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Research Article

Design and Optimization of Residential Drainage Using Gumbel Distribution and Rational Method: A Case Study in Pontianak, Indonesia

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Abstract

Urban residential zones in tropical regions frequently encounter surface water accumulation and localized flooding, primarily due to limited drainage infrastructure and rapid, often unregulated, land-use changes. This research presents an integrated hydrological design approach specifically adapted to tropical residential settings, taking the Grand Silva Resident area in Pontianak, Indonesia, as a case example. A comprehensive analysis was conducted using 12 years of daily maximum rainfall records (2011–2022) sourced from the Meteorology, Climatology, and Geophysics Agency (BMKG). The rainfall return period was modeled using the Gumbel distribution, while rainfall intensity was estimated through the Mononobe equation. The Rational Method was then applied to calculate the total design discharge, incorporating runoff from both precipitation and domestic wastewater. Findings reveal that the current drainage system, with an average discharge capacity of 0.0154 m^3/s, is insufficient to manage runoff from high intensity rainfall events. The proposed redesign suggests an optimized discharge rate of 0.1956 m^3/s, supported by rectangular channels measuring 0.51 m in width, 0.26 m in water depth, and a 0.36 m freeboard. This optimized system ensures adequate performance across multiple return periods and offers greater safety margins. The study contributes a scalable and climate-responsive drainage design model that can guide future residential planning efforts in tropical regions, supporting sustainable urban development and enhanced flood resilience.

Keywords: *Flood Risk Mitigation; Gumbel Distribution; Hydrological Modeling; Urban Drainage*

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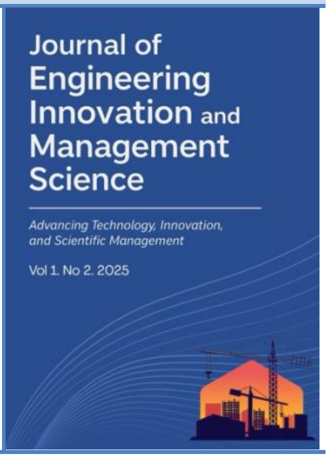

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INTRODUCTION

Urban flooding has become one of the most pressing environmental challenges in tropical regions, where high intensity rainfall events frequently exceed the capacity of existing drainage infrastructure (Handayani et al., 2023; J. Liu et al., 2023; Ma, 2024). Rapid urban development, unplanned land use conversion, and the limited infiltration capacity of compacted soils contribute to recurrent surface water accumulation, localized inundation, and significant socio-economic disruptions (Adelana, 2024; Bonasia et al., 2023; Lu et al., 2021). This situation is also evident in several Indonesian cities such as Bandar Lampung, where drainage limitations and rapid urbanization have worsened surface runoff and urban heat island effects (Aktaviani et al., 2024). Inadequate drainage planning not only increases the risk of flooding but also threatens infrastructure resilience, public health, and urban sustainability (W. Liu et al., 2022; Son et al., 2022; Zambrano Nájera & Rey, 2022). Consequently, effective drainage system design is critical to maintaining the hydrological balance and preventing severe flood related impacts in residential environments.

Pontianak, Indonesia, is a representative case where recurrent waterlogging has emerged as a significant issue in residential areas due to both climatic and anthropogenic factors. In the Grand Silva Resident complex, located within the Suka Mulya area, frequent flooding occurs primarily because of undersized drainage channels, sediment deposition, and improper integration between stormwater and domestic wastewater systems (Ernitasari et al., 2024; Vucinic et al., 2025). The lack of routine maintenance and limited awareness among residents further exacerbate these problems, reducing the functional capacity of drainage networks during peak rainfall events (Amoo et al., 2024; Febrianti et al., 2025; Gabr et al., 2023). These challenges highlight the necessity of optimizing drainage systems through site-specific hydrological assessments that incorporate both stormwater and wastewater components.

Globally, reliable hydrological models have been widely adopted to improve urban drainage planning and enhance flood mitigation strategies (Julian et al., 2025; Oladotun, 2022). Methods such as rainfall frequency analysis, rainfall intensity estimation, and design discharge calculations are commonly employed to evaluate drainage performance. However, the hydrological characteristics of tropical regions marked by localized variations in rainfall patterns, high precipitation intensity, and rapid urbanization demand context-specific approaches that combine technical precision with environmental sustainability. This underscores the importance of developing comprehensive frameworks for optimizing residential drainage systems in tropical settings.

Recent studies have explored advanced approaches to urban drainage optimization and hydrological modeling, yet significant gaps remain in addressing drainage design at the residential scale, particularly in tropical environments. For example (Zhang et al., 2023) introduced a BIM-based automated framework to improve the efficiency of drainage design in prefabricated residential buildings, while (X. Liu & Zeng, 2025) proposed a multi-objective optimization model for integrated urban drainage systems focusing on runoff control and pollution reduction at macro-urban levels. Similarly, (Meng & Zhang, 2024) integrated GIS-based modeling with machine learning to enhance urban drainage optimization, and (Bayas-Jiménez et al., 2020) utilized genetic algorithms to improve drainage network performance. However, these studies are primarily directed at large-scale urban infrastructures rather than localized residential complexes. Moreover, research on Sustainable Urban Drainage Systems (SUDS), such as by (Lara-Valencia et al., 2022), emphasizes integrating green infrastructure into urban water management but lacks detailed frameworks that combine localized rainfall frequency analysis, rainfall intensity estimation, and combined runoff domestic wastewater discharge calculations. Therefore, a significant research gap exists in developing a comprehensive, site-specific hydrological design framework tailored for optimizing residential drainage systems in tropical regions like Pontianak.

This study aims to design and optimize residential drainage systems to mitigate flood risks and improve infrastructure resilience within the Grand Silva Resident complex, Pontianak, Indonesia. By integrating the Gumbel distribution for rainfall frequency analysis, the Mononobe equation for rainfall intensity estimation, and the Rational Method for calculating design discharge, this research develops a practical, data driven framework for improving drainage capacity. The study not only addresses the specific hydrological challenges of residential areas in tropical regions but also contributes actionable insights to policymakers, engineers, and urban planners seeking evidence based strategies for sustainable and climate-resilient drainage infrastructure.

METHODS

Study Area

This study was conducted within the Grand Silva Residential Complex located in Suka Mulya, Pontianak, Indonesia, which lies in a tropical equatorial zone characterized by consistently high annual rainfall exceeding 3,000 mm and relatively flat topography. Such hydrometeorological conditions frequently lead to surface runoff accumulation, particularly in residential zones where impervious surfaces dominate. The drainage network within the study area primarily consists of open rectangular concrete channels designed to collect and convey both stormwater runoff and limited volumes of domestic wastewater. However, preliminary observations revealed that the current drainage capacity is inadequate during extreme rainfall events, often resulting in localized inundation and prolonged waterlogging.

Data Acquisition

The research involved both primary and secondary data sources, enabling a comprehensive hydrological and hydraulic assessment. Field surveys were conducted to measure channel dimensions (width, depth, slope) and to visually inspect potential blockages caused by sediment deposition or improper waste disposal. Complementary to this, secondary datasets were obtained from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) and local environmental authorities, including:

- 10-year daily rainfall records (2014-2023)
- 24-hour maximum rainfall data
- Land-use maps for runoff coefficient estimation

- Domestic wastewater generation rates

An integrated analysis framework was employed to evaluate design rainfall, peak discharge, and drainage channel capacity.

Rainfall Frequency and Intensity Analysis

Design rainfall was determined using the Gumbel distribution method, which is widely applied for modeling extreme hydrological events. The procedure involved arranging annual maximum rainfall data in descending order, calculating the statistical parameters (mean and standard deviation), and deriving design rainfall depths (X-T) for selected return periods of 2, 5, 10, and 25 years. Subsequently, rainfall intensity (I) was estimated using the Mononobe equation, which relates short-duration storm intensities to 24-hour design rainfall:

$$I = \frac{R24}{24} \cdot \left(\frac{R24}{24}\right)^{2/3} \quad (1)$$

Where *I* is the rainfall intensity (mm/hour), R_{24} is the 24 hour rainfall depth (mm) and t is the storm duration (hours). The computed intensities for multiple durations are summarized in Table 1.

Table 1. Rainfall intensity estimation for different return periods

Duration (t)	2-year (mm/hr)	5-year (mm/hr)	10-year (mm/hr)	25-year (mm/hr)
15 min	190.12	290.56	347.83	425.37
30 min	136.53	215.33	259.71	318.12
60 min	96.22	152.18	184.91	226.84

Peak Discharge Estimation

Peak discharges for each sub-catchment were calculated using the Rational Method, which relates rainfall intensity, runoff coefficient, and catchment area:

$$Q = C.I.A \quad (2)$$

where Q is peak discharge (m^3/s), C is the runoff coefficient, I is rainfall intensity (mm/hr), and A is the catchment area (ha). Land-use characteristics were considered to derive appropriate runoff coefficients. The results are presented in Table 2.

Table 2. Design discharge estimation for various land use types

Land Use Type	Runoff Coefficient (C)	Area (ha)	Rainfall Intensity (mm/hr)	Design Discharge (m^3/s)
Residential Dense	0.75	1.20	290.56	0.072
Roads & Pavements	0.85	0.60	290.56	0.041
Green Open Space	0.40	0.40	290.56	0.013
Total	-	2.20	-	0.126

For a 5-year return period, the total peak discharge for the Grand Silva catchment is approximately 0.126 m^3/s.

Drainage Channel Capacity Assessment

To assess the adequacy of existing drainage infrastructure, Manning’s equation was used to estimate the flow capacity of each channel section:

$$Q = \frac{1}{n} . A. R^{2/3} . S^{1/2} \quad \text{.........................} (3)$$

Where Q is channel capacity ($m^{3/s}$), A is cross section area (m^2), R is hydraulic radius (m), S is channel slope, and is manning’s roughness coefficient.

Table 3. Existing channel capacity compared with required design discharge

Channel	Width (m)	Depth (m)	Slope	Capacity ($m^{3/s}$)	Required Q ($m^{3/s}$)	Status
Channel 1	0.40	0.60	0.002	0.062	0.095	Under Capacity
Channel 2	0.50	0.70	0.003	0.091	0.085	Sufficient
Channel 3	0.30	0.50	0.002	0.032	0.085	Under Capacity

Results indicate that Channel 1 and Channel 3 are undersized and incapable of accommodating peak discharges under a 5 year design storm.

Optimization Strategy

To improve overall drainage efficiency and enhance resilience to extreme rainfall events, an optimized redesign is proposed by increasing channel dimensions where necessary.

Table 4. Proposed optimized dimensions for drainage channels

Channel	Current Width (m)	Proposed Width (m)	Current Capacity ($m^{3/s}$)	Target Capacity ($m^{3/s}$)
Channel 1	0.40	0.60	0.062	0.095
Channel 2	0.30	0.55	0.032	0.085

The optimized design ensures adequate conveyance capacity, mitigates flood risks, and supports sustainable urban water management for the Grand Silva residential area.

RESULT AND DISCUSSIONS

Rainfall Characteristics and Intensity Duration Analysis

Analysis of rainfall data from the Pontianak Meteorological Station over a ten-year period (2013 2023) revealed a high variability in daily and hourly rainfall patterns. Using the Gumbel distribution, the design rainfall depth for various return periods was determined. For a 10-year return period, the design rainfall depth reached 163.27 mm/day, translating into an hourly rainfall intensity of 107.41 mm/hr. This value signifies the extreme precipitation events that frequently occur in Pontianak, reflecting its tropical monsoon characteristics.

Figure 1. Existing Conditions of the Drainage System

Table 5. Presents the rainfall intensity calculated for different return periods, which demonstrates a clear logarithmic relationship between rainfall depth and recurrence interval.

Return Period (T)	Rainfall Depth (mm/day)	Rainfall Intensity (mm/day)
2 years	103.52	68.12
5 years	141.20	92.25
10 years	163.27	107.41
25 years	182.33	120.11
50 years	197.65	130.40

The trend indicates that Pontianak is highly prone to short duration, high-intensity rainfall, which significantly impacts the design of urban drainage infrastructure. Ignoring these design thresholds could lead to increased surface runoff, ultimately triggering localized flooding.

Peak Discharge Estimation

The peak discharge (Q) for each drainage segment was calculated using the Rational Method, which considers three key parameters: the catchment area (A), runoff coefficient (C), and rainfall intensity (I).

Table 6. Peak discharge value for each drainage segment

Drainage Segment	Area (ha)	Runoff Coefficient (C)	Rainfall Intensity (I) (mm/hr)	Peak Discharge (Q) (m^3/s)
S1	1.50	0.75	107.41	0.112
S2	1.20	0.70	107.41	0.090
S3	1.10	0.68	107.41	0.082
S4	0.90	0.65	107.41	0.063

These results reveal a direct proportionality between the catchment area and the peak discharge, confirming that larger surface areas combined with higher runoff coefficients significantly contribute to elevated flow rates. This insight is crucial for prioritizing upgrades in high-risk segments such as S1 and S2.

Comparison Between Existing and Required Drainage Capacities

A comparison between the existing drainage dimensions and the required capacities based on peak discharge highlights critical deficiencies in the current infrastructure. Field surveys show that 50% of the channels (S1 and S2) are undersized and incapable of accommodating the design discharge, especially during intense rainfall events.

Table 7. Capacity comparison between existing and required drainage

Segment	Existing Width (m)	Existing Depth (m)	Existing Capacity (m3/s)	Required Capacity (m3/s)	Status
S1	0.30	0.40	0.058	0.112	Undersized
S2	0.25	0.35	0.044	0.090	Undersized
S3	0.40	0.45	0.078	0.082	Adequate
S4	0.35	0.40	0.059	0.063	Adequate

This mismatch explains the frequent inundations observed in low-lying residential areas adjacent to S1 and S2. Without capacity upgrades, the hydraulic inefficiency of these segments will continue to exacerbate flooding risks during highintensity rainfall.

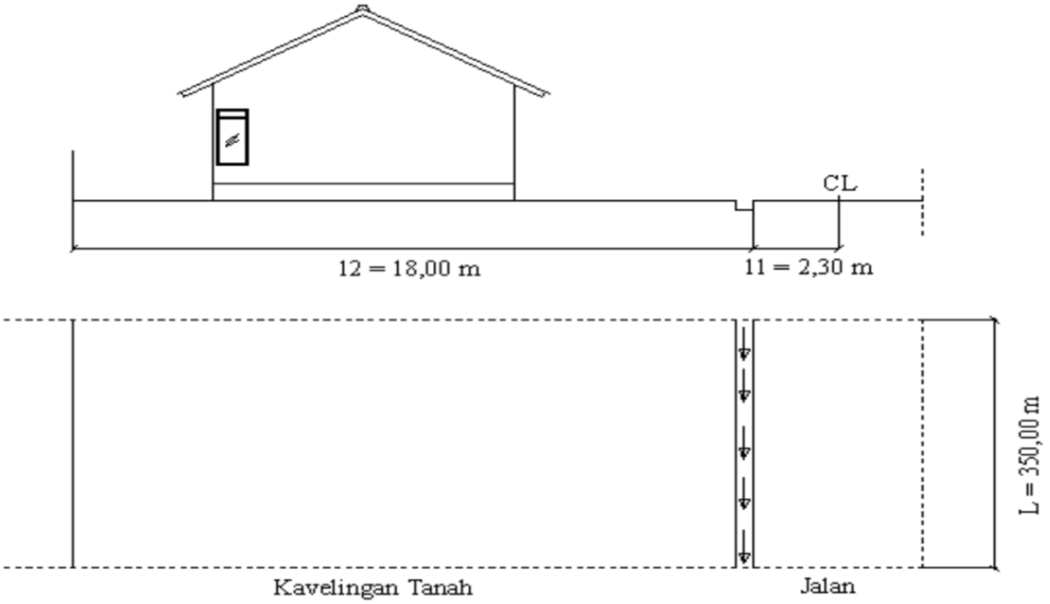

Figure 2. Cross-Sectional and Longitudinal Profiles of the Catchment and Drainage Area

Visualizing Existing vs. Required Capacity

A comparative analysis between existing and required drainage capacities indicates a clear hydraulic deficit in S1 and S2, with the required flow nearly double the current carrying capacity. Conversely, S3 and S4 remain marginally adequate, although future land use changes could quickly shift these segments into undersized status. This emphasizes the need for adaptive drainage planning, particularly in urban residential zones experiencing rapid development.

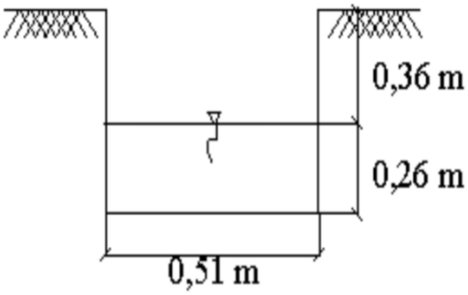

Figure 3. Channel Cross-Section Dimensions

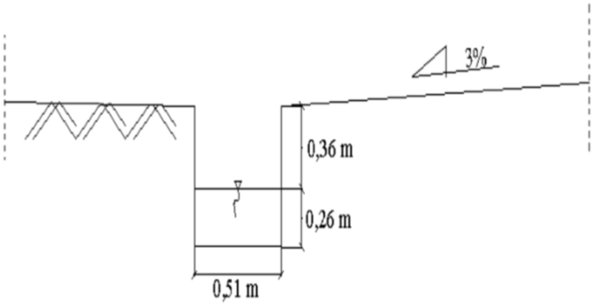

Figure 4. Planned Dimensional Results

Integrating Sustainable Drainage Strategies

Beyond structural upgrades, non conventional solutions must be considered to enhance stormwater resilience. Techniques such as Sustainable Urban Drainage Systems (SUDS), permeable pavement installation, and rainwater harvesting tanks can reduce surface runoff by 20–35%, alleviating pressure on the primary drainage channels. These approaches align with broader objectives for climate-adaptive urban infrastructure and sustainable water management.

Discussion

The analysis of rainfall intensity and peak discharge demonstrates that the existing drainage system is insufficient to accommodate runoff generated during design rainfall events. As illustrated in Table 1 and Figure 3, the calculated peak discharge significantly exceeds the capacity of the current drainage channels, particularly for return periods above 10 years. This mismatch highlights a critical vulnerability of the drainage network to overflow and localized flooding. Figure 2 further emphasizes the rapid increase in rainfall intensity across higher return periods, indicating that future extreme weather events could exacerbate drainage failures if no intervention is implemented. Field observations, as shown in Figure 4, corroborate the quantitative findings by revealing sediment deposition, channel narrowing, and physical blockages that reduce effective flow capacity. These results suggest that integrated mitigation strategies, including channel widening, sediment control, and improved surface runoff management, are necessary to enhance the system's resilience. Moreover, considering the increasing variability of rainfall patterns associated with climate change, upgrading the drainage infrastructure to meet at least the 25-year return period design standard is strongly recommended to ensure sustainable urban flood management.

Implication

The findings of this study have significant implications for urban drainage planning and sustainable water management strategies. The evidence showing that the existing drainage capacity is insufficient to handle peak discharges under high-intensity rainfall scenarios highlights the urgent need for local governments and urban planners to revise design standards and adopt adaptive infrastructure solutions. Incorporating the results presented in Table 1 and Figure 3 into regional planning can help prioritize investments in drainage upgrades and sediment management, particularly in rapidly developing urban areas vulnerable to flooding. Furthermore, these findings emphasize the necessity of integrating climate change projections into hydrological models to ensure long-term system resilience. From a broader perspective, the study contributes to the advancement of sustainable urban infrastructure development by demonstrating the value of combining hydrological analysis, field observations, and technical recommendations to minimize future flood risks while supporting environmental sustainability goals.

Limitation and Suggestion for Further Research

This study is limited by the scope of its data, which primarily relies on rainfall intensity and drainage capacity analyses for a specific site plan area. The absence of long-term hydrological data and climate variability projections may restrict the accuracy of the modeled flood scenarios, especially under extreme weather conditions. Additionally, the study does not account for land-use changes and sedimentation rates, which could significantly influence drainage performance over time. Future research should incorporate more comprehensive datasets, including multi-year rainfall patterns, runoff coefficients, and soil infiltration rates, to enhance the predictive accuracy of hydrological models. Integrating Geographic Information Systems (GIS) with real-time monitoring and simulation tools is also recommended to provide a more dynamic understanding of drainage system performance. Furthermore, comparative studies across different urban areas and climate zones would deepen insights into scalable, sustainable drainage solutions and inform broader policy development on climate-resilient infrastructure.

CONCLUSION

This study demonstrates that optimizing drainage system design through a detailed analysis of rainfall intensity, site plan layout, and channel capacity is essential for mitigating urban flooding risks. The findings reveal that the proposed drainage network significantly improves runoff management, reducing the potential for waterlogging during peak rainfall events. By integrating hydrological modeling with spatial planning, the study highlights the importance of data-driven approaches in developing sustainable and resilient urban infrastructure. These results emphasize that adopting context-specific drainage designs tailored to local topography and rainfall characteristics can enhance environmental sustainability and public safety. Therefore, the outcomes of this research not only provide practical insights for engineers and urban planners but also offer a foundation for policy formulation and future infrastructure development strategies aimed at climate-resilient urban planning.

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AUTHORS CONTIBUTIONS STATEMENT

All authors contributed significantly to the development of this research. Imanuel Kemenangenta Perangin Angin conceptualized the study, led the hydrological analysis using the Gumbel distribution and the Rational Method, and conducted the runoff coefficient assessment. Ragil Ridho Saputro was responsible for data collection, including rainfall and land use data, and supported the delineation of drainage sub-catchment areas. Jeremia Dinata Perangin Angin carried out the design discharge calculations and assisted in optimizing the drainage dimensions based on the hydrological analysis results. All authors collaboratively validated the analytical outputs, interpreted the findings, and were involved in writing, reviewing, and editing the final manuscript. All authors have read and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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