^{-6} mm/s). Such hydraulic characteristics impose a fundamental limitation on infiltration capacity, particularly during prolonged rainfall events.

Fine-grained soils with high plasticity are known to exhibit low pore connectivity and reduced effective permeability, which significantly restrict vertical water movement [9][10]. The measured hydraulic conductivity in this study falls within the range typically associated with clayey soils where infiltration transitions rapidly from suction-controlled flow to conductivity-controlled flow. This behavior is consistent with the theoretical framework established by Green and Ampt [11], where infiltration capacity progressively declines as the wetting front advances and soil suction effects diminish.

Recent experimental investigations on unsaturated soils confirm that matric suction initially enhances infiltration rates but becomes progressively less influential as saturation increases [12][19]. The convergence of infiltration rates toward a quasi-steady value close to Ks observed in this study directly reflects this hydraulic control mechanism. Therefore, even under higher rainfall intensities associated with larger return periods, infiltration is ultimately bounded by intrinsic soil properties rather than rainfall magnitude.

These findings reinforce the interpretation that infiltration losses in the study area cannot be treated as a flexible or scalable parameter during extreme rainfall. Instead, infiltration acts as a rapidly exhausted buffer, after which additional rainfall is converted predominantly into surface runoff.

Transient Infiltration Dynamics and Return Period Effects

The simulated infiltration curves indicate that rainfall return period influences infiltration primarily during the early stage of rainfall events. Higher rainfall intensities produce higher initial infiltration rates due to increased hydraulic gradients at the soil surface. However, as rainfall duration increases, infiltration rates for different return periods converge.

This behavior aligns with classical infiltration theory, which predicts that infiltration under ponded or near-ponded conditions becomes governed by saturated hydraulic conductivity once soil suction is dissipated [11][15]. Beven further emphasized that cumulative infiltration in fine-grained soils is constrained by soil hydraulic properties rather than rainfall intensity alone [22].

The cumulative infiltration curves obtained in this study exhibit similar long-term slopes across return periods, indicating a hydraulic upper bound. Comparable results were reported by Rawls et al. (1983), who demonstrated that Green–Ampt parameters derived from soil properties strongly dictate infiltration limits under design storm conditions [9].

From a flood risk perspective, this convergence is critical. It implies that under high-return-period rainfall, infiltration does not proportionally increase to offset additional rainfall input. Consequently, incremental rainfall depth is translated almost directly into increased runoff volume.

Rainfall–Runoff Response in Semi-Urban Catchments

Rainfall frequency analysis shows a substantial increase in design rainfall depth from 104.123 mm/day (2-year) to 160.924 mm/day (20-year). The Rational Method results indicate a corresponding increase in runoff volume. In semi-urban environments such as campus areas, runoff generation is strongly influenced by impervious surfaces and limited infiltration capacity. Brattebo and Booth demonstrated that surface sealing significantly increases runoff response even when partial permeable areas exist [18]. Similarly, Mardiah et al. reported that infiltration-based mitigation in campus environments becomes less effective when soil permeability is inherently low [19].

The runoff behavior observed in this study supports the classification of flooding as urban pluvial flooding, which is primarily driven by local rainfall–runoff imbalance rather than riverine overflow [1][2]. The results confirm that runoff generation is controlled by short-duration rainfall intensity exceeding infiltration and drainage response capacity. Furthermore, studies in Indonesian urban contexts have highlighted similar mechanisms, where localized drainage exceedance rather than watershed-scale processes dominates flood occurrence [5][6][7][8].

Drainage Storage Capacity and Inundation Risk

The total available drainage storage capacity within the study area is approximately 1270,38 m³, as summarized in Table 2. When compared with effective runoff volumes, the drainage system appears capable of accommodating runoff for all analyzed return periods in terms of total volume balance. However, the safety margin between runoff volume and drainage storage decreases substantially with increasing rainfall return period.

Specifically, the storage margin decreases from approximately 928,69 m³ for the 2-year return period to 742,50 m³ for the 20-year return period. This reduction indicates that the drainage system operates increasingly close to its capacity threshold during extreme rainfall events. Similar patterns have been reported in urban drainage studies, where localized inundation occurs despite sufficient total storage due to temporal concentration of runoff and hydraulic bottlenecks within the drainage network [1][5]. Thus, the results suggest that pluvial flooding in the study area is governed not merely by total volume balance, but by the interaction between transient infiltration exhaustion, rapid runoff concentration, and drainage surcharge dynamics.

Influence of Drainage Geometry Variability on Hydraulic Performance

The heterogeneous distribution of drainage storage capacity introduces potential hydraulic imbalance within the network. Even when total system storage appears adequate, localized segments with limited cross-sectional capacity may experience surcharge earlier than others.

Urban drainage literature emphasizes that bottlenecks within drainage networks can trigger surface ponding despite sufficient aggregate capacity [1]. Flow concentration from impervious surfaces may rapidly load downstream segments, particularly those situated in micro-topographic depressions.

In the present study, the spatial variability of channel dimensions suggests that pluvial flooding risk is not solely dependent on total storage volume but also on the geometric configuration of individual segments. This finding supports the argument that drainage system evaluation should incorporate spatial distribution analysis rather than relying exclusively on cumulative capacity. The interaction between concentrated runoff input and heterogeneous storage distribution further amplifies vulnerability during high-intensity rainfall events.

Integrated Infiltration–Runoff–Drainage Interaction

The integrated framework adopted in this study highlights the coupled hydrological and geotechnical controls on pluvial flooding. Infiltration is initially governed by matric suction but quickly transitions to conductivity-controlled flow. Once infiltration capacity is exceeded, additional rainfall contributes directly to runoff generation. The drainage system then functions as temporary storage, but its safety margin diminishes with increasing return period.

Beven emphasized the necessity of process-based rainfall–runoff modeling to capture such nonlinear interactions [22]. Similarly, Butler and Davies argued that urban flood mitigation requires integration of hydrological losses and drainage hydraulics rather than treating them independently [1]. The results demonstrate that limited infiltration capacity in fine-grained tropical soils constrains the effectiveness of natural infiltration as a mitigation mechanism. As rainfall intensity increases, the system response becomes dominated by runoff concentration and drainage storage utilization. This integrated interpretation provides a mechanistic explanation for recurrent pluvial flooding at the campus scale and reinforces the importance of coupling infiltration enhancement strategies with drainage capacity optimization in semi-urban tropical environments.

Engineering Implications for Campus-Scale Stormwater Management

The hydraulic characteristics identified in this study indicate that stormwater mitigation in the investigated campus environment cannot rely solely on natural infiltration. The very low saturated hydraulic conductivity limits sustained vertical percolation once near-saturation conditions are reached. Although matric suction enhances infiltration at the onset of rainfall, this effect diminishes rapidly as the wetting front advances, a transition consistent with classical infiltration theory [11] and subsequent experimental findings on unsaturated soils [12].

Similar limitations have been reported in semi-urban environments where infiltration-based measures become less effective in fine-textured soils [19]. Under such conditions, rainfall excess generation increases rapidly once infiltration capacity is exceeded, leading to higher hydraulic loading on drainage systems. The present results confirm that runoff amplification under higher return periods is primarily governed by intrinsic soil permeability rather than rainfall magnitude alone, which aligns with process-based rainfall–runoff interpretations [22].

From a drainage perspective, the declining storage margin suggests that system resilience depends not only on total volumetric capacity but also on hydraulic continuity and segment configuration. Urban drainage studies emphasize that localized surcharge may occur despite adequate aggregate storage due to flow concentration and network bottlenecks [1]. Consequently, improvement strategies at the campus scale should prioritize distributed storage enhancement, conveyance optimization, and localized geometric adjustments rather than exclusively expanding total storage volume. Qin et al. showed that distributed stormwater management measures can help reduce runoff accumulation during high-intensity rainfall conditions [23].

These findings highlight the importance of integrating soil hydraulic characterization with drainage system evaluations in tropical, semi-urban environments. Consistent with Peng et al. [24], this study confirms that pairing drainage management with low-impact development is superior for runoff reduction, highlighting the crucial need to understand infiltration limitations.

Study Limitations and Research Outlook

Several limitations should be acknowledged. The infiltration analysis was based on the Green–Ampt model, which assumes a sharp wetting front and homogeneous soil conditions. While suitable for representing transient infiltration processes, this assumption may simplify actual field heterogeneity. In addition, runoff estimation was performed using the Rational Method, which emphasizes peak discharge and does not simulate full hydrograph routing within the drainage network.

The rainfall analysis was derived from a ten-year data record, which may not fully capture long-term climate variability or potential intensification trends. Future studies could incorporate longer rainfall datasets, dynamic hydraulic routing models, and two-dimensional surface flow simulations to improve predictive capability. More detailed hydraulic simulations may also support future urban drainage adaptation under changing rainfall conditions [21]. Despite these limitations, the integrated framework developed in this study provides a consistent and physically grounded basis for evaluating pluvial flooding at the campus scale.

4. Conclusions

This study shows that pluvial flooding at the Politeknik Negeri Semarang campus is mainly controlled by limited infiltration capacity and increasing surface runoff during high-intensity rainfall. The investigated soil is dominated by fine-grained material classified as OH/MH and A-7-5 with a saturated hydraulic conductivity of only 4.209×10^{-6} mm/s. Such conditions cause infiltration capacity to decrease rapidly once the soil approaches saturation.

The Green–Ampt analysis indicates that infiltration is effective only during the initial stage of rainfall. Afterward, most additional rainfall is converted into surface runoff because the infiltration rate gradually approaches the saturated hydraulic conductivity. This condition is reflected by the increase in runoff volume from 341.308 m^3 for the 2-year return period to 527.498 m^3 for the 20-year return period.

The existing drainage system still has a total storage capacity of 1,270.38 m^3, which is larger than the estimated runoff volume for all analyzed return periods. However, the available storage margin decreases from 928.692 m^3 under the 2-year return period to 742.502 m^3 under the 20-year return period. This trend indicates that the drainage system will experience higher hydraulic loading during extreme rainfall events, particularly in drainage segments located near local topographic depressions.

Based on these results, flood mitigation at the campus scale should focus on preserving the effective performance of the existing drainage network. Routine sediment cleaning and maintenance are necessary to prevent reduction of channel storage capacity. In addition, drainage sections with relatively small dimensions and located in areas with lower ground elevation should be prioritized for hydraulic improvement because these locations are more susceptible to temporary surcharge during peak runoff conditions.

The results also suggest that future campus development should maintain existing permeable areas and avoid reducing green areas that could increase runoff contributions to the drainage network. The integrated infiltration–surface flow–drainage approach used in this study provides a practical framework for evaluating potential rainfall-induced flooding in tropical semi-urban environments with low-permeability soils.

Acknowledgments

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