

Optimization of Infiltration-Based Water Recharge System for Urban Stormwater and Flood Mitigation

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ABSTRACT

Urban waterlogging caused by high-intensity rainfall represents a critical hydrological challenge in rapidly developing cities, including along Dayanu Ikhsanuddin Street, Lipu Sub-district, Baubau City, Indonesia. The problem is exacerbated by inadequate drainage infrastructure, which significantly disrupts daily community activities and urban mobility. This study aims to: (1) quantify the volume of surface water ponding based on maximum daily rainfall data, (2) assess the soil infiltration capacity of the study area, and (3) design an optimized infiltration well system as a sustainable stormwater management solution. Maximum daily rainfall data spanning 10 years (2014–2024) were obtained from the Betoambari Meteorological Station and analyzed using four probability distribution methods: Normal, Log Normal, Gumbel, and Log Pearson III. In-situ soil infiltration rates were measured using the Horton method with a double ring infiltrometer. The infiltration well design was developed by integrating hydrological analysis results with site-specific soil infiltration parameters. The expected outcomes include an optimally designed infiltration well system tailored to local soil conditions, capable of significantly reducing surface waterlogging while simultaneously supporting groundwater recharge and conservation. Practically, this research provides a technical basis for sustainable drainage planning in Baubau City; theoretically, it contributes to the advancement of applied hydrology, particularly in the implementation of infiltration-based technologies in tropical urban environments.

Keywords: Urban Waterlogging, Infiltration Well, Soil Infiltration Capacity, Rainfall Frequency Analysis, Engineering Hydrology.

1. INTRODUCTION

Urban flooding has become one of the most common environmental problems in rapidly developing cities. Increasing impervious surfaces reduce natural infiltration capacity, resulting in excessive surface runoff during rainfall events (Liu et al., 2022). In areas where drainage systems are absent or insufficient, water accumulates on road surfaces, causing transportation disruption, pavement deterioration, and safety hazards (Suripin, 2004).

Jalan Dayanu Ikhsanuddin in Lipu Village, Baubau City, is one of the locations frequently affected by waterlogging due to poor stormwater management. The road lacks a functioning drainage network, and runoff from surrounding areas converges onto the road surface during moderate to heavy rainfall events. Instead of relying solely on conventional drainage systems, infiltration wells represent an environmentally friendly approach by allowing rainwater to infiltrate into the ground, thereby reducing runoff while simultaneously recharging groundwater (Hendrarto, 2019; Prasetyo & Lestari, 2020).

Several previous studies have demonstrated that infiltration wells significantly reduce flood volumes in urban areas. Haryanto (2018) reported that properly designed infiltration wells reduced surface inundation by up to 40% in urban residential areas. Pamungkas et al.

(2025) demonstrated that infiltration wells in Denpasar City were capable of reducing flood volume by as much as 59.58% when designed in accordance with local watershed and soil characteristics (Pamungkas et al., 2025). Similarly, Pamungkas et al. (2023) showed that GIS-based spatial planning of infiltration wells effectively optimized flood risk reduction in Bali's provincial government center. However, most investigations have focused on regions already equipped with drainage infrastructure (Pamungkas et al., 2023). This study specifically investigates the design of infiltration wells in an area without an existing drainage system, which represents a more challenging and underexplored condition.

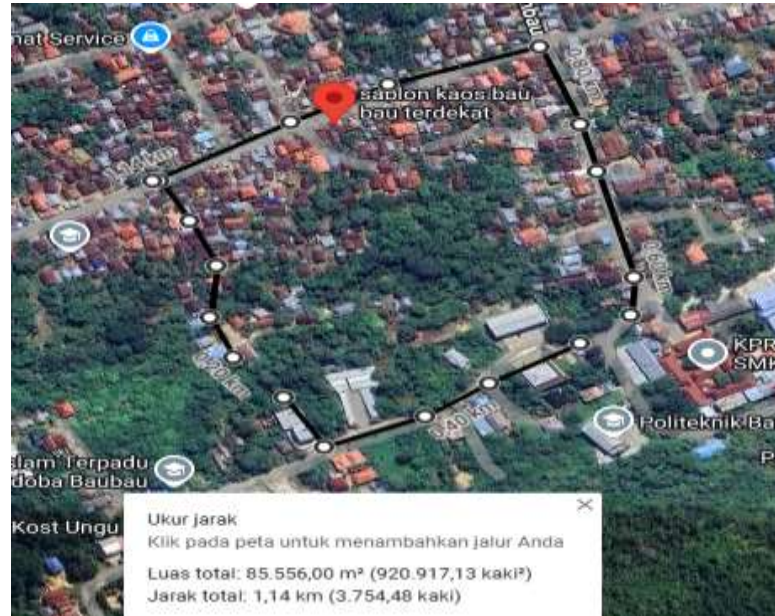
The soil infiltration rate is a critical parameter in determining the feasibility and design of infiltration wells (Ren et al., 2020). Double-ring infiltrometer testing provides a reliable field measurement of stable infiltration capacity, which directly governs the drainage performance of the well system (Diamond & Shanley, 2003). Hydrological frequency analysis using the Log Pearson Type III distribution has been widely applied in Indonesian hydrology to estimate design rainfall for various return periods (Phien & Ajirajah, 1984; Sri Harto, 1993).

Therefore, this research aims to: (1) estimate the inundation volume at the study site; (2) evaluate soil infiltration capacity using field measurements; and (3) design an appropriate infiltration well system to reduce waterlogging at Jalan Dayanu Ikhsanuddin, Baubau City.

2. METHODS

2.1. Study Area

The study was conducted at Jalan Dayanu Ikhsanuddin, Lipu Village, Baubau City, Southeast Sulawesi, Indonesia. The road segment is located in a low-lying area with no existing stormwater drainage infrastructure. Waterlogging events regularly occur following rainfall of moderate to high intensity, with inundation persisting for several hours due to limited natural drainage pathways.



2.2. Rainfall Data Collection and Frequency Analysis

Daily maximum rainfall data were collected for a ten-year period from 2015 to 2024 from the nearest meteorological station. Three statistical distributions were evaluated for goodness-of-fit: Normal, Log Normal, and Log Pearson Type III. Suitability was assessed using the Chi-Square and Kolmogorov–Smirnov tests. The Log Pearson Type III distribution was selected as the best-fitting model based on the lowest deviation values in both tests (Suripin, 2018; Triatmodjo, 2008).

Design rainfall for the 10-year return period was estimated using the selected distribution. Rainfall intensity was subsequently calculated using the Mononobe equation (Equation 1):

$$I = \frac{R_{24}}{24} \left(\frac{24}{t_c} \right)^{2/3}$$

where I is rainfall intensity (mm/h), R_{24} is the 24-hour design rainfall (mm), and t_c is the time of concentration (hours), calculated using the Kirpich (1940) formula.

Peak surface runoff discharge was estimated using the Rational Method (Equation 2):

$$Q = 0.278 \cdot C \cdot I \cdot A$$

where Q is peak discharge (m³/s), C is the runoff coefficient, I is rainfall intensity (mm/h), and A is the catchment area (km²).

2.3. Field Measurement of Inundation Volume

The geometry of the inundation area was measured directly in the field using a measuring tape. Length, width, and average water depth were recorded along the affected road segment. Total inundation volume was estimated using the simple prismatic formula (Suripin, 2004):

$$V = A \times h \dots (4)$$

where V is inundation volume (m^3), A is the inundation surface area (m^2), and h is the average inundation depth (m).

2.4. Soil Infiltration Measurement

Soil infiltration capacity was measured using a double-ring infiltrometer following the field procedure described by Diamond & Shanley (2003). The inner ring had a diameter of 30 cm and the outer ring 60 cm; both were driven approximately 10–15 cm into the soil. Water was added to maintain a constant head of approximately 10 cm in the inner ring. Cumulative infiltration was recorded at 5-minute intervals from the start of the test until a stable (constant) infiltration rate was reached. The stable infiltration rate (f_c), calculated as the average of the final readings where the rate had stabilized, was adopted as the design infiltration rate for well calculations. The Horton infiltration model was used to describe the temporal decay of infiltration rate (Horton, 1940, as cited in Suripin, 2004):

$$f = f_c + (f_0 - f_c) \cdot e^{-kt} \dots (5)$$

where f is the infiltration rate at time t (cm/h), f_0 is the initial infiltration rate (cm/h), f_c is the final stable rate (cm/h), and k is the decay constant (1/h).

2.5. Infiltration Well Design

The Infiltration wells were designed as open-bottom cylindrical structures. The storage volume of a single well was calculated as:

$$V_{well} = \pi \cdot r^2 \cdot H \dots (6)$$

where r is the well radius (m) and H is the well depth (m). The number of wells required was determined by dividing the total inundation volume by the storage volume per well. The infiltration discharge capacity per well per hour was estimated as:

$$Q_{inf} = A_{base} \times f_c \dots (7)$$

where $A_{base} = \pi \cdot r^2$ is the base area of the well (m^2) and f_c is the stable infiltration rate (m/h). Total infiltration time was then estimated by dividing the total inundation volume by the aggregate infiltration capacity of all wells (Kementerian Pekerjaan Umum dan Perumahan Rakyat Republik Indonesia, 2014; Suryadi & Kurniawan, 2021).

3. RESULTS AND DISCUSSIONS

3.1. Rainfall Frequency Analysis

Statistical parameter analysis of the ten-year annual maximum rainfall series yielded the following values: mean ($\bar{X}$) = 101.70 mm, standard deviation (S) = 21.26 mm, coefficient of variation (CV) = 0.21, skewness coefficient (CS) = -0.85, and kurtosis coefficient (CK) = 3.82. Comparison against the theoretical requirements for each distribution — as prescribed by Suripin (2004) and Triatmodjo (2008) — showed that the Normal, Log Normal, and Gumbel distributions did not satisfy their respective parametric conditions at the computed CS and CK values. The Log Pearson Type III distribution, which accepts all values not captured by the other three, was therefore selected as the most appropriate statistical model, consistent with findings from previous Indonesian urban hydrology studies (Phien & Ajirajah, 1984; Sri Harto, 1993).

Using the Log Pearson Type III distribution with logarithmic mean ($Log \bar{X}$) = 2.00 and logarithmic standard deviation (S) = 0.10, design rainfall for multiple return periods was estimated. For the 10-year return period with $KT = 1.28$, the design rainfall was $R_{24} = 133.49$ mm. Results for all return periods are presented in Table 1.

The time of concentration was calculated using the Kirpich (1940) formula with channel length $L = 285.96$ m and slope $S = 0.0280$, yielding $t_c = 6.015$ minutes (0.10025 hours). The 10-year design rainfall intensity of 214.45 mm/h was adopted for all subsequent runoff and well design calculations. This value is notably high, reflecting the intense convective rainfall characteristic of the equatorial maritime climate of Southeast Sulawesi, and underscores the need for effective stormwater management infrastructure at the study site.

Table 1. Field Measurement Results of Inundation Area

Period	R_{24}	t		I (mm/h)
		Min	Hours	
T_2	99,41	6,015	0,10025	159,70
T_5	120,63			193,78
T_{10}	133,49			214,45
T_{20}	145,02			232,98

T ₅₀	159,38			256,04
T ₁₀₀	170,00			273,10

3.2. Inundation Volume

Field survey measurements of the waterlogged area along Jalan Dayanu Ikhsanuddin are presented in Table 2. The total inundation volume was calculated using Equation 4.

Table 2. Field Measurement Results of Inundation Area

Parameter	Value
Inundation length	46.5 m
Road width	10.5 m
Average inundation depth	0.302 m
Total inundation volume	147.45 m ³

The calculated inundation volume of 147.45 m³ confirms that the existing site has insufficient natural drainage capacity to manage stormwater during design rainfall events. The absence of a drainage network means that all surface runoff accumulates on the road surface, creating a hazardous condition for road users and accelerating pavement deterioration (Suripin, 2004; Haryanto, 2018).

3.3. Soil Infiltration Capacity

Double-ring infiltrometer testing was conducted at the study site from 19:20 to 20:25 WITA, with measurements recorded at 5-minute intervals. Results are presented in Table 3.

Table 3. Infiltration Rate Measurement Using Double-Ring Infiltrimeter

T ke	Time	Elapsed Time (min)	Δt (min)	Hc (cm)	Δhc (cm)	F (cm/hour)
t0	19:20	0	5	20		
t1	19:25	5	5	17,7	2,3	0,46
t2	19:30	10	5	15,9	1,8	0,36
t3	19:35	15	5	14,3	1,6	0,32
t4	19:40	20	5	12,6	1,7	0,34

t5	19:45	25	5	11,2	1,4	0,28
t6	19:50	30	5	9,7	1,5	0,30
t7	19:55	35	5	8,3	1,4	0,28
t8	20:00	40	5	6,6	1,7	0,34
t9	20:05	45	5	5,2	1,4	0,28
t10	20:10	50	5	3,6	1,6	0,32
t11	20:15	55	5	2,5	1,1	0,22
t12	20:20	60	5	1,7	0,8	0,16
t13	20:25	65	5	0	1,7	0,34

The highest infiltration rate was recorded at t_1 (0.46 cm/min), reflecting dry initial soil conditions with high pore availability. The rate decreased progressively as soil pores became saturated, consistent with the Horton infiltration model (Suripin, 2004). Stable infiltration was reached between t_5 and t_{13} , with rates ranging from 0.28 to 0.34 cm/min. The average stable infiltration rate was:

$$f_c = \frac{0.28 + 0.30 + 0.28 + 0.34 + 0.28 + 0.32}{6} = 0.30 \text{ cm/min} = 18 \text{ cm/h}$$

A value of 18 cm/h falls within the "moderate-to-high" permeability range for soil infiltration capacity, consistent with the classification provided by Diamond & Shanley (2003) and Chen et al. (2020). This indicates that the subsurface soil at Jalan Dayanu Ikhsanuddin is suitable for infiltration well application and capable of receiving and transmitting infiltrated water without excessive ponding within the well structure.

3.4. Infiltration Well Design and Performance

Based on the inundation volume of 147.45 m³ and the stable soil infiltration rate of 18 cm/h, twenty cylindrical infiltration wells were designed. Design parameters and estimated performance are summarized in Table 4.

Table 4. Proposed Design Parameters of the Infiltration Wells

Parameter	Value
Well type	Cylindrical, open bottom
Diameter	2.0 m
Depth	2.5 m
Volume per well	7.85 m ³

Number of wells	20
Total storage capacity	157.0 m ³
Infiltration capacity per well	0.56 m ³ /h
Total infiltration capacity	11.2 m ³ /h
Estimated infiltration time	±13 hours

The volume of a single well was calculated as $V = \pi \times r^2 \times H = 3.14 \times 1^2 \times 2.5 = 7.85 \text{ m}^3$. The number of wells required was determined as $147.45 / 7.85 = 18.79$, rounded up to **20 units** to provide a safety margin against sediment accumulation and long-term reduction in infiltration efficiency. The total storage capacity of 157.0 m³ exceeds the estimated inundation volume of 147.45 m³, confirming that the system is volumetrically adequate to contain all surface runoff generated during the 10-year design rainfall event.

The infiltration discharge per well was computed as $Q = A_{\text{base}} \times f_c = 3.14 \text{ m}^2 \times 0.18 \text{ m/h} = 0.56 \text{ m}^3/\text{h}$, yielding a total system infiltration capacity of $20 \times 0.56 = 11.2 \text{ m}^3/\text{h}$. The estimated time to fully infiltrate 147.45 m³ is therefore $147.45 / 11.2 \approx 13$ hours. While this duration extends beyond the rainfall event itself, it represents a practical timeframe for road surface clearance in the absence of any drainage infrastructure (Prasetyo & Lestari, 2020; Pamungkas et al., 2025).

The twenty wells are proposed to be distributed along both sides of the 46.5 m affected road segment at regular intervals. This decentralized layout ensures that runoff is intercepted before it accumulates to critical depths, a strategy demonstrated by Zhang et al. (2022) to be more effective than centralized storage for managing localized urban waterlogging. The design complies with the technical requirements of Peraturan Menteri PUPR Nomor 11/PRT/M/2014 regarding minimum setback distances from buildings (3.0 m), property boundaries (1.5 m), and drinking water pipes (3.0 m) (Kementerian Pekerjaan Umum dan Perumahan Rakyat Republik Indonesia, 2014).

Beyond flood mitigation, the infiltration wells provide the secondary benefit of groundwater recharge — a critical function in coastal urban areas such as Baubau City, where over-extraction of groundwater and saltwater intrusion are emerging concerns (Hendrarto, 2019). This dual function aligns with the principles of low-impact development and sustainable urban water management increasingly advocated in the global literature (Yekti et al., 2021; Zhu et al., 2024).

4. CONCLUSION

This study demonstrates that infiltration wells are an effective and sustainable solution for mitigating urban waterlogging at Jalan Dayanu Ikhsanuddin, Baubau City, a road corridor with no existing conventional drainage infrastructure.

The Log Pearson Type III distribution, selected based on statistical parameter testing of ten years of daily maximum rainfall data, yielded a 10-year design rainfall intensity of 214.45

mm/h. Field measurement recorded an inundation volume of 147.45 m³ and a stable soil infiltration rate of 18 cm/h, confirming moderate-to-high soil permeability suitable for infiltration well implementation. Based on these parameters, a system of twenty cylindrical infiltration wells — each 2.0 m in diameter and 2.5 m deep — was designed, providing a total storage capacity of 157.0 m³ and an estimated runoff infiltration time of approximately 13 hours.

This study has several limitations that should be acknowledged. First, the infiltration test was conducted at a single location and time point; spatial variability in soil properties across the 46.5 m road segment was not fully accounted for. Second, the long-term reduction in infiltration capacity due to sediment clogging was not modeled. Third, the inundation volume was estimated using a simple prismatic geometry, which may not capture complex topographic variations. These factors may influence the actual performance of the well system over time. Future research should incorporate multi-point infiltration testing, numerical hydrological modeling (e.g., SWMM), and long-term field monitoring to evaluate maintenance requirements and the sustainability of infiltration capacity. An economic feasibility analysis comparing infiltration wells with conventional drainage is also recommended to support evidence-based decision-making for urban infrastructure planning in Baubau City and comparable contexts.

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