



Hydrological Assessment of Urban Flood Potential for Micro-Hydropower Development in Malang City Using the Rational Method

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Abstract

Flooding is a recurring hydrometeorological hazard in Malang City, Indonesia, driven by high-intensity tropical rainfall and rapid urbanization that reduces infiltration and increases surface runoff. While prior studies have focused mainly on flood mitigation, the use of urban floodwater as a renewable energy resource remains underexplored. This study evaluates the preliminary potential of converting urban flood discharge into micro-hydropower (MHP) energy within urban drainage systems. Design rainfall was estimated using the Log-Pearson Type III distribution based on a 10-year dataset, and peak flood discharge was calculated using the Rational Method. Drainage channel hydraulics were analysed using Manning's equation, and energy conversion was assessed with standard hydropower formulations under low-head conditions (2–4 m). Design discharges of 2.215 to 2.758 m³/s can generate an estimated power output of 36.89 to 91.90 kW, showing that urban flood runoff has measurable energy potential within the micro-hydropower range (<100 kW). However, this is a preliminary feasibility assessment focusing on peak discharge without fully capturing temporal flow variability. The Rational Method assumes uniform rainfall intensity and cannot represent hydrograph dynamics, which may affect estimation accuracy, and validation is constrained by limited observed discharge data. Despite these limitations, the findings show that flood-prone urban drainage corridors can serve as dual-purpose infrastructure for flood mitigation and decentralized energy generation, supporting sustainable, resilient urban systems aligned with renewable energy and climate adaptation goals.

Keywords: Malang City; Micro-Hydropower Potential; Rational Method; Renewable Energy; Urban Drainage Systems

1. Introduction

Flood disasters remain a significant environmental challenge currently faced by Indonesia. These disasters are natural phenomena that frequently occur across nearly all regions of the country. According to the Aqueduct Global Flood Analyzer, Indonesia ranks as the sixth country with the largest population exposed to flood risks globally, affecting approximately 640,000 people annually. Data from the National Disaster Management Agency (BNPB) further indicate that flood events occur around 464 times each year in Indonesia. The main contributing factors to flooding include insufficient vegetation cover, extreme weather variability, and the topographic characteristics of river basins or watersheds (Ariyani et al., 2023). One notable example of recurrent urban flooding occurs in Malang City, where rapid urbanization and inadequate drainage infrastructure exacerbate flood impacts. Similar urban flood patterns have been reported in other Indonesian cities, underscoring the need for integrated watershed management and climate-adaptive urban planning (Rahmasary et al., 2020; Yamamoto et al., 2021; Yulianto et al., 2023; Dwirahmadi et al., 2019; Dwirahmadi et al., 2023).

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Malang City is currently recognized as one of the urban areas in Indonesia that experiences recurrent flooding events almost every year. Geomorphologically, Malang is located in a highland region at an elevation of approximately 380–667 meters above sea level. Under natural hydrological conditions, such a topography should provide favorable drainage capacity, reducing the likelihood of flood occurrences during the rainy season. However, despite its elevated terrain, Malang frequently suffers from inundation events, particularly during periods of intense rainfall. Meteorological records classify the city's precipitation pattern as belonging to the category of very heavy rainfall (100–150 mm/day) to extreme rainfall (>150 mm/day) (Krisnayanti et al., 2022), with occasional occurrences of moderate (20–50 mm/day) to heavy (50–100 mm/day) rainfall during peak monsoon months. These hydrometeorological conditions often cause localized waterlogging in road networks and residential areas.

Further hydrological investigations have identified a significant reduction in the city's water absorption capacity as the primary driver of flooding. This phenomenon is strongly associated with rapid urban expansion and infrastructure development within critical water catchment zones, leading to the loss of permeable surfaces and disruption of natural drainage pathways. For instance, the degradation of the City Forest area near the Tanjung Agricultural Extension Academy on Jalan Ir. Rais, the conversion of open green space near the Pulosari Sports Center into a commercial retail hub, and the transformation of the area behind the Brawijaya Museum into residential housing exemplify the urban encroachment that compromises the city's infiltration zones. Such land-use changes reduce soil infiltration rates and increase surface runoff, thus amplifying flood vulnerability even in upland settings. These findings align with broader research on the hydrological impacts of urbanization in tropical cities, where impervious surface expansion, inadequate drainage infrastructure, and weak enforcement of spatial planning regulations have been identified as dominant factors contributing to flood hazards (Abass et al., 2020; Alshaikh et al., 2023; Ebrahimnia et al., 2025). Integrating sustainable urban drainage systems (SUDS), nature-based solutions, and strict land-use control within watershed management policies is therefore crucial to improving the city's resilience against recurrent flood events.

Flood management in Malang City is currently undertaken by the local government through the Department of Public Works, Spatial Planning, Housing, and Settlement Areas as a key strategy to mitigate recurrent inundation. These initiatives are implemented annually as part of routine preventive measures against urban waterlogging. In the short term, flood control activities primarily focus on dredging solid waste and sediment from drainage channels to restore their hydraulic capacity in flood-prone zones. Accumulation of waste and sediment has been identified as a major issue during the rainy season (Abdul Maulud et al., 2021), as floating debris obstructs drainage inlets and reduces flow efficiency. When channel sediments are not periodically removed, the effective cross-sectional area of the drainage system decreases, resulting in a reduced discharge capacity and subsequent surface flooding during peak rainfall events. Persistent sedimentation and waste blockages underscore the structural and behavioural challenges of urban drainage maintenance in Indonesian cities, including inadequate waste management systems, lack of public awareness, and insufficient integration between spatial planning and stormwater management (Sari et al., 2020; Hadini et al., 2023; Irawan et al., 2025). Therefore, while short-term interventions such as channel dredging remain essential, they should be complemented by long-term, systemic solutions. One of the strategic approaches is the development of a comprehensive Urban Drainage Master Plan, which integrates hydrological modelling, green infrastructure, and solid waste management policies (Kuiper, 2013). Such master plans not only enhance the technical efficiency of drainage networks but also support sustainable urban resilience through adaptive, ecosystem-based flood mitigation frameworks.

Several notable research cases of successful flood control and utilization in various countries demonstrate diverse approaches. In Japan, integrated urban flood risk management incorporates underground stormwater facilities, detention ponds, and enhanced sewerage systems, effectively reducing urban surface water floods and river flood risks while promoting urban redevelopment and resilience (World Bank, 2019). China's Nansi Lake basin exemplifies basin-wide floodwater utilization, balancing flood risks and water scarcity by strategically managing reservoirs, detention areas, and river sluices to maximize floodwater retention and reuse, alleviating water shortages with a utilization rate of 65% (Wang et al., 2024). The Netherlands has implemented the Delta Programme, a large-scale nature-based solution emphasizing "room for rivers" by creating space for intentional flooding to reduce flood risk sustainably (Edelenbos et al., 2017). These examples highlight the value of integrated infrastructure, ecological design, and multifunctional water management for flood control and utilization.

Despite these advancements, there remains a critical research gap. Existing studies on urban flood management have predominantly focused on risk reduction, drainage optimization, and climate adaptation strategies, with limited attention to the productive utilization of urban floodwaters as a renewable energy resource, particularly in rapidly urbanizing tropical cities. Moreover, while micro-hydropower systems have been extensively studied in riverine and rural contexts, their application in ephemeral, high-intensity urban flood flows, characterized by short duration, fluctuating discharge, and constrained infrastructure, remains underexplored. There is also a lack of integrated frameworks that combine urban hydrodynamic modelling, flood volume estimation, and real-time energy conversion potential within existing drainage systems. In the context of Malang City, no prior study has systematically quantified the relationship between flood discharge characteristics and their feasibility for micro-hydropower generation embedded within urban flood control infrastructure.

Micro-hydroelectric power represents a promising renewable energy technology, particularly in countries with abundant water resources such as Indonesia. In 2015, the national hydropower potential exceeded 75,000 MW, with mini- and micro-hydropower in Table 1, contributing more than 19,000 MW (Widyaningsih, 2017). Micro-hydropower systems are known for their relatively high efficiency (60–90%) compared to other renewable energy technologies such as solar (10–12%) (Laghari et al., 2013), as well as shorter payback periods ranging from 1 to 6 years (Kusakana et al., 2008). However, despite this significant potential, the implementation of micro-hydropower in Indonesia remains limited (Erinofardi et al., 2017), particularly in unconventional settings such as urban drainage systems.

Table 1. Scale of Hydroelectric Power

Type	Power Capacity (kW)
Large-hydro	> 100,000
Medium-hydro	15,000 – 100,000
Small-hydro	1,000 – 15,000
Mini-hydro	100 – 1,000
Micro-hydro	5 – 100
Pico-hydro	< 5

Source: Singh, 2009

This study aims to address the identified research gap by proposing an integrated approach that links urban flood management with renewable energy generation. Specifically, this research investigates the hydrological characteristics of urban flood events in Malang City, including discharge, flow velocity, and flood volume, and evaluates their potential for micro-hydropower generation within urban drainage networks. The main contributions of this study are threefold. First, it provides a novel conceptual framework for transforming urban floodwater from a hazard into a productive resource through micro-hydropower integration. Second, it delivers an empirical assessment of flood energy potential based on site-specific hydrological data, contributing to the limited body of knowledge on urban flood-based energy systems. Third, it proposes a design-oriented approach for integrating micro-hydropower technology into urban drainage infrastructure, supporting the development of sustainable and resilient cities aligned with renewable energy and climate adaptation goals. By bridging flood risk management and renewable energy utilization, this study offers a dual-benefit solution that not only mitigates urban flooding but also contributes to sustainable energy generation, thereby supporting the transition toward resilient and low-carbon urban systems.

2. Methods

2.1 Study Area and Research Framework

This study focuses on one of the flood-prone areas in Malang City, specifically along Raden Panji Suroso Road. The road has an effective carriageway width of approximately 12 meters and extends for about 1,543 meters. Adjacent to this road lies the Kajar River, which serves as one of the tributaries of the Bango Watershed (DAS Bango). The river extends approximately 11,318 meters in length with an average width of 15 meters. Based on hydrological measurements, the maximum discharge of the Kajar River reaches 0.672 m³/s, while the minimum discharge is approximately 0.224 m³/s.

The research framework integrates hydrological analysis, hydraulic modelling, and energy conversion assessment. Flood discharge generated from rainfall events is first estimated using a rainfall–runoff approach. The resulting discharge is then analysed within the drainage system to determine flow characteristics, which are subsequently converted into potential electrical energy using micro-hydropower principles. Finally, spatial interpretation is incorporated to evaluate the suitability of the study area for energy extraction within the urban drainage network.

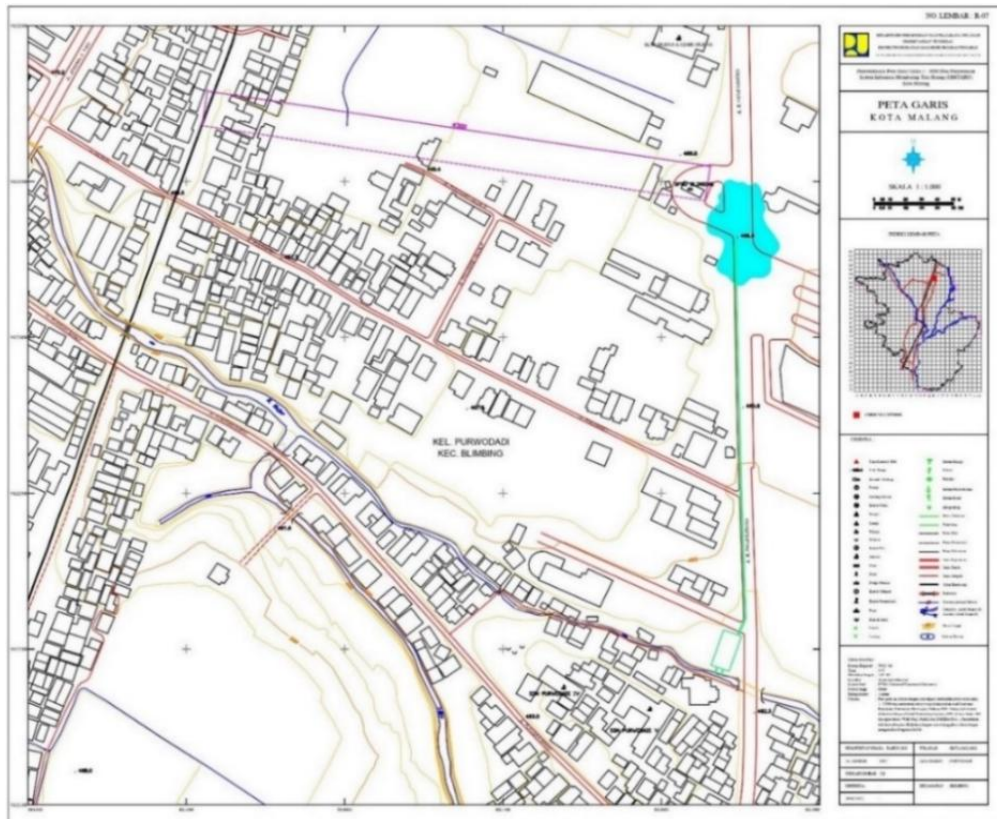


Figure 1. Location and Initial Research Design
(Source: Author's analysis, 2025)

Figure 1 illustrates the study area and the overall research framework. The green line represents the proposed flood control and water utilization infrastructure, whereas the light blue area indicates the estimated inundation zone, as identified in the official flood hazard map released by the Malang City Regional Disaster Management Agency (BPBD). The research employs detailed topographical data to model drainage flow beneath the roadway, which serves as the primary conduit for stormwater runoff. The discharge volume from the drainage network is subsequently analysed to determine the potential electrical power output based on the planned micro-hydropower turbine configurations. Following energy extraction, the outflow is directed back into the Kajar River to maintain hydrological continuity and minimize ecological disturbance.

2.2 Data Collection and Processing

This study utilizes three primary datasets: rainfall data, topographic data, and spatial land-use information. Daily rainfall data were obtained from three climatological stations (Karangploso, Sukun, and Ciliwung) over a 10-year period (2009–2018). These datasets were used to derive regional rainfall characteristics and design rainfall values. Topographic data were acquired from the Department of Housing and Regional Infrastructure, with a contour interval of 1 m, enabling detailed representation of micro-topographic variations influencing flow direction and hydraulic head. Spatial data, including land use and drainage configuration, were obtained from satellite imagery (Google Earth) and verified through field observations. All datasets were processed to ensure spatial and temporal consistency. Rainfall data were aggregated to obtain representative regional rainfall, while topographic data were used to delineate the catchment area and estimate flow paths.

2.3 Design Rainfall Analysis

The design rainfall analysis aims to determine the recurrence of rainfall events of specific magnitudes within a defined return period. In this study, the Log Pearson Type III method was employed to estimate design rainfall for return periods of two and five years. Following Kementerian Pekerjaan Umum (2012), the selection of the return period was adjusted to city typology and site-specific hydrological and infrastructure conditions, as summarized in Table 2. Malang City is classified as a Big City. The Log Pearson Type III distribution was further analysed using the skewness coefficient (C_s) and kurtosis coefficient (C_k), as shown in Equation (2).

$$S = \sqrt{\frac{\sum (xi - \bar{x})^2}{n-1}} \quad (1)$$

$$\text{Log } x_{TR} = \text{Log } \bar{x} + G.S \quad (2)$$

where x_{TR} —design rainfall (mm/d), x —rainfall data (mm/d), $\bar{x}$ —average rainfall data (mm/d), G —constant value based on return period, and S —standard deviation.

Table 2. Return Period based on City Typology

City Typology	Water Catchment Area (Ha)			
	<10	10 – 100	101 – 500	>500
Metropolis	2 years	2 – 5 years	5 – 10 years	10 – 25 years
Big city	2 years	2 – 5 years	2 – 5 years	5 – 20 years
Medium city	2 years	2 – 5 years	2 – 5 years	5 – 10 years
Small town	2 years	2 years	2 years	2 – 5 years

Source: Kementerian Pekerjaan Umum, 2012

2.4 Flood Discharge Estimation Using the Rational Method

Flood discharge estimation was carried out using the rational method, which requires determining the time of concentration, rainfall intensity, and runoff coefficient. The time of concentration was calculated using Equation (3) (Suripin, 2003), rainfall intensity using Equation (6) (Loebis, 1992), and the runoff coefficient values were adopted from Table 3 (Adiwijaya, 2016). Subsequently, the design discharge was obtained using Equation (7) (Suripin, 2003).

$$t_c = t_0 + t_d \quad (3)$$

$$t_0 = \left[\frac{2}{3} \cdot 3.28 \cdot L_0 \cdot \frac{n}{\sqrt{s}} \right]^{0.167} \quad (4)$$

$$t_d = \frac{L_d}{60V} \quad (5)$$

$$I = \frac{R24}{24} \left(\frac{24}{t_c} \right)^{\frac{2}{3}} \quad (6)$$

$$Q = \frac{1}{360} C \cdot I \cdot A \quad (7)$$

where t_c —concentration time (minutes), t_0 —longest time required for rainwater to flow over the ground surface of the nearest channel (minutes), t_d —time required for rainwater to flow into the channel (minutes), L_0 —path length flow over the land surface (m), n —Manning's roughness number, s —slope of the runoff field, L_d —length of channel/river (m), V —ideal flow speed in the channel (m/s), $R24$ —design rainfall (mm/d), Q —design flood discharge (m^3/s), C —runoff coefficient, I —rainfall intensity (mm/h), A —drainage area (ha).

Table 3. Determination of Runoff Coefficient

Ground Surface Conditions	Runoff Coefficient (C)
Concrete roads and asphalt roads	0.70-0.95
Gravel roads and dirt roads	0.40-0.70
Roadside	
- Fine grained soil	0.40-0.65
- Coarse grained soil	0.10-0.20
- Hard massive rocks	0.70-0.85
- Soft massive rocks	0.60-0.75
Urban area	0.70-0.95
Suburban area	0.60-0.70
Industrial area	0.60-0.90
Dense settlement	0.40-0.60
The settlement is not dense	0.40-0.60
Parks and gardens	0.20-0.40
Rice fields	0.45-0.60
Hills	0.70-0.80
Mountains	0.75-0.90

Source: Adiwijaya, 2016

To improve parameter transparency, each variable is defined and justified as follows:

1. Runoff Coefficient (C)

A value of 0.7 was adopted to represent predominantly impervious urban surfaces, including asphalt roads and dense built-up areas. This selection is consistent with standard classifications for urban environments (Table 3). The chosen value reflects moderate-to-high runoff conditions typical of rapidly urbanizing areas.

2. Catchment Area (A)

The drainage area was determined as 120,000 m^2 (12 ha) based on topographic delineation. This parameter represents the contributing area to the drainage channel under study.

3. Rainfall Intensity (I)

Rainfall intensity was derived from design rainfall using the Mononobe equation (Loebis, 1992), which accounts for the time of concentration. This approach enables conversion of daily rainfall into short-duration intensity relevant for urban flooding.

4. Time of Concentration (t_c)

The time of concentration was calculated as the sum of overland flow time and channel flow time. Parameters such as surface roughness, slope, and flow path length were explicitly considered to reflect local physical conditions.

This parameterization ensures that the discharge estimation is physically grounded and contextually relevant to the study area.

2.5 Hydraulic Analysis of Drainage Channel

Hydraulic analysis was conducted to determine the optimal drainage channel dimensions and assess the water surface elevation relative to the designed ground or road level. The average flow velocity and cross-sectional area of the channel were calculated using Manning's equation, which offers a simple yet highly reliable approach for uniform flow estimation (Equation 8). The flow rate was determined using Equation (9), considering the influence of boundary roughness. Maximum permissible velocities were 0.7 m/s for earthen channels, 2 m/s for rock channels, and 3 m/s for concrete channels, while minimum velocities were 0.2 m/s and 0.6 m/s, respectively (DPU, 1986).

$$V = \frac{1}{n} \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \quad (8)$$

$$Q = V \cdot A \quad (9)$$

$$Fr = \frac{V}{\sqrt{g \cdot h}}, \quad Fr < 1 \quad (10)$$

where V—average speed in the channel (m/s), n—Manning roughness coefficient, R—hydraulic radius (m), S—slope of the channel bottom, Q—discharge in the channel (m³/s), V—flow velocity (m/s), A—channel cross-sectional area (m²), h—flow depth (m), g—gravitational acceleration (m/s²).

The parameter justification: (i) Manning's roughness coefficient (n = 0.017), this value corresponds to precast concrete channels, based on standard hydraulic design references (DPU, 1986); (ii) The channel geometry and slope were derived from field observations and topographic data, ensuring consistency with actual site conditions. Flow regime classification was determined using the Froude number to identify whether the flow is subcritical or supercritical, which is essential for assessing turbine suitability.

2.6 Energy Conversion Analysis

Furthermore, the selection of turbine type for hydropower generation was based on the available hydraulic head and discharge rate. This classification influences the potential suitability of an area for micro-hydropower development. Table 4 presents turbine type classifications corresponding to head ranges, while Figure 2 illustrates the general scheme of energy conversion in hydroelectric systems (YoosefDoost & Lubitz, 2020).

$$P = Q \cdot g \cdot h \cdot \eta \quad (11)$$

where P—power (W), Q—designed flood discharge (m³/s), g—gravity force (m/s²), h—effective fall height (m), η—hydroelectric power efficiency.

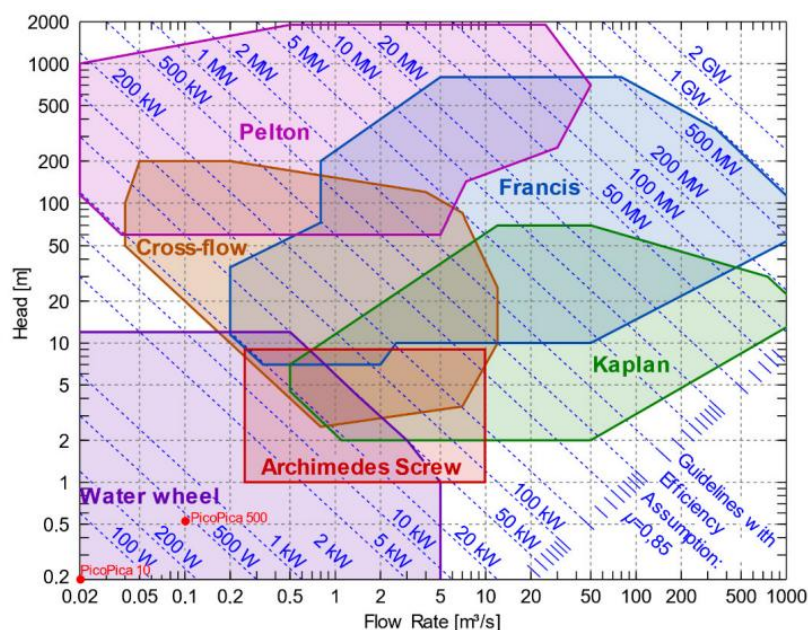


Figure 2. Head and Flow Rate for Electric Power Generated based on Turbine Type (Source: YoosefDoost & Lubitz, 2020)

Table 4. Classification of Water Turbine Types

Type	Turbine	Head (m)	References
Impulse	Pelton	50 – 1,000	Williamson et al., 2014
	Turgo	50 – 250	Subramanya, 2013
Reaction	Francis	40 – 600	Subramanya, 2013
	Kaplan	< 50	Kothandaraman, 2007
Quasi-static Pressure	Water wheels	< 10	Quaranta & Revelli, 2018
	Archimedes screw	< 10	Lashofer et al., 2012

Source: Compiled from the references listed in the table

The parameter assumptions: (i) hydraulic head ($H = 2\text{--}4\text{ m}$), this range was determined based on local elevation differences and channel slope conditions; (ii) system efficiency ($\eta = 0.85$), an upper-end value or low-head turbines such as Archimedes screw and water wheels, sensitivity range of $\eta = 0.6\text{--}0.8$ is reported in the Electric Power Potential section. This approach ensures a physically consistent conversion from hydrological output to electrical energy potential.

2.7 Comparison with Observed Flows

To evaluate the reliability of the estimated discharge, model results were compared with observed discharge data from the Kajar River. The observed discharge ranges from 0.224 to $0.672\text{ m}^3/\text{s}$, while the modeled discharge is significantly higher ($2.215\text{--}2.758\text{ m}^3/\text{s}$). This discrepancy is expected, as the modeled values represent peak runoff conditions during extreme rainfall events, whereas observed values correspond to typical river flow conditions. Therefore, the rational method provides an upper-bound estimation suitable for flood event analysis. Although direct measurements of peak flood discharge were not available, the comparison indicates that the model outputs are within a reasonable hydrological range when considering differences in temporal scale and flow conditions.

2.8 Flow Duration and Hydrograph Consideration

The rational method provides peak discharge values but does not account for the temporal variation of flow. To address this limitation, a simplified hydrograph approach is proposed for future work to estimate flow duration. A triangular hydrograph assumption, in which discharge increases linearly to peak flow and then decreases symmetrically, with the event duration approximated from the time of concentration, would allow estimation of total flow volume and energy (kWh), which is critical for evaluating the feasibility of micro-hydropower systems. In the present study, however, the assessment is limited to instantaneous power (kW), and more advanced hydrodynamic modelling is recommended for future studies to capture detailed temporal flow dynamics.

3. Results

3.1 Design Rainfall

The water catchment area of this canal is bounded by the water canal to the north, the Kajar River to the south, and the railway to the west. The area of this area is $120,000\text{ m}^2$. In Table 5, rainfall for 10 years was obtained at 110.83 mm/d and the standard deviation of log rainfall ($S \log X$) = 0.10 . The C_s and C_k values obtained from rainfall for 10 years using the Log Pearson III method are 1.22 and 4.43 .

Table 5. Rainfall Data at Climatology Stations in Malang City

Year	Karangploso Station	Ciliwung Station	Sukun Station	Regional Rainfall	Log X
2018	92	97	110	99.67	1.99
2017	93	104	132	109.67	2.04
2016	62	64	122	82.67	1.92
2015	67	98	170	111.67	2.04
2014	105	125	134	121.33	2.08
2013	77	93	101	90.33	1.95
2012	108	138	125	123.67	2.09
2011	91	113	101	101.67	2.00
2010	190	186	178	184.67	2.26
2009	68	73	108	83.00	1.91
Mean				110.83	2.03

Source: Author's analysis, 2025

Table 6 shows the highest planned rainfall in the 5-year return period of 128.16 mm/d . The lowest design rainfall occurred in the 2-year return period of 102.90 mm/d . This shows that the longer the return period is taken, the higher the design rainfall, but this is inversely proportional to the percentage probability of design rainfall occurring. This research is in line with Devianti et al., (2020) which obtained the same pattern for design rainfall in the Lawe Sempali Sub-Watershed.

Table 6. Design Rainfall based on Return Period

Return Period (year)	Design Rainfall (mm/d)	Design Rainfall Logs	Probability (%)
2	102.90	2.01	50
5	128.16	2.10	20

Source: Author's analysis, 2025

3.2 Rational Method Design Flood Discharge and Drainage Channel

The length of the river at this research location is 300 m with a runoff slope of 1 %. The Manning roughness coefficient is $n = 0.05$. The length of the flow path above the land surface is 5 m. The ideal flow speed in this river is 0.4 m/s. To indicate that a point of water can reach the catchment outlet is to know the time of rain concentration (Devianti et al., 2020). So, the rain concentration time obtained with a return period of 2 years and 5 years is 0.23 h. Then the rain concentration time is used to calculate the design rainfall intensity so that it is obtained for the 2-year and 5-year return periods of 94.91 mm/h and 118.20 mm/h. To calculate the design flood discharge using the rational method, it is known that the water catchment area is 120,000 m² with a runoff coefficient of 0.7, based on the condition of the land surface in urban areas. The characteristics of a region's water catchment area have a close relationship with runoff discharge (Salami et al., 2017) so the rational method design flood discharge for the 2-year and 5-year return periods is obtained at 2.21 m³/s and 2.75 m³/s.

Table 7. Design Flood Discharge on Raden Panji Suroso Road

Parameter	Return Period (year)	
	2	5
Concentration time, T_c (h)	0.23	0.23
Rain intensity, I (mm/h)	94.91	118.20
Flow coefficient, C	0.7	0.7
Design flood discharge, Q (m ³ /s)	2.21	2.75

Source: Author's analysis, 2025

In this study, a rectangular drainage channel was planned from precast concrete with a side length of 1.05 m. Thus, a hydraulic radius of 0.35 m is obtained, with a channel bottom slope of 0.01, and a Manning roughness coefficient (based on the type of channel and materials used) of 0.01. The analysis results to determine the average speed in the channel flowing full (depth 1.05 m) are 3.188 m/s, and the channel capacity was obtained at 3.51 m³/s. Froude number at full depth is 0.99, i.e., practically critical flow ($Fr < 1$). Because the design discharges (2.21 and 2.75 m³/s) are smaller than the capacity, the channel does not flow full; with the same Manning parameters the normal depths are 0.72 m and 0.86 m, giving velocities of 2.92 and 3.05 m/s and Froude numbers of 1.09 and 1.05, i.e., marginally supercritical flow. The velocity at the 5-year design discharge therefore slightly exceeds the 3 m/s limit for concrete channels adopted in the Methods (DPU, 1986), and energy dissipation at the turbine inlet should be considered. The Froude number is used as the standard criterion for classifying free-surface flow regimes (Peng et al., 2011) and the friction of the channel material determines how well the discharge to flow water well or not.

Table 8. Hydraulic Analysis on Raden Panji Suroso Road

Parameter	Results
Manning's Roughness, n	0.01
Hydraulic radius, R (m)	0.35
Channel bottom slope, S (m/m)	0.01
Channel cross-sectional area, A (m ²)	1.10
Velocity at full depth, V (m/s)	3.18
Channel Capacity, Q (m ³ /s)	3.51
Froude Number at full depth, Fr ($Fr < 1$)	0.99

Source: Author's analysis, 2025

3.3 Electric Power Potential

Based on the analysis of the power potential of the micro-hydroelectric power on Raden Panji Suroso Road, a head rate scenario of 2 – 4 m is planned for return periods of 5 years. The upstream water source comes from urban rainwater and the downstream part is the Kajar River. The land surface in urban areas with river levels is low, so a low-head scenario is used. This also has an impact on the use of turbine types that are suitable for low-head. According to YoosefDoost & Lubitz (2020), a low-head turbine is a quasi-static pressure turbine type. This type of turbine moves when driven by the weight of the water, causing a pressure difference on the blades.

Turbine water wheels are divided into three models, including overshot wheels, breastshot wheels, and undershot wheels. These three models can produce different water discharges. However, there is one model that is suitable based on the scenario used, namely overshot wheels. This model has a head rate of 3 – 6 m with a flow rate obtained reaching < 5 m³/s (Quaranta & Revelli, 2018). Meanwhile, the Archimedes screw turbine has a low-head of < 10 m with the ability to produce a flow rate of < 10 m³/s (Lashofer et al., 2012).

The results of the analysis of the potential power of micro-hydroelectric power during flooding on Raden Panji Suroso Road, Malang City were obtained with a head scenario of 2 m with a return period of 2 years and 5 years of 36.89 kW and 45.95 kW respectively. The potential power of a micro-hydroelectric power during flooding on Raden Panji Suroso Road, Malang City is obtained with a head scenario of 4 m with a return period of 2 years and 5 years of 73.79 kW and 91.90 kW respectively. The electric power potential for each head scenario and return period is presented in Figure 3.

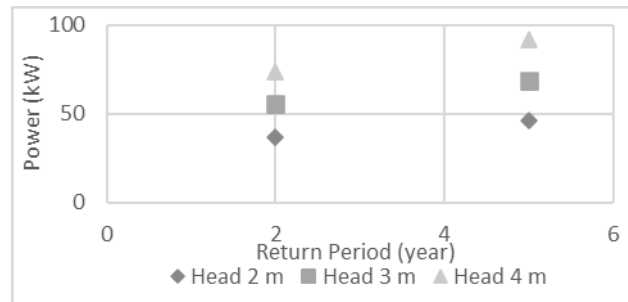


Figure 3. Electric Power Potential
(Source: Author's analysis, 2025)

3.4 Energy Conversion Analysis

To quantitatively assess the feasibility of utilizing urban flood discharge as a renewable energy source, the calculated design flood discharge was converted into potential electrical power using the fundamental hydropower equation $P = \rho g Q H \eta$. In this study, the discharge values obtained from the rational method ranged from 2.21 m³/s to 2.758 m³/s for return periods of 2 and 5 years, respectively. Considering the urban typology of Malang City, a low-head scenario (2–4 m) was adopted to reflect realistic hydraulic conditions within drainage channels. Furthermore, a system efficiency (η) of 0.85 was applied, which lies at the upper end of the performance of low-head turbines such as overshoot wheels and Archimedes screw turbines. Based on these parameters, the estimated electrical power output ranges from approximately 36.89 kW to 91.90 kW, depending on the head and discharge scenario. For a more conservative efficiency range of $\eta = 0.6$ –0.8, the output would be approximately 26.1–86.6 Kw. The results indicate that even under relatively low hydraulic head conditions, urban flood discharge possesses significant energy potential when appropriately harnessed. This analysis demonstrates that the transformation of floodwater into electrical energy is physically viable and can be systematically quantified using hydrological and hydraulic parameters. Moreover, the integration of such energy conversion mechanisms into urban drainage systems offers a dual-functional infrastructure, serving both flood mitigation and renewable energy generation purposes.

3.5 Spatial Interpretation of Flood and Energy Potential

The spatial characteristics of the study area play a critical role in determining both flood behavior and energy generation potential. The selected study location, Raden Panji Suroso Road, represents a hydrologically strategic zone within the urban drainage network of Malang City. This area functions as a runoff convergence corridor, receiving surface flow contributions from surrounding impervious urban surfaces. The catchment area of approximately 120,000 m² is dominated by built-up land, which significantly reduces infiltration capacity and increases surface runoff coefficients. As a result, rainfall events are rapidly transformed into concentrated flow within the drainage system, leading to elevated discharge levels during peak rainfall periods. This spatial configuration explains the relatively high discharge values obtained despite the limited catchment size.

From a spatial perspective, three key factors contribute to the high energy potential observed at the study site:

1. **Impervious Surface Dominance**
Urban land-use changes, including road infrastructure and commercial development, increase runoff coefficients, thereby amplifying discharge magnitude.
2. **Drainage Network Geometry**
The linear configuration of the drainage channel enhances flow concentration and velocity, which are critical parameters for hydropower generation.
3. **Topographic Gradient and Flow Direction**
Although Malang is generally a highland city, localized micro-topographic variations create sufficient hydraulic head within drainage segments, enabling energy extraction under low-head conditions.

Furthermore, the spatial analysis suggests that the identified location is not an isolated case but part of a broader network of potential micro-hydropower sites within the city. Similar urban corridors with high runoff accumulation and defined drainage channels may exhibit comparable energy potential. Therefore, the findings of this study can be extended to support a distributed micro-hydropower system integrated within the urban drainage infrastructure. This spatial interpretation highlights that flood-prone urban areas should not only be viewed as risk zones but also as opportunity zones for energy recovery. By integrating spatial hydrological characteristics with energy conversion analysis, urban flood management can evolve into a multifunctional system that enhances resilience while contributing to sustainable energy production.

4. Discussion

4.1 Comparison with Similar Studies

The design flood discharges and estimated micro-hydropower (MHP) potential in this study—2.21 m³/s for a 2-year return period and 2.75 m³/s for a 5-year return period, yielding an estimated power range

of 36.89–91.90 kW depending on the available head—fall clearly within the technical boundaries of MHP systems. Such systems are commonly defined as small-scale hydropower plants with capacities below 100 kW and are generally considered feasible for localized applications, including small run-of-river schemes, detention outlets, or large drainage channels (Kougias et al., 2014; Belu, 2014). Several international case studies and literature reviews on the utilization of stormwater runoff or detention/retention basin outlets have reported comparable capacities in the order of tens of kilowatts for urban sites with low heads and intermittent peak discharges, indicating that the results of this study are consistent with existing empirical evidence (Samora et al., 2016; Koroll et al., 2025).

When compared with Indonesian studies (Syahputra & Soesanti, 2021; Rumbayan & Rumbayan, 2023), our findings are considered competitive but not exceptionally high. Research on MHP development in Indonesia has largely focused on rural or pressurized channel settings, where adequate head and discharge volumes can generate potentials ranging from several hundred kilowatts to megawatts. In contrast, studies evaluating urban infrastructure or decentralized water networks, such as water distribution systems and detention outlets—typically report capacity ranges within tens of kilowatts, consistent with the present study's outcomes. The principal difference between this study and others reporting higher outputs lies in the hydraulic source: installations utilizing significant head drops, extended falls, or pressure-reducing valves (PRVs) tend to deliver outputs in the hundreds of kilowatts, whereas systems based on rainfall or retention runoff provide intermittent, event-driven energy in the lower tens of kilowatts range (McNabola et al., 2012).

Furthermore, the technical and economic sustainability of urban MHP implementation critically depends on peak flow duration, sediment and debris management, low-head turbine efficiency, and the viability of the local business model—factors that similarly constrain capacity expansion in related Indonesian studies (Tuapetel et al., 2025; Widiarti et al., 2024). In summary, the estimated range of 36.89–91.90 kW derived in this research is both contextually appropriate and practically viable for urban micro-hydropower applications in Indonesia (sufficient for localized loads such as street lighting or pumping). However, the capacity is generally lower than installations exploiting higher heads or pressurized flows. Therefore, practical implementation decisions should incorporate considerations of flow variability, maintenance demands, and site-specific cost–benefit analysis (Rospriandana et al., 2023; Samora et al., 2016; Kougias et al., 2014).

4.2 Limitations of the Rational Method in Urban Flood Energy Assessment

The rational method employed in this study provides a simplified yet widely accepted approach for estimating peak discharge in urban catchments. However, several inherent limitations must be explicitly acknowledged when interpreting the results, particularly in the context of energy conversion analysis. First, the rational method assumes uniform rainfall intensity and steady-state flow conditions, which rarely occur in real urban flood events. In highly dynamic tropical rainfall systems such as those in Malang City, rainfall intensity varies significantly over time and space, potentially leading to overestimation or underestimation of peak discharge. Consequently, the calculated discharge values (2.21–2.75 m³/s) may not fully capture temporal variability in flood hydrographs. Second, the method does not account for storage effects, flow routing, and hydraulic interactions within drainage networks. Urban drainage systems are complex, involving detention, backwater effects, and flow attenuation, which influence the actual discharge reaching a given point. The omission of these processes introduces uncertainty in translating hydrological output into energy potential. Third, the runoff coefficient ($C = 0.7$) applied in this study represents a generalized approximation of urban land use conditions. In reality, urban catchments exhibit heterogeneous land cover characteristics, including varying degrees of imperviousness, vegetation, and soil infiltration capacity. This simplification may affect the accuracy of runoff estimation, particularly in mixed-use urban environments.

These limitations are consistent with broader hydrological literature, which highlights that simplified empirical models such as the rational method are best suited for preliminary design rather than detailed process-based simulation. Advanced approaches, such as distributed hydrological modelling or real-time hydrodynamic simulations, are recommended to improve discharge prediction accuracy and better capture the transient nature of urban flooding systems. Despite these limitations, the rational method remains appropriate for this study as a first-order estimation tool, providing a baseline for evaluating the feasibility of converting urban flood discharge into energy. The integration of energy conversion analysis with simplified hydrological modelling offers a practical framework for early-stage feasibility assessment, particularly in data-limited urban contexts.

4.3 Feasibility Challenges of Micro-Hydropower in Urban Settings

While the results demonstrate that urban flood discharge in Malang City has measurable energy potential (36.89–91.90 kW), the practical implementation of micro-hydropower systems in urban environments presents several critical challenges. One of the primary challenges is the high variability and intermittency of flow. Unlike river-based systems, urban flood flows are episodic, short-duration, and highly dependent on rainfall events. This variability reduces the reliability of energy generation and limits the capacity factor of micro-hydropower systems. Boroomandnia et al. (2022) indicate that fluctuating discharge and low-head conditions are among the main technical barriers in urban micro-hydropower deployment. Another key constraint is the low hydraulic head available in urban drainage systems. As observed in this study, the head range is limited to 2–4 m, requiring the use of specialized low-head turbines such as Archimedes screw or overshot wheels. These systems, while technically feasible, often

exhibit lower economic competitiveness due to higher installation costs per unit energy output and site-specific design requirements.

Economic feasibility also remains a significant barrier. The cost of installation, operation, and maintenance of micro-hydropower systems in urban infrastructure must be justified against relatively modest energy outputs. Previous studies highlight that economic feasibility is one of the main limitations in real-world implementation of urban micro-hydro systems, particularly when energy generation is not continuous (Boroomandnia et al., 2022). In addition, integration constraints within existing urban infrastructure pose technical and institutional challenges. Urban drainage systems are primarily designed for flood conveyance, not energy production. Retrofitting these systems with turbines requires careful consideration of hydraulic performance, sediment transport, debris accumulation, and maintenance accessibility.

To provide a preliminary economic reference for the Indonesian context, a national-level cost-breakdown study by Indonesia's Fiscal Policy Agency reports that micro-hydropower civil construction works, including closed waterways, powerhouses, dams, and penstocks, account for 67.94% of total capital expenditure (CAPEX), while turbine and generating equipment account for approximately 25.62% (Pusat Kebijakan APBN, 2018). Based on the same study's projected national investment requirement of IDR 132.7 trillion for 2,987.54 MW of planned PLTMH capacity, the implied average investment cost is approximately IDR 44 million (USD 2,700–2,800) per kW; however, this figure reflects projects in the 1–10 MW range and is therefore not directly transferable to small-scale systems. Smaller-capacity systems, such as the 12.5 kW rural electrification scheme reported for Lalumpe Village, North Sulawesi, have shown investment costs of approximately USD 2,000 per kW with a payback period of 3.5 years (Rumbayan & Rumbayan, 2023). Analysis of project-level investment data for 10–50 kW PLTMH installations in Indonesia similarly indicates total investment costs in the range of IDR 1–2 billion, with implied electricity unit costs of IDR 848–5,333/kWh, reflecting substantial site-to-site cost variability (Baldi et al., 2014).

Installed capacity strongly influences cost per kW. Because construction works represent the dominant cost share and do not scale down proportionally with capacity or head, smaller systems and lower-head configurations are expected to fall toward the higher end of these ranges. This pattern is consistent with international benchmarks, IRENA (2012) reports installed costs for small hydropower projects of USD 1,300–8,000 per kW globally, with low-head and pico-scale systems typically at the upper end due to limited economies of scale, while retrofits of existing infrastructure can lower costs to as low as USD 500/kW. Given the 2–4 m head range and intermittent flow regime identified in this study, the installation cost per kW for an urban flood-discharge micro-hydropower system in Malang City is likely to approach or exceed USD 2,000–3,000 per kW, with construction (civil works) rather than turbine procurement representing the dominant cost driver. A site-specific cost assessment is recommended to validate this estimate, as no published cost data specific to urban drainage-based micro-hydropower in Indonesia were identified in the literature reviewed.

Finally, regulatory and institutional barriers may hinder implementation. The integration of energy systems into urban water infrastructure requires coordination across multiple sectors, including water management authorities, energy regulators, and urban planners. The absence of integrated policy frameworks often limits the adoption of such hybrid systems. Despite these challenges, the concept remains promising within the framework of the water-energy nexus, where urban water systems are increasingly recognized as potential sources of decentralized renewable energy. Micro-hydropower systems can contribute to peak load reduction, energy recovery, and sustainable urban infrastructure when integrated with adaptive management strategies and smart water systems.

4.4 Implications for Urban Planning and Policy

The findings of this study have significant implications for urban planning and policy development, particularly in the context of sustainable and resilient cities. First, the integration of flood management and energy generation introduces a paradigm shift from risk mitigation to resource utilization. Urban floodwaters, traditionally treated as hazards, can be reinterpreted as potential energy resources. This dual-function approach aligns with the principles of sustainable urban development and supports the achievement of SDGs, particularly SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) (United Nations, 2021). Second, the spatial analysis highlights the importance of incorporating energy recovery considerations into urban drainage planning. Urban planners should identify high-discharge corridors, such as major drainage channels and runoff convergence zones, as potential sites for micro-hydropower integration. This requires the development of multi-functional infrastructure design frameworks, where drainage systems are optimized not only for hydraulic performance but also for energy efficiency.

Third, the study underscores the need for integrated urban water-energy policies. The implementation of micro-hydropower systems in urban drainage networks necessitates coordination between sectors that are traditionally managed separately. Policy frameworks should promote cross-sectoral collaboration, enabling the co-design of water management and renewable energy systems. Fourth, the adoption of such systems can contribute to decentralized energy generation and urban resilience. By generating electricity locally, micro-hydropower systems reduce dependency on centralized power grids and enhance the reliability of urban energy systems, particularly during extreme weather events. Finally, this study highlights the importance of advancing data-driven and model-based urban

planning approaches. Urban energy and climate adaptation strategies require integrated, multi-dimensional assessment frameworks that consider hydrological, spatial, and energy variables simultaneously. The incorporation of such approaches can support the development of low-carbon, climate-resilient urban systems.

5. Conclusion

This study shows that urban flood runoff in Malang City has quantifiable potential as a renewable energy source when micro-hydropower (MHP) systems are integrated into urban drainage infrastructure. The Rational Method gave design discharges of 2.21 m³/s and 2.75 m³/s for 2- and 5-year return periods, which translate into an electrical power potential of 36.89 to 91.90 kW, within the feasible range for micro-hydropower (<100 kW). High rainfall intensity, increasing impervious surfaces, and local topographic gradients produce a flashy runoff regime, and runoff convergence zones in particular concentrate discharge, making them candidates for decentralized energy recovery. Flood-prone areas can thus be seen as opportunity zones within the water–energy nexus, and coupling flood control with renewable generation supports resilience and low-carbon development in line with SDG 7 and SDG 11. Several limitations apply: the Rational Method simplifies peak discharge and ignores flow duration and hydrograph shape, parameters such as runoff coefficient and system efficiency rest on generalized assumptions, observed discharge data for validation are limited, and the assessment covers instantaneous power (kW) rather than cumulative energy (kWh). Practical challenges also remain, including intermittent flows, low hydraulic head, sediment and debris, integration with existing infrastructure, and the balance between costs and energy output.

Future research should therefore apply dynamic hydrological and hydrodynamic models and hydrograph-based and flow duration analyses to estimate cumulative energy production and reliability. It should also assess economic feasibility and life-cycle costs, test turbine performance in pilot-scale studies under sediment-laden and debris-prone conditions, and explore smart monitoring and real-time control to optimize energy recovery without compromising drainage performance. In conclusion, this study offers a foundational framework for turning urban flood runoff into a renewable energy resource, and although further refinement and validation are needed, the approach is a promising pathway toward resilient, energy-efficient, and sustainable urban water systems.

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7. Conflict of Interest Statement

The authors report no conflicts of interest related to the study, its authorship, or the publication of this manuscript.

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