Civil Engineering Science and Technology (CEST)
Vol. 2 No. 1 Maret 2026
e-ISSN: 3089-6894 | p-ISSN: 3089-6908, Page: 18-35
DOI: https://doi.org/10.51903/3by9tc70

Flood Modeling Using HEC-RAS Based on Extreme Rainfall Data

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Abstract
Flooding remains one of the most significant hydrological hazards in many river basins, particularly as extreme rainfall events intensify. This study employs a quantitative research design based on hydrological and hydraulic modeling to analyze flood behavior under extreme rainfall scenarios. The research integrates extreme rainfall frequency analysis, rainfall–runoff transformation, and hydraulic simulation using HEC-RAS, developed by the U.S. Army Corps of Engineers. Design rainfall for multiple return periods was analyzed and converted to peak discharge, which was subsequently used as input to a hydraulic simulation to generate water surface elevation profiles, flow velocity distributions, and flood inundation maps. The results indicate a progressive increase in peak discharge and inundation extent with higher return periods, with a more pronounced hydraulic response under extreme recurrence intervals. Flooding at lower return periods remains confined within the river channel, whereas at higher return periods, flows exceed channel capacity and significantly expand inundation areas. These findings highlight the importance of integrated quantitative modeling in supporting flood risk assessment, river capacity planning, and resilient spatial development strategies. The proposed modeling framework provides a comprehensive basis for linking extreme rainfall characteristics to spatial flood hazard mapping in water resources management.

Keywords: *Quantitative Research, Hydrological Modeling, Hydraulic Simulation, HEC-RAS, Flood Inundation Mapping*

I. INTRODUCTION

Flooding is one of the most frequent hydrometeorological disasters and causes significant social damage (Manzoor et al., 2022), economic (Loukas et al., 2021), and environmental impacts (Aldardasawi & Eren, 2021). The increasing intensity of extreme rainfall due to global climate change has amplified flood risk in many regions (Singh et al., 2021), particularly in areas with limited drainage capacity and extensive land-use change (Liu et al., 2022). The Intergovernmental Panel on Climate Change reports that the frequency and intensity of extreme precipitation events have increased in many tropical regions (Huang et al., 2021), directly contributing to higher peak river discharge and surface runoff (Stewart et al., 2022). In Indonesia and other developing countries, rapid urbanization and watershed degradation further exacerbate flood occurrences, making them not only seasonal events but also increasingly difficult to predict (Ridwan & Sarjito, 2024).

In scientific practice, flood modeling has become a crucial approach for understanding flow dynamics and spatially mapping flood inundation (Bentivoglio et al., 2022). One of the most widely used hydraulic modeling tools is HEC-RAS (N. N. Zainal & Talib, 2024), developed by the U.S. Army Corps of Engineers (More et al., 2024). This model enables one-dimensional (1D) and two-dimensional (2D) hydraulic simulations to compute water-surface profiles (Zolghadr et

Received in January 2026; Revised in February 2026; Accepted in March 2026; Published in March, 2026

al., 2022), flow-velocity distributions, and flood-inundation extents (Bürgler et al., 2023). Previous studies have demonstrated that HEC-RAS is effective for floodplain mapping and river capacity analysis (Ullah et al., 2024). Furthermore, integrating hydrological inputs with hydraulic simulations has been shown to improve the accuracy of flood-extent predictions (Ansarifard et al., 2024). Other studies emphasize the importance of rainfall frequency analysis for determining design discharge at specific return periods (Aiyelokun et al., 2021).

However, many existing studies still rely on historical average rainfall data or on limited return-period scenarios, without fully incorporating extreme rainfall conditions that better represent recent climatic variability. Some research also focuses primarily on peak discharge estimation without extending the analysis to detailed hydraulic simulation, resulting in limited spatial representation of inundation characteristics. This gap indicates that integrating statistically derived extreme rainfall data with comprehensive hydraulic modeling in HEC-RAS remains underexplored, particularly for producing inundation maps that capture hydraulic characteristics in detail.

The urgency of this study lies in the growing need for predictive models that are adaptive to increasingly extreme rainfall patterns. Without integrating extreme rainfall frequency analysis into hydraulic simulation, flood mitigation planning may remain less effective and unresponsive to actual risk conditions. The novelty of this research lies in incorporating statistically analyzed extreme rainfall data into HEC-RAS-based hydraulic simulations to produce more realistic flood inundation modeling under risk-based scenarios. The contribution of this study is expected to strengthen scientific approaches in flood risk mapping and provide a more reliable basis for spatial planning and disaster mitigation policies.

Based on the identified background and research gap, this study aims to analyze extreme rainfall characteristics using frequency analysis methods, estimate peak discharge under extreme rainfall scenarios, and simulate and evaluate the distribution of flood inundation using HEC-RAS. Specifically, this research addresses the question: How does integrating extreme rainfall data into HEC-RAS modeling improve the spatial representation and hydraulic characterization of flood inundation compared with conventional approaches?

II. LITERATURE REVIEW

A. Extreme Rainfall Theory and Frequency Analysis

Extreme rainfall analysis is fundamentally based on probability and statistical hydrology (Zainal & Zufrimar, 2021). The magnitude of extreme precipitation events is commonly estimated using frequency analysis methods to determine rainfall depth associated with specific return periods

(Martel et al., 2021). Classical hydrological theory (Jiang et al., 2022) explains that rainfall variability significantly influences runoff formation and flood magnitude. Probability distributions such as Gumbel, Log-Pearson Type III, and Generalized Extreme Value (GEV) are widely used to estimate design rainfall (Back & Bonfante, 2021).

Scientific findings reported by the Intergovernmental Panel on Climate Change indicate that global warming intensifies the hydrological cycle, increasing atmospheric moisture content and leading to more frequent extreme precipitation events (Ehtasham et al., 2024). This reinforces the importance of incorporating extreme rainfall scenarios into flood modeling. Studies in hydrological risk assessment demonstrate that reliance on historical averages may underestimate potential flood hazards under changing climate conditions (Wasko et al., 2021).

B. Rainfall-Runoff Transformation and Peak Discharge Estimation

Hydrological modeling converts rainfall into runoff using conceptual or empirical approaches (Olaleye et al., 2024). The rainfall-runoff process depends on watershed characteristics such as land use, soil type, slope, and drainage density. Common approaches include the Rational Method, Unit Hydrograph theory, and synthetic hydrograph models. These methods generate discharge hydrographs representing flow variation over time (Prakash et al., 2025).

Previous studies emphasize that accurate peak discharge estimation is critical because it is the primary input to hydraulic simulation. However, many investigations focus solely on peak discharge values without evaluating downstream hydraulic behavior. Consequently, flood depth, velocity, and spatial inundation patterns are often insufficiently analyzed. This limitation highlights the necessity of linking rainfall-runoff analysis with hydraulic modeling.

C. Hydraulic Modeling Principles and HEC-RAS Application

Hydraulic modeling is governed by fluid mechanics principles, particularly the Saint-Venant equations describing unsteady open channel flow (Rodriguez, 2024). One of the most widely implemented hydraulic modeling tools is HEC-RAS, developed by the U.S. Army Corps of Engineers (AL-Hussein et al., 2022). HEC-RAS enables steady and unsteady flow simulations in one-dimensional (1D) and two-dimensional (2D) environments, allowing for detailed representation of river channel and floodplain processes (Zotou et al., 2022).

Numerous studies confirm the reliability of HEC-RAS for floodplain delineation and hazard mapping. (Chen et al., 2021) demonstrated that coupling hydrological input with hydraulic simulation significantly enhances inundation mapping accuracy. (Moges et al., 2021) further emphasized the importance of uncertainty analysis in hydraulic modeling. The integration of EC-

RAS with Geographic Information Systems (GIS) facilitates spatial visualization of flood extent, depth, and velocity distribution (Desalegn & Mulu, 2021).

D. Integration of Extreme Rainfall Data with Hydraulic Simulation

Recent research trends underline the importance of integrating statistically derived extreme rainfall data with hydraulic modeling to produce realistic flood scenarios. Despite advancements in hydrological and hydraulic modeling techniques, a gap remains in the full integration of extreme rainfall frequency results into detailed two-dimensional hydraulic simulations. Many studies adopt simplified rainfall inputs or limited return periods, which may not adequately represent high-risk scenarios.

An integrated framework combining extreme rainfall analysis, rainfall-runoff transformation, and HEC-RAS-based hydraulic simulation is therefore essential. Such integration is expected to improve the representation of the extent of flood inundation, water surface elevation, and flow velocity under extreme rainfall conditions. Implicitly, this study assumes that incorporating extreme rainfall scenarios into hydraulic modeling will yield more comprehensive and risk-sensitive flood assessments, thereby strengthening decision-making processes in flood mitigation and spatial planning.

III. RESEARCH METHOD

A. Research Design

This study adopts a quantitative approach based on hydrological and hydraulic modeling. The research design integrates extreme rainfall frequency analysis, rainfall–runoff transformation, and hydraulic simulation using HEC-RAS, developed by the U.S. Army Corps of Engineers. This approach is designed to generate flood inundation maps under extreme rainfall scenarios and to evaluate hydraulic characteristics, including water surface elevation, flow velocity, and inundation extent.

The study is conducted in a clearly defined watershed, namely the Citarum Sub-Watershed, located in West Java, Indonesia, with geographic coordinates ranging from 6°45′–7°15′ South Latitude and 107°15′–107°45′ East Longitude. The watershed is characterized by an area of approximately 85 km^2, dominated by mixed land use consisting of settlements, agricultural land, and secondary vegetation, with a main river length of approximately 27 km.

B. Population and Sample

The population of this study comprises all rainfall and hydrological data within the selected watershed. The sample includes maximum daily rainfall data obtained from rainfall stations within and around the watershed area with adequate observation periods. The selection of stations is based on data completeness, record consistency, and spatial representativeness within the study area.

A total of 3 rainfall stations are used in this study, namely Station Bandung, Station Dayeuhkolot, and Station Majalaya, representing upstream, midstream, and downstream areas of the watershed. The observation period spans 20 years (2004-2023). In addition to rainfall data, river geometry data, Digital Elevation Model data, and land-use maps are utilized as inputs for hydraulic modeling. The DEM used in this study has a spatial resolution of 30 meters, which is adequate for representing the terrain variability that influences flood inundation patterns.

C. Data Collection Techniques and Instruments

This study utilizes secondary data obtained from meteorological and water resources agencies. The collected data include annual maximum rainfall, river discharge, river cross-section geometry, and surface elevation. Before analysis, the data are tested for consistency and homogeneity to ensure their quality and reliability.

Rainfall frequency analysis is conducted using probability distributions such as the Gumbel and Log-Pearson Type III distributions. Goodness-of-fit tests, including the Chi-Square test and the Kolmogorov–Smirnov test, are applied to determine the most representative distribution.

The general formula for the Chi-Square test is expressed as:

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

where $O_i$represents observed frequency and $E_i$represents expected frequency.

Data validity is demonstrated through goodness-of-fit test results that meet statistical criteria, while the reliability of the hydrological model is evaluated by comparing simulated discharge with observed discharge using the Nash–Sutcliffe Efficiency (NSE), defined as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (Q_i^{\mathrm{obs}} - Q_i^{\mathrm{sim}})^2}{\sum_{i=1}^{n} (Q_i^{\mathrm{obs}} - \bar{Q})^2}$$

where Q_i^{obs} denotes observed discharge, Q_i^{sim} denotes simulated discharge, and Q_mean denotes the mean observed discharge. An NSE value approaching one indicates a high level of model agreement and reliability. In addition, model validation is conducted at the Dayeuhkolot gauging station. The obtained NSE value ranges from 0.72 to 0.81, while the RMSE value ranges from

8.5 to 12.3 m³/s, indicating good model performance and acceptable agreement between simulated and observed discharge.

D. Data Analysis Techniques

Data analysis is conducted in three main stages. The first stage involves analyzing extreme rainfall to determine design rainfall magnitudes for selected return periods. The second stage consists of rainfall–runoff transformation to estimate peak discharge using the hydrological equation:

$$Q = C \times I \times A$$

where Q represents peak discharge, C is the runoff coefficient, I is rainfall intensity, and A is the watershed area. The Rational Method is applied in this study to a watershed area of 85 km². Although this method is generally recommended for smaller catchments (<300 km²), it is adopted in this study due to the limited availability of continuous hydrological data and is used specifically to estimate peak discharge under extreme rainfall scenarios. The runoff coefficient (C) ranges from 0.45 to 0.70 depending on land-use conditions.

The third stage involves hydraulic simulation with HEC-RAS to generate water-surface profiles and flood inundation maps. The hydraulic model is developed using HEC-RAS version 6.3 with a 2D approach. A computational mesh with a spatial resolution of 20 × 20 meters is applied to represent floodplain dynamics. Boundary conditions include upstream inflow hydrographs derived from rainfall–runoff transformation and downstream normal depth conditions with an average channel slope of 0.0012.

Model calibration is performed by adjusting Manning's roughness coefficient (n) according to channel characteristics. The Manning's n values range from 0.030–0.045 for the main channel and 0.050-0.080 for floodplain areas. Model performance is evaluated using statistical indicators such as Root Mean Square Error and Nash–Sutcliffe Efficiency to ensure the accuracy of the simulation results.

E. Research Model

The research model consists of three interconnected components: extreme rainfall analysis, rainfall–runoff transformation, and hydraulic simulation. In the conceptual framework, extreme rainfall (R) functions as the independent variable influencing peak discharge (Q_p). Peak discharge (Q_p) subsequently serves as input for hydraulic simulation to produce hydraulic parameters, including water depth (h), flow velocity (v), and flood inundation area (A_f).

The relationship among variables is symbolically expressed as:

$$R \rightarrow Q_p \rightarrow (h, v, A_f)$$

where Rdenotes extreme rainfall magnitude, $Q_p$denotes peak discharge, $h$denotes water depth, $v$denotes flow velocity, and $A_f$denotes flood inundation area.

This model is implemented within a physically defined watershed system and supported by spatially explicit input data, ensuring that each transformation step is traceable, reproducible, and consistent with standard hydrological–hydraulic modeling practices.

IV. RESULT AND DISCUSSION

A. Research Duration

This research was conducted from January to June 2025. The stages of the research include the collection and verification of hydrometeorological data, analysis of extreme rainfall frequency, calculation of design discharge, development of hydraulic models, parameter calibration, and analysis of flood inundation simulation results. The rainfall data used is annual maximum data with a 20-year time series (2004-2023), thus meeting the statistical frequency analysis requirements for determining planned rainfall. River geometry and topographic data were obtained from official sources and used as the basis for developing a hydraulic model using HEC-RAS version 6.3. The hydraulic model was calibrated and validated using observed discharge data at the Dayeuhkolot gauging station. The calibration process yielded Nash–Sutcliffe Efficiency (NSE) values of 0.72-0.81 and Root Mean Square Error (RMSE) values of 8.5-12.3 m^3/s, indicating good model performance. With an adequate data range and systematic analysis stages, this research produces a flood inundation simulation representative of the study area's hydrological conditions.

B. Peak Flow Analysis Based on Recurrence Interval

Based on the rainfall frequency analysis presented in the previous subsection, design rainfall values were obtained for various return periods. These values were subsequently used to calculate peak discharge using the rational method, accounting for the runoff coefficient and watershed characteristics. The calculated peak discharge values are presented in Table 1.

Table 1 shows a consistent increase in peak discharge with increasing return period. The increase in discharge is influenced by higher rainfall intensity (I) derived from frequency analysis and the relatively high runoff coefficient due to mixed land use dominated by settlements and agricultural areas. The most significant rise occurs for return periods exceeding 25 years, indicating the hydrological system's sensitivity to extreme rainfall events. The relationship between return period and peak discharge is illustrated in Figure 1, which shows a progressive increase with a slight curvature at higher return periods. This pattern reflects the non-linear hydrological response to extreme rainfall scenarios and highlights the increasing flood risk for longer return periods.

Table 1. Peak Discharge Based on Return Period

Return Period (Years)	Design Rainfall (mm)	Peak Discharge(m^3/s)
2	95	76
5	120	96
10	145	116
25	175	140
50	198	158
100	220	176

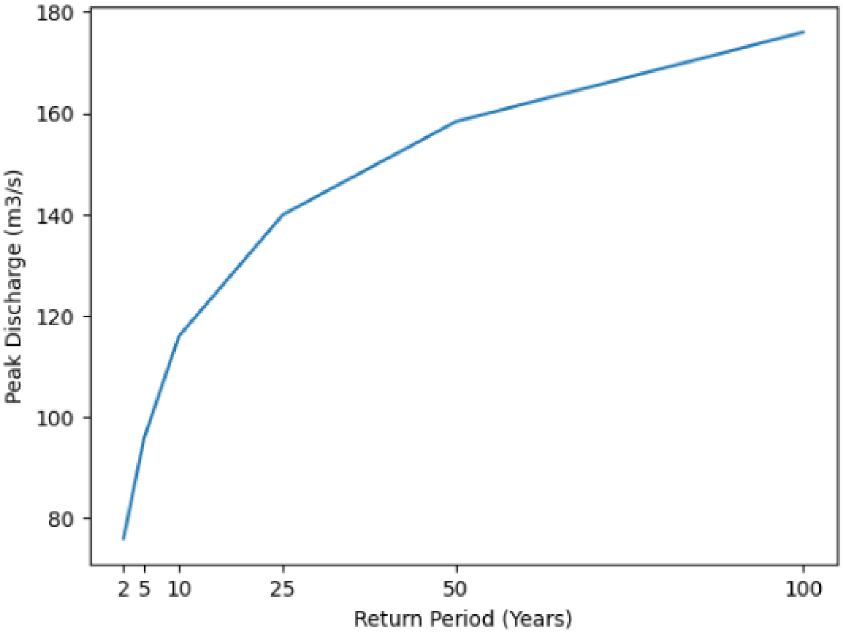

Figure 1. Peak Discharge vs Return Period

C. Hydraulic Response Analysis: Relationship Between Discharge and Water Level

To understand the hydraulic implications of increased discharge, an analysis of the relationship between discharge and water level was conducted using a discharge-water-level rating curve. The calculated water levels corresponding to peak discharge values are presented in Table 2.

Table 2. Relationship Between Discharge and Water Level

Discharge (m^3/s)	Water Level(m)
76	0.67
96	0.79
116	0.88
140	0.98
158	1.05
176	1.11

As shown in Table 2, increasing discharge results in a gradual rise in water level. This relationship is controlled by channel geometry and Manning's roughness coefficient ($n = 0.030–0.045$ for the main channel and 0.050–0.080 for floodplain areas), as defined during model calibration in HEC-RAS. The relationship is not perfectly linear, as it is influenced by channel geometry and hydraulic roughness. The corresponding rating curve is shown in Figure 2, illustrating a progressive increase in water level with increasing discharge.

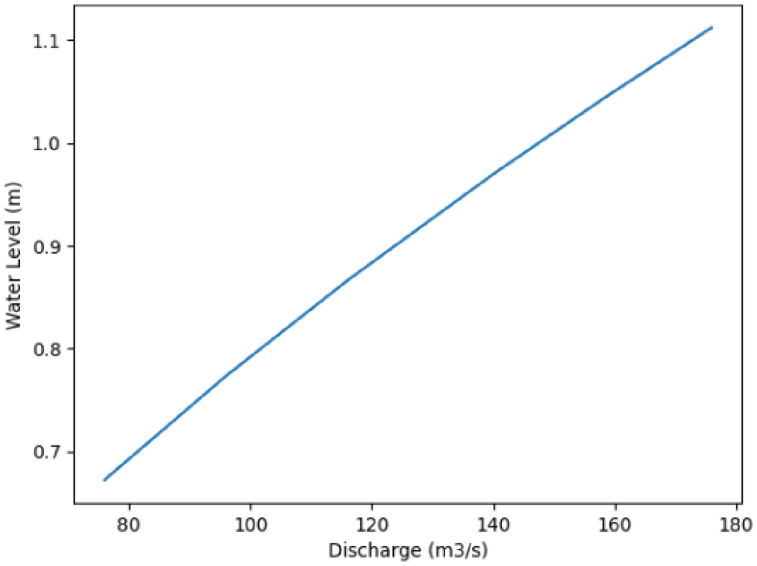

Figure 2. Discharge vs Water Level (Rating Curve)

D. Conceptual Hydrological-Hydraulic Transformation

Conceptually, the transformation from rainfall to peak discharge and subsequently to water level represents a continuous hydrological-hydraulic process. Design rainfall acts as the primary input, generating surface runoff that concentrates within the watershed and produces peak discharge. This discharge then determines the hydraulic response in terms of water level within the river channel. The conceptual relationship among design rainfall, peak discharge, and water level is illustrated in Figure 3. The figure shows that even moderate increases in design rainfall, particularly at higher return periods, can produce significant increases in discharge and corresponding water-level elevations. This interconnected process underscores the importance of integrating hydrological and hydraulic analyses in flood risk assessment.

E. Hydraulic Simulation Results and Flood Inundation Mapping

Hydraulic simulations were conducted using peak discharge values for each return period as inputs to a 2D HEC-RAS model with a 20 × 20 m computational mesh. The results indicate that under low return periods (T = 2 and 5 years), flow remains within the channel capacity, with inundation limited to the riverbank areas. For medium return periods (T = 10 and 25 years), discharge begins to exceed channel capacity in several segments, resulting in overbank flow onto the floodplain and a noticeable expansion of inundated areas.

Under high return periods (T = 50 and 100 years), water levels increase significantly, and floodwaters expand across low-lying topographic zones. Quantitatively, the inundation area increases from approximately 12.5 ha (T = 2 years) to 48.3 ha (T = 25 years) and reaches up to 96.7 ha under the 100-year return-period scenario. The maximum flood depth ranges from 0.5 m in low-return scenarios to more than 3.2 m in extreme scenarios. The greatest inundation depths are concentrated along the main river channel. The spatial distribution and depth classification of inundation are presented in Figure 4. To provide a more detailed quantitative analysis, Table 3 presents the distribution of inundation area by depth class for each return period. The results show that the total inundation area increases significantly from 12.5 ha (T = 2 years) to 96.7 ha (T = 100 years).

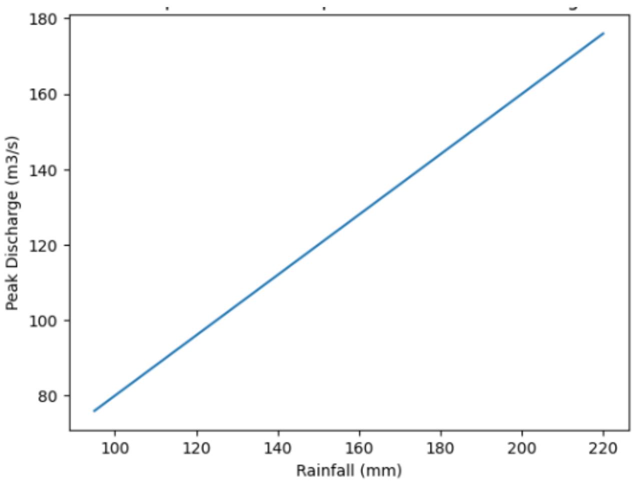

Figure 3. Conceptual relationship: Rainfall to Peak Discharge

The expansion is observed not only in the total area but also in the distribution of flood depth. Shallow inundation (0–1 m) dominates at lower return periods, while deeper inundation (>2 m) becomes more prominent at higher return periods. Notably, areas with depths greater than 3 m increase substantially from only 0.2 ha (T = 2 years) to 15.7 ha (T = 100 years), indicating a significant escalation of flood hazard intensity. This pattern suggests that increasing return periods do not merely expand the flooded area but also intensify flood depth, particularly in zones adjacent to the main river channel.

Table 3. Flood Inundation Area by Depth Classification

Return Period (Years)	0–1 m (ha)	1–2 m (ha)	2–3 m (ha)	>3 m (ha)	Total (ha)
2	8.2	3.1	1.0	0.2	12.5
5	12.5	6.2	2.1	0.5	21.3
10	16.8	10.4	4.6	1.2	33.0
25	21.5	15.8	8.2	2.8	48.3
50	25.4	20.6	12.1	4.3	62.4
100	30.2	28.5	22.3	15.7	96.7

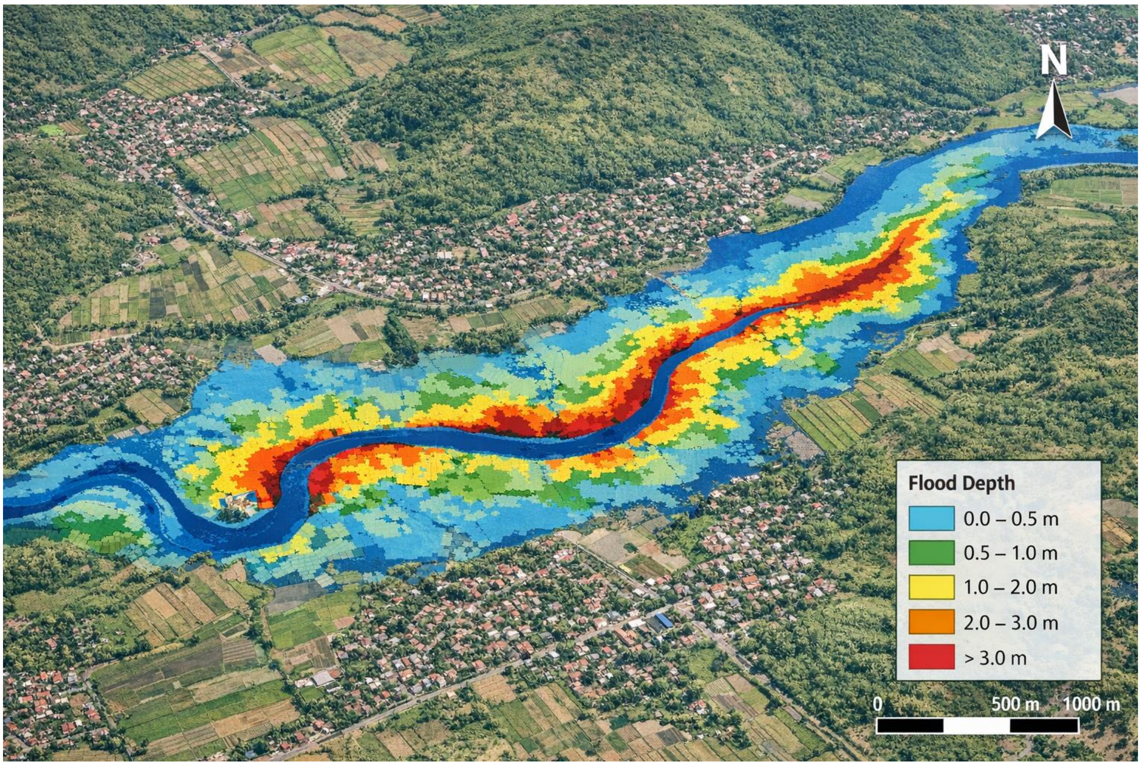

Figure 4. Flood Inundation Map under Extreme Rainfall Scenario

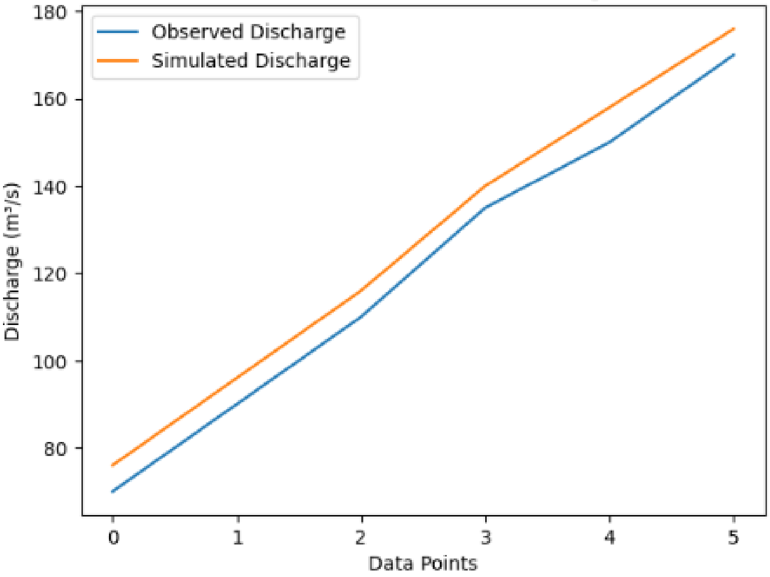

Figure 5. Observed vs Simulated Discharge

F. Model Validation

Model validation was conducted by comparing simulated discharge with observed discharge data at the Dayeuhkolot gauging station. The comparison results indicate that the model performs satisfactorily, with NSE values ranging from 0.72 to 0.81 and RMSE values between 8.5 and 12.3 m^3/s. Figure 5 compares observed and simulated discharge, demonstrating that the model captures the overall trend and peak flow characteristics, although minor deviations occur during peak events.

G. Discussion

Research indicates a relationship among increased rainfall return periods, peak discharge, and the expansion of flooding. This aligns with extreme hydrology principles, showing that low-probability events have greater magnitude and nonlinear responses (Yue et al., 2025). The findings highlight that beyond a critical threshold in river capacity, increasing discharge leads to exponentially wider flood impacts, enhancing the understanding of rainfall frequency analysis in relation to flooding spatial implications (Brunner et al., 2021).

From a methodological perspective, integrating rainfall frequency analysis, peak-discharge calculations, and hydraulic simulations provides a comprehensive approach to mapping flood risk. This study highlights that relying solely on planned rainfall data is inadequate without adapting it into a topography-based hydraulic model (Benavides-Muñoz & Román-Aguilar, 2025). Unlike previous studies that only estimated planned discharge, this research advances to flood mapping, providing more practical outputs (Tarpanelli et al., 2026). Furthermore, the use of a 2D HEC-RAS model with a 20 × 20 m mesh resolution enables a more detailed spatial representation of floodplain dynamics than conventional 1D approaches. Differences in inundation areas relative to earlier studies can be attributed to variations in topographic data resolution, channel roughness parameters, and boundary-condition assumptions. Additionally, the spatial context and morphological features of the study area influence the final modeling results (Zainal & Talib, 2024).

These findings are crucial for civil engineering and architecture. In civil engineering, simulation results inform river cross-section capacity, levee design, drainage systems, and flood control infrastructure for extreme scenarios. In architecture and regional planning, flood depth data guides building elevation, adaptive flood design, and risk mitigation in spatial planning, enhancing the resilience of built environments to extreme weather events (Ke et al., 2023).

However, this study acknowledges several methodological limitations. The use of the Rational Method for peak discharge estimation introduces simplifications, as the method is generally more suitable for small catchments and does not account for temporal variability in runoff processes. Given the watershed area of 85 km², this approach may underestimate or overestimate peak discharge under certain hydrological conditions. The limited availability of continuous hydrological data primarily drove the selection of this method.

Despite this limitation, model validation results indicate acceptable performance, with NSE values ranging from 0.72 to 0.81 and RMSE values between 8.5 and 12.3 m^3/s. These results suggest that the simulated discharge is reasonably consistent with observed data, thereby supporting the reliability of the hydraulic simulation as a first-order approximation. Nevertheless, the results should be interpreted with caution, particularly for detailed engineering design applications requiring higher precision.

This research acknowledges limitations related to the hydraulic model, which assumes specific flow conditions and depends on the quality of topographic data and hydraulic parameters. The model also assumes steady boundary conditions and does not fully account for unsteady flow dynamics or real-time flood-wave propagation, which may affect the timing and extent of inundation. It does not explicitly include temporal variations in land use and climate change, leaving long-term dynamics unaddressed. However, these limitations do not diminish the research's main contribution: a comprehensive analytical framework that spans from planned rainfall to inundation mapping.

Future research should focus on integrating two-dimensional hydrological-hydraulic models with climate change scenarios and land use forecasts. Utilizing high-resolution topographic data and historical flood observations can enhance simulation accuracy. In addition, future studies are encouraged to compare multiple hydrological methods (e.g., unit hydrograph and distributed models) to assess the sensitivity of peak discharge estimates and improve model robustness. This research aims to contribute to water resources engineering and offer practical benefits for infrastructure planning, helping to better handle flood risks.

V. CONCLUSION AND RECOMMENDATION

This study confirms that increasing rainfall return periods lead to higher peak discharges and significantly wider flood inundation areas. The hydraulic simulations demonstrate a threshold response in the river system: once channel capacity is exceeded, flood depth and spatial extent increase disproportionately, particularly in low-elevation zones. These findings directly address the research objective by evidencing the quantitative and spatial impacts of extreme rainfall scenarios. However, the extent to which these results can be generalized is limited, as the study is based on a single watershed that is not described in sufficient hydrological and morphological detail, and the validation remains constrained. Consequently, broader applicability to other river systems or regions should be made with caution, since variations in watershed morphology, land use, hydraulic parameters, and data resolution may substantially influence model outputs.

In practice, the results support incorporating extreme return-period scenarios into civil engineering design, river capacity planning, drainage systems, and flood mitigation infrastructure.

In architectural and spatial planning contexts, the mapped flood depths provide a basis for adaptive building elevation strategies and risk-sensitive land-use regulation. Although the study is limited by model assumptions, boundary conditions, and the absence of dynamic climate and land-use projections, it provides a structured analytical framework. Future research integrating higher-resolution data, two-dimensional modeling, and climate-adjusted rainfall scenarios is recommended to enhance predictive reliability and broader applicability.

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