Linking the Reservoir Volume to the Flood Inundation Extent: A Multi-Dam Empirical Model for Indonesian Dam Safety

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ABSTRACT

Indonesia rapidly expands its dam infrastructure to meet the water resource and development needs. This expansion, however, coupled with more extreme rainfall events due to the climate change, significantly increases the risk of catastrophic dam failures and downstream flooding. Existing studies of dam-break floods in Indonesia are typically limited to single-dam case analyses or theoretical models. Consequently, no comprehensive empirical model exists to predict the flood inundation from dam failures across varied locations or dam types, particularly for vulnerable earth fill dams. The present study addresses this gap by analyzing 12 representative dams across Indonesia, spanning various regions, reservoir capacities, and hydrological settings, to develop an empirical relationship between the reservoir storage volume and downstream flood inundation area. By integrating structural variables (e.g., dam height, storage area, reservoir capacity) with hydrological factors, an empirical multi-dam volume–area inundation model is derived applicable to overtopping and piping failure scenarios. The results demonstrate that the dam height and reservoir size strongly influence the flood extent, and the proposed volume–area model can reasonably estimate the inundation areas for different collapse scenarios. This is the first multi-dam empirical flood inundation model in the Indonesian context. The findings provide improved insight into the dam failure impacts and offer a practical tool to enhance the risk assessment, guide emergency response planning, and inform the national dam safety policy.

Keywords-rock-fill type; dam; reservoir storage volume; flood inundation; dam break analysis

I. INTRODUCTION

Dams are essential infrastructures constructed across rivers, and they provide irrigation, drinking water supply, hydropower generation, and flood control [1]. Dam construction has been practiced for centuries as one of the most effective solutions for ensuring sustainable water resource management [2]. Dams store water and significantly contribute to the national economic development through agriculture, energy production, and urban water supply systems [3]. Indonesia has actively pursued the dam development, with 63 new dams constructed in 2018 alone, signaling a strong governmental commitment to the water infrastructure development. Despite their advantages, dams also pose severe hazards in the event of structural failure. Dam-break floods are among the most devastating hydrological disasters, resulting in profound social, ecological, and economic losses [4]. Historical records and previous studies have demonstrated that the dam breach processes can be analyzed and, to some extent, predicted based on past failure events [5, 6]. However, these assessments often lack a comprehensive integration of the diverse dam characteristics and downstream topographical variability, limiting their applicability for broader risk management strategies.

A key component of dam failure analysis is the Probable Maximum Precipitation (PMP) estimation, which is subsequently used to calculate the Probable Maximum Flood (PMF). These hydrometeorological parameters are critical for simulating the flood inundation patterns, particularly in downstream areas vulnerable to extensive damage [7]. Furthermore, the spatial relationship between the inundation depth and distance from the dam centerline offers valuable insights into how dam features, such as type, height, and reservoir volume affect the flood behavior. Such analyses also consider breach scenarios, catchment topography, land use, and infrastructure vulnerability, which are crucial for effective emergency planning, infrastructure design, and public safety [8].

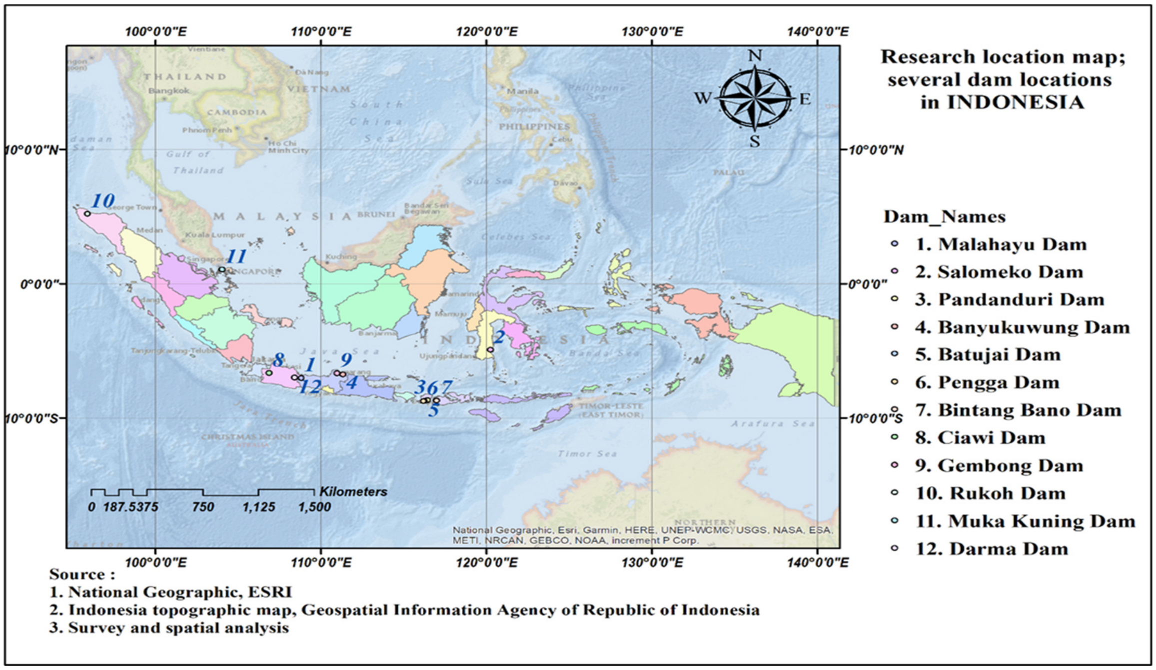
In Indonesia, the ongoing dam development includes a wide variety of dam types and reservoir capacities. However, a significant gap remains in understanding the potential inundation impacts across different dam sites. Most existing research focuses on isolated case studies or theoretical breach modeling, without evaluating the dam collapse scenarios within a spatially and structurally diverse context [9]. Furthermore, there is no national framework or predictive model capable of estimating the potential inundation volume resulting from dam failures particularly in the case of earthfill-type dams, which are generally more vulnerable to internal erosion and overtopping [10]. To bridge these gaps, the current study investigates twelve distinct dams across Indonesia, ranging from Malahayu in Central Java to others in regions, such as South Sulawesi and Aceh. These selections reflect the geographical diversity, varied reservoir volumes, and hydrological conditions. This research focuses on modeling the correlation between the reservoir volume and the extent of potential flood inundation, aiming to establish an empirical framework that can enhance the dam failure risk assessment and emergency response strategies. This novel methodology employs an integrative approach for predicting the dam failure impacts, particularly concentrating on earthfill dam types. This represents Indonesia's inaugural comprehensive analysis, potentially improving the pre-construction risk evaluations, operational safety measures, and informing the national dam safety policies [11, 12]. The novelty of this research lies in its integrative and comparative approach to modelling the inundation scenarios across multiple dams, with a focus on earthfill dam types.

This is Indonesia's first study that systematically predicts the impact of dam failures on the influence of inundation using a volume-area relationship approach applied to multiple dam sites. This approach is expected to enhance pre-construction risk evaluations, support operational safety strategies, and inform national dam safety policies.

II. MATERIALS AND METHODS

A. *Research Location and Data Preparation*

In this study, twelve dams were examined: Malahayu Dam, Salomeko Dam, Pandanduri Dam, Banyukuwung Dam, Batujai Dam, Pengga Dam, Bintang Bano Dam, Ciawi Dam, Gembong Dam, Rukoh Dam, Muka Kuning Dam, and Darma Dam. Their respective geographic locations are provided in Figure 1. The hydraulic model HEC-RAS 5.0 tool determines the breach outflow hydrograph and hydraulic conditions at critical downstream locations [13, 14]. The breach outflow hydrographs are then routed using dynamic flood wave routing [13] HEC-RAS is used for dam break analysis, and RAS-MAPPER is employed to generate river geometric data and floodplain mapping [14]. HEC-RAS deploys flood routing techniques proposed by St. Venant's equations for unsteady flow [6-15]. The 1-D St. Venant's unsteady flow equations of conservation of mass and conservation of momentum are utilized [16]. The methodology adopted for performing dam break analysis is portrayed in Figure 2, and the following subsections explain the steps followed in the hydraulic modeling, simulation model, and floodplain mapping.



Source :
1. National Geographic, ESRI
2. Indonesia topographic map, Geospatial Information Agency of Republic of Indonesia
3. Survey and spatial analysis

Fig. 1. Research location.

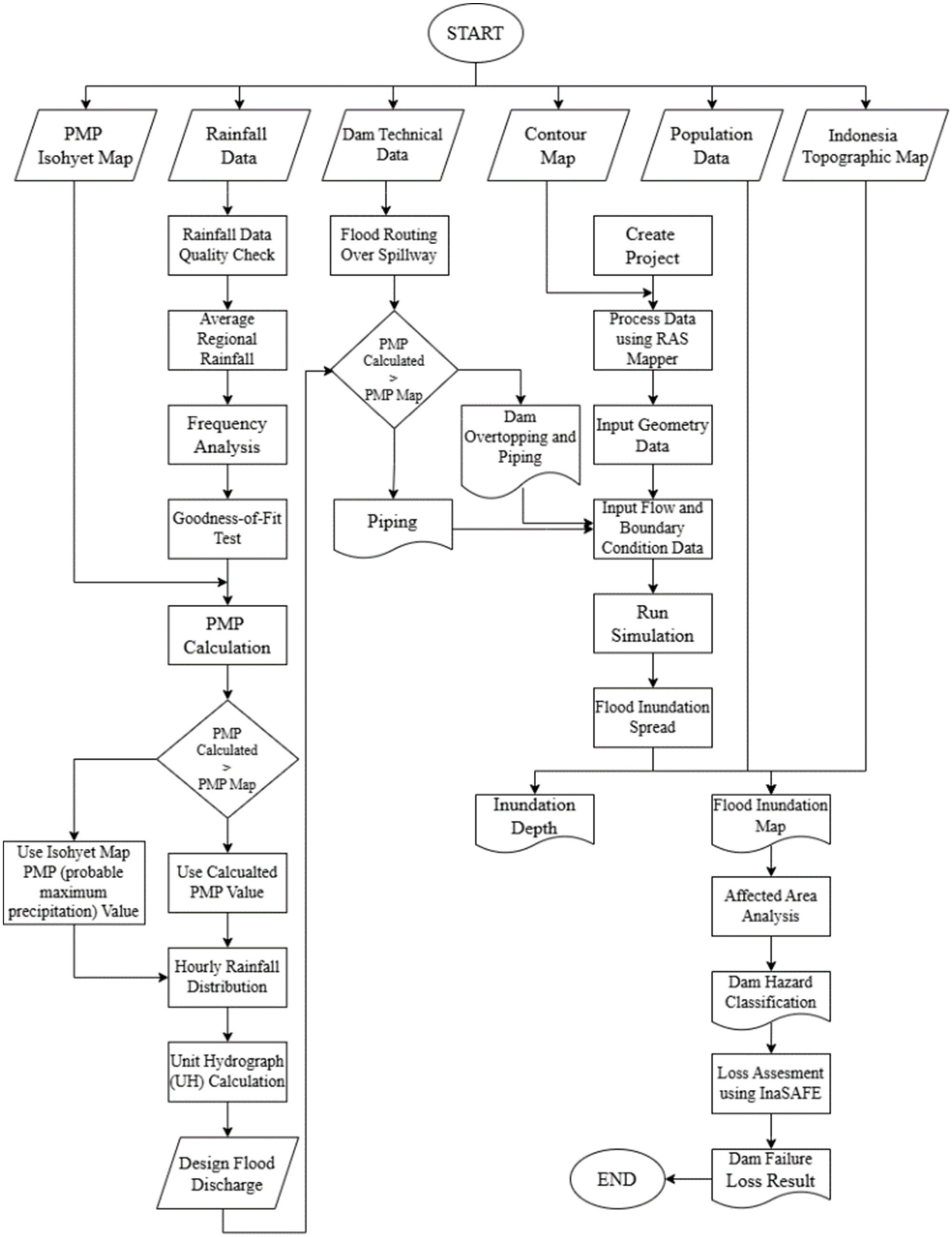


Fig. 2. Dam collapse analysis research flow chart.

1) Rainfall Data

Rainfall data spanning 15 years (2005–2020) were obtained from rain recording stations located at each dam, managed by the Ministry of Public Works and Public Housing. The data were collected manually daily. These rainfall records were then used in the hydrological analysis to calculate the design flood discharge for each dam [17]. In this context, the annual maximum daily rainfall was derived from one or more rain stations associated with each dam.

2) Dam Technical Data

Most dam failures have occurred in earthen dams. Various factors can trigger such failures, including overtopping and internal erosion (piping) [1]. The following data are required for the analysis:

1. Annual maximum daily rainfall data at each rain station post, which are used as the primary data in calculating the design flood discharge contained in the 12 dams/reservoirs studied.
2. The technical characteristics of each dam were determined through a combination of field-based and documentary sources. Specifically, on-site surveys were conducted to gather primary data regarding the structural and operational features of the dams. These were supplemented by interviews with on-duty dam personnel to capture the local insights and operational history. Additional secondary data were obtained from official records provided by the Ministry of Public Works and Public Housing, ensuring a comprehensive understanding of each dam's design, capacity, and current condition.
3. Reservoir capacity curve current.
4. An isohyetal PMP map of the dam area was used. The corresponding value was compared with the calculated PMP to determine the design flood discharge, set at 0.5 of the PMF.
5. Digital Elevation Model (DEM) data and the results of topographic measurements of the river downstream of the dam are used to depict the conditions downstream of the dam in dam break modeling.
6. A national map of Indonesia was used to identify the areas affected by the potential dam collapse and to classify the dam's hazard level accordingly.
7. Population and infrastructure data downstream of the dam.

B. Methods

In this study, hydrological analysis was conducted using data from rain stations available at each dam. Prior to analysis, the consistency of the rainfall data was tested using the Rescaled Adjusted Partial Sums (RAPS) method, and an outlier test was also applied. The regional average rainfall was then determined deploying the arithmetic mean method. Frequency analysis was performed using the Normal, Log-Normal, Log-Pearson Type III, and Gumbel distributions. The goodness of fit for each distribution was evaluated employing the Smirnov-Kolmogorov and Chi-Square tests to identify the most appropriate design rainfall [16]. The flood discharge was subsequently estimated using the Nakayasu Synthetic Unit Hydrograph and the Gama I Synthetic Unit Hydrograph. Following this, flood routing was carried out to assess the possibility of dam overtopping. After completing the hydrological analysis, a flood simulation was performed utilizing the HEC-RAS Mapper software. The results included a flood inundation map, arrival time, peak time, flood depth, velocity, water surface elevation, and cross-sectional profiles. Based on the inundation distribution, the affected downstream villages were identified.

1) Design Flood Discharge

The Unit Hydrograph method is used in the analysis to estimate the design flood when only rainfall data are available. This approach is widely adopted due to its simplicity, ease of implementation, and relatively low data requirements. Despite its simplicity, it can provide reasonably accurate flood discharge estimations. In this study, the Nakayasu Synthetic Unit Hydrograph was employed to determine the peak flood discharge [14–18].

$$Q_p = \frac{A.R_0}{3.6(0.3T_p + T_{0.3})} \quad (1)$$

$$T_p = t_g + 0.8t_r \quad (2)$$

$$t_{0.3} = \alpha.t_g \quad (3)$$

$$t_g = 0.4 + 0.058L, for\ L > 15\ Km \quad (4)$$

$$t_g = 0.21L^{0.7}, for\ L < 15\ Km \quad (5)$$

The flood peak discharge (Qp, m³/s) is estimated using key hydrological parameters, including unit rainfall (R_0, mm), grace period from rainfall onset to peak (T_p, h), and recession time to 30% of peak discharge ($T_{0.3}$, h). The contributing Catchment Area (CA) is denoted as A (km²), while t_g represents the time lag between the rainfall and flood peak (h), and t_r indicates the effective rainfall duration (0.5–1.0 tg, h). The coefficient α reflects the watershed-specific characteristics and hydrograph response behavior.

2) Dam Break

Before the dam experiences a total break, it is preceded by the occurrence of breaching. Froechlich's regression equation for the average breaching width and breaking time is [15, 19]:

$$B_{ave} = 9.5 \cdot K_0 \cdot ((V_r \cdot hd)^{0.25}) \quad (6)$$

$$TIME_{BF} = 0.8((Vr/\ hd^2)^{0.5}) \quad (7)$$

The average breaching width (B_{ave}, m) is estimated to use several key parameters. K_0 is an empirical constant, typically valued at 1.3 for overtopping failure and 1.0 for piping failure mechanisms. Vr represents the reservoir storage volume at the time of failure (m³), while hd denotes the final breaching height (m). The parameter Tf corresponds to the breach formation time (s), capturing the temporal evolution of the dam failure.

3) Dam Hazard Classification

The determination of the level class was based on the number of population at risk/PenRis (population exposed to risk, namely residents or people living in areas affected by flood inundation). The population at risk is the entire population in the downstream region of the dam that is threatened or affected by danger in the event of a dam breaking. Inundation maps from dam break studies can identify the population at risk. The level of dam hazard is obtained from the relationship between the number of populations at risk in life/person or the Head of the Family/KK (1 KK = 5 people) and the distance of the population at risk location from the dam [20].

III. RESULTS AND DISCUSSION

A. Hydrological and Hydraulics Analysis

Figure 3 shows one of the hydrological analysis results for calculating the flood discharge QPMF (1845.87 m^3/s) and flood routing at Ciawi Dam. Figure 4 displays the results of the flood inundation scenario downstream due to the Ciawi Dam collapse, based on the DEM data used. The complete calculation results of 12 dams are tabulated in Table I, which denotes the variable of CA, QPMF flood discharge, height, reservoir storage volume, reservoir inundation area, and flood inundation area downstream if the dam breaks/collapses due to overtopping based on the latest hydrological and hydraulics analysis, using RAS-MAPPER. Each dam has a varying height depending on the topographic conditions of the field. Generally, a high dam will produce a large reservoir storage volume, and vice versa. Based on the analysis of 12 dams, the following correlation graph is obtained.

The relationship between the dam height and reservoir storage was analyzed using exponential regression modeling, specifically through a second-degree exponential equation that captures the nonlinear nature of this association. The derived equation is:

$$S_1 = 4.6584 + e^{0.0354H} \quad (8)$$

where S_1 is reservoir storage at High Water Level (HWL) (10^6 m^3) and H is the dam height (m).

The results indicate a strong positive relationship between the dam height and the practical storage capacity of the reservoir. Specifically, the coefficient of determination (R^2) was calculated as 0.8785, implying that approximately 87.85% of the variability in the reservoir storage can be attributed to variations in the dam height. This high level of correlation highlights the dominant role of the dam height in determining the storage potential. Nonetheless, this relationship should not be interpreted as universally deterministic. Previous studies have emphasized that factors, such as the catchment hydrology, rainfall variability, geological conditions, and especially the sedimentation dynamics can substantially alter the storage performance over time [21]. Therefore, further empirical analysis across different climatic and geological settings is necessary to validate and refine this observed correlation [21].

The results of the analysis regarding the dam height can be conceptually divided into three phases: low, intermediate, and high. These phases are consistent with established findings in hydrological research. For dam heights below approximately 20 m, the increases in storage capacity are relatively limited, as smaller dams generally do not have a significant impact on the flow regulation or storage dynamics. This observation aligns with previous studies that highlight the limited operational performance of low-elevation structures [22]. In the intermediate range (20–50 m), the reservoir storage exhibits greater sensitivity to the changes in the dam height, suggesting more pronounced volumetric gains with increasing elevation [23]. For dam heights exceeding 50 m, the storage capacity increases substantially due to nonlinear gains associated with elevated dam configurations and the larger CAs they typically serve [24, 25].

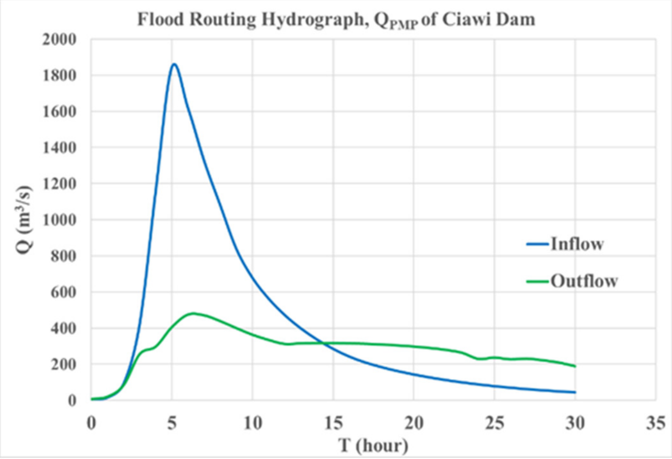


Fig. 3. Flood routing hydrograph analysis at Ciawi Dam under PMF conditions.

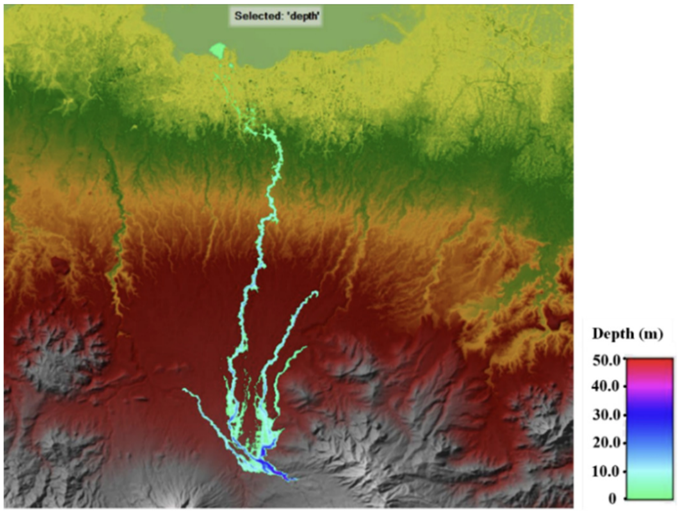


Fig. 4. Downstream flood inundation from Ciawi Dam failure under HWL scenario simulated in HEC-RAS mapper.

Engineering considerations regarding the design efficiency and optimization become particularly relevant in this context. The nonlinear benefits identified suggest that while increasing the dam height generally optimizes storage, engineers must also contend with the rising costs and structural constraints associated with taller dams. This point is supported by insights indicating that while taller structures may maximize the reservoir volume, they could also amplify the engineering complexities and project costs [23]. As noted in [26], the flow dynamics influenced by varying dam heights require careful engineering considerations to maintain the operational effectiveness, particularly in sediment management.

The relationship between the dam height and reservoir storage informs the engineering design and necessitates ongoing sediment management to sustain effective operation over time. The analysis emphasizes the importance of examining the sediment dynamics in dam operations, especially considering the climate variability that may further impact the reservoir efficiency during extreme weather events [24]. The results of the analysis are presented in Figure 5. So, the detailed exploration of how the dam height affects the reservoir storage capacity is substantiated by existing literature illustrating the practical applications and theoretical implications of these relationships in hydrology and civil engineering.

TABLE I. RESULTS OF HYDROLOGICAL AND HYDRAULIC ANALYSIS WITH THE RAS MAPPER COLLAPSE MODEL

No	**Name of DAM**	**CA** (km^2)	**Q PMF** (m^3/s)	***H*** (m)	***S$_1$*** (10^6. m^3	***Ag*** (ha)	***A$_{o\text{-}flood}$*** (ha)
1	Malahayu	61.96	1599.81	29.75	29.11	943.67	16032.26
2	Salomekko	13.2	753.86	30	10.34	850.70	1569.40
3	Pandanduri	64.51	1673.54	42	31.14	322.50	8861.12
4	Banyukuwung	11.75	478.57	13.5	3.19	95.63	1423.72
5	Batujai	56.45	2036.15	15	12.26	520.50	3412.66
6	Pengga	177.594	3204.09	18	7.48	1196.00	10702.47
7	Ciawi	88.5	1845.87	51	6.45	39.02	10803.87
8	Gembong	15	724.14	36	9.50	109.29	5468.20
9	Rukoh	19.63	517.10	85	128.65	687.37	23737.34
10	Bintang Bano	212	2625.89	72	65.40	277.52	5714.14
11	Muka Kuning	9.7373	463.60	16.75	13.05	186.78	1811.00
12	Darma	25.85	300.32	35.5	37.90	411.62	5104.10

Where CA denotes the CA, Q_{PMF} represents the PMF discharge, H is the dam height, S_1 refers to the reservoir storage at high water level, Ag is the reservoir inundation area, and Ao-flood is the extent of downstream flood inundation due to overtopping. The relationship between the dam height and storage volume under HWL conditions also results in a strong relationship with an excellent coefficient of determination, R^2=0.9047. The relationship fulfills:

$$S_1 = 1.8918 * e^{0.048H} \tag{9}$$

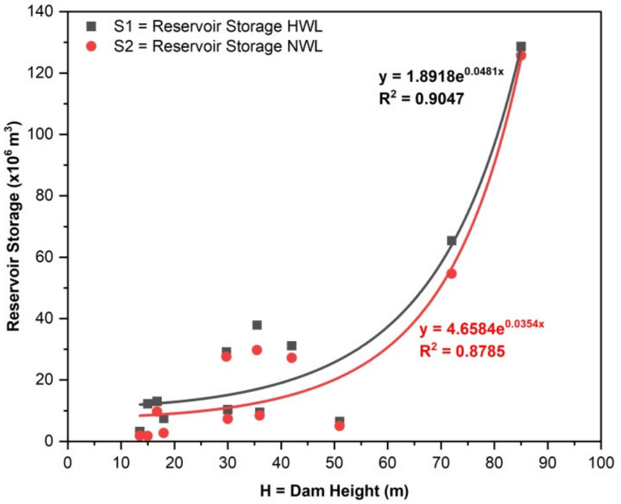


Fig. 5. Relationship of dam height to reservoir storage (HWL condition).

B. *Relationship Between Catchment Area and Flood Discharge*

The watershed area is generally strongly correlated with the magnitude of the flood discharge from dams, as larger CAs tend to produce greater runoff volumes. In the case of the 12 dams analyzed in this study. The following results were observed, as illustrated in Figure 6.

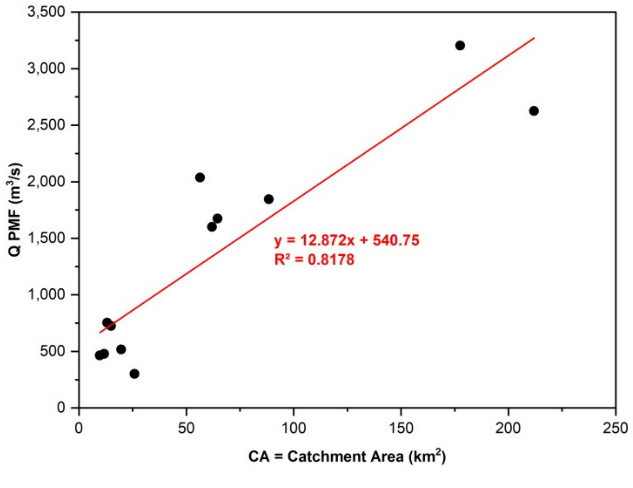


Fig. 6. Relationship between CA and flood discharge (Q_{PMF}).

The relationship between CA and Q_{PMF} is well-established in hydrological studies, as larger watershed areas typically generate higher flood runoff. In the analysis of the twelve dams in Indonesia, a strong linear correlation was observed, with an R² of 0.8178. This suggests that approximately 81.78% of the variation in the peak maximum flood discharge can be attributed to the differences in CA. The relationship was modeled using a linear regression equation:

$$Q_{PMF} = 12.872 * \mathrm{CA} + 540.75 \quad (10)$$

According to (10), for every additional m² of CA, the PMF discharge increases by approximately 12.87 m³/s. In contrast, a baseline discharge of around 540.75 m³/s accounts for other influencing factors beyond the catchment size, such as the local rainfall intensity, terrain slope, and land use. These catchment characteristics, particularly the area and land cover are critical in flood risk assessment [27–29].

It has been shown that scaling relationships for flood parameters can be used to estimate the magnitude of the peak floods, highlighting the importance of geophysical characteristics in peak discharge estimations [27]. This supports the observed strong relationship between the catchment size and flood discharge, which enables more effective flood risk management strategies through established monitoring networks in upper catchments. Furthermore, the predictive potential of analyzing the flood discharges within nested basins is consistent with the direct relationship between the CA and Q_{PMF} identified in [29].

The influence of climatic and hydrological conditions on the flood peaks has been extensively studied, contributing to a theoretical framework that supports the present findings. Factors, such as land use patterns within the catchment, have been identified as essential for developing a comprehensive understanding of the flood behaviour [30]. Additionally, the catchment characteristics have been shown to significantly affect the water management strategies, reinforcing the need to incorporate such variables into the dam safety assessments [31].

The practical implications of this study highlight the importance of CA as a key parameter in estimating the peak flood discharge, particularly in the Indonesian context. This finding aligns with literature advocating for engineered flood management solutions and dam safety protocols tailored to the regional hydrology [32–34]. Accordingly, CA data serve as a valuable input for preliminary flood risk assessments and dam design planning, especially in regions vulnerable to hydrological variability. Overall, the observed correlation between the catchment size and flood discharge is strongly supported by hydrological literature, underscoring its relevance in both early-stage evaluations and long-term infrastructure management strategies.

C. Relationship Between Reservoir Storage Volume and Downstream Flood Inundation Under Overtopping and Piping Failure Scenarios

The relationship between the reservoir storage volume and downstream flood inundation due to overtopping and piping is a critical area of study in the dam safety and flood management. Analyzing this relationship reveals significant findings about how the floodwater's behavior correlates with the reservoir storage capacity. From the results depicted in Figure 7, it was determined that the correlation between the reservoir storage at HWL elevation (S_1) and the area affected by the flood inundation due to overtopping ($A_{o-Flood}$) possesses a coefficient of determination of R^2=0.5373, translating to a correlation coefficient (r) of approximately 0.733:

$$A_{o-Flood} = 1.0906(S_1)^2 - 7.155(S_1) + 5852.6 \quad (11)$$

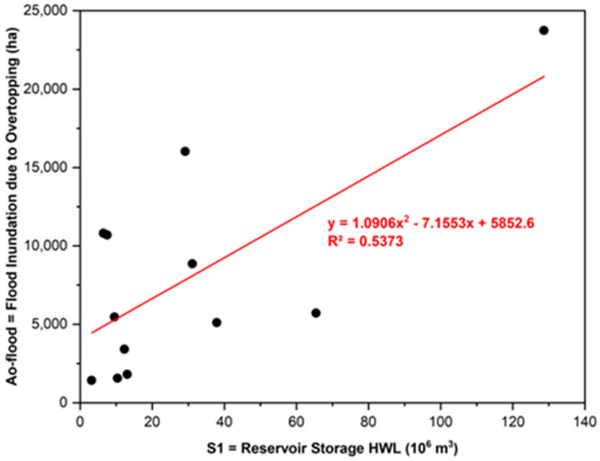


Fig. 7. Relationship between reservoir storage volume and downstream flood inundation caused by overtopping.

This indicates that while approximately 54% of the variation in flood inundation can be explained by the reservoir storage, other factors including topography, floodplain characteristics, breach parameters, and local hydrology also play influential roles. Studies highlighting the complexity of the flood dynamics, emphasizing that the reservoir storage is vital but insufficient alone to predict flood outcomes, corroborate this. Furthermore, the analysis regarding the piping-induced collapse leading to an inundation ($A_{p-Flood}$) presents a coefficient of determination of R^2 = 0.4859, with the relationship modeled by:

$$A_{p-Flood} = 1.0906(S_1)^2 - 133.03(S_1) + 3532.2 \quad (12)$$

This suggests that while there is a moderate correlation, other critical variables must be considered in flood risk assessments. The finding that the inundation areas can increase rapidly with increasing storage volume stems from real phenomena observed during dam failures, where larger reservoirs can release significantly larger volumes of water, presenting a challenging scenario for flood management [35]. The trend observed, where inundation areas generally remain below approximately 10,000 Ha at lower storage volumes (< 20 million m³) but spike sharply at higher volumes, aligns with the existing literature on reservoir operations and failure scenarios. For instance, it has been discussed how reservoir operations significantly impact the floodplain inundation, emphasizing the need for effective planning based on empirical data from the dam operations [36].

The need for comprehensive modeling is emphasized since the dam characteristics, including reservoir volume, directly influence the flood risk and inundation potential downstream [37]. As such, engineers and planners must prioritize robust safety measures and emergency response strategies for larger reservoirs to mitigate the exponentially higher risks present during potential dam failures. This aligns with the findings in [38], where the importance of reservoir management strategies that account not only for storage volume, but also for local geographical and hydrological complexities was emphasized. Thus, the findings underscore the potential risks associated with larger reservoir capacities and the need for detailed flood risk assessments that consider the storage volume and surrounding environmental factors. The regression equations derived from the analysis provide valuable tools for estimating the flood extents based on the storage capacity, reinforcing the need for a multidisciplinary approach in flood risk management and dam safety assessments.

D. Relationship between Dam Height and Downstream Flood Inundation Due to Overtopping

Analyzing the relationship between the dam height and downstream flood inundation due to overtopping is crucial for understanding the flood risk associated with the dam structures. The results illustrated in Figure 8, reveal a significant correlation, with a coefficient of determination (R^2=0.4347), indicating that approximately 43.47% of the variation in flood inundation area (($A_{o-Flood}$) can be explained by the dam height. The exponential equation describes the established relationship:

$$A_{o-Flood} = 2271 * e^{20.0024H} \quad (13)$$

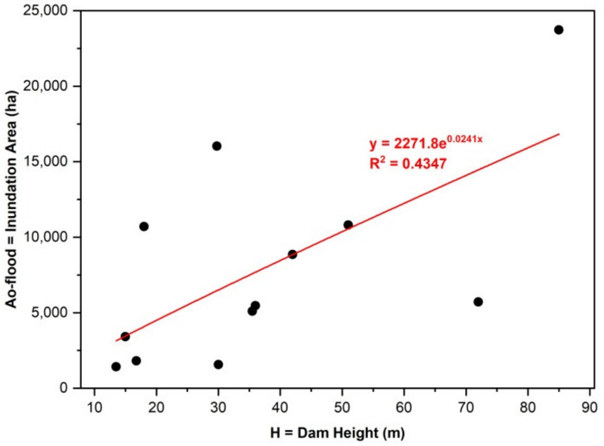


Fig. 8. Relationship between dam height and downstream flood inundation due to overtopping.

These findings indicate that while the dam height is a significant factor influencing the extent of flood inundation, other variables must also be considered. The observed correlation coefficient of 0.659 ($r > 0.5$) supports the conclusion that taller dams generally present a higher inundation potential in the event of failure, especially due to overtopping [39]. Previous studies have confirmed that the dam height has a substantial impact on the flood dynamics, demonstrating that increased height is associated with more severe downstream flooding. This is consistent with the regression results of the present analysis, which show a disproportionate increase in the inundation area as the dam height rises reinforcing the practical relevance of the dam height as a key design parameter in flood risk management.

The importance of the dam height in flood inundation dynamics particularly during breach events and their associated hydraulic characteristics has been well established, emphasizing the complex ways in which the dam infrastructure influences the flood impacts [6]. Nevertheless, while dam height shows a strong correlation with the inundation extent, other factors, such as the local topography, hydrological conditions, and specific design features of the dam also play critical roles in shaping the overall flood risk profile [40, 41].

E. Simultaneous Equation Analysis of Flood Inundation Area Downstream

The simultaneous equation analysis of the flood inundation areas downstream, as related to independent variables, such as the dam height and reservoir storage area, is crucial for understanding the flood dynamics and risk management. The foundational equation employed for the multiple regression analysis can be represented as:

$$Y = a + b_1 x_1 + b_2 x_2 \quad (14)$$

where (Y) is the dependent variable, specifically the flood inundation area, and x_1 , x_2 represent independent variables, including the dam height (H) and storage area (Ag) of the reservoir. The derived simultaneous equation is:

$$A_{o-Flood} = 3393.676 + 198.555\,(H) + 8.293\,(Ag) \quad (15)$$

As shown in (15), there is a noteworthy correlation, with an R value of 0.752 and an R^2 of 0.565, indicating that the specified independent variables, namely the dam height and reservoir storage can explain 56.5% of the variance in the downstream flood inundation area. These results reflect a substantial relationship between the structural dam parameters and their combined influence on flood dynamics [42, 43].

The method employed in this work underscores the necessity of robust statistical techniques for model validation. The statistical significance indicated by the ANOVA results, with (F=5.193) and a significance level of ($0.036 < 0.05$), supports the rejection of the null hypothesis ($H0$) and the acceptance of the alternative hypothesis ($H1$), demonstrating that the dam height and storage area significantly influence the flood inundation area downstream. This is crucial for effective flood risk management where dam safety is concerned; understanding these relationships provides insights into making informed structural and non-structural decisions regarding the flood mitigation [36-44]. Collinearity tests yielding (VIF <10) reinforce the stability of the regression model, highlighting that the relationship between the independent variables is strong without multicollinearity issues. Additionally, the results of the (t)-tests affirm the significance of both the dam height and storage area concerning the flood impacts, suggesting that these parameters play vital roles in assessing the flood risks associated with the dam performance during extreme weather events [45, 46].

Moreover, practical implications drawn from this analysis emphasize the necessity of implementing structural safety measures. Enhancements to spillway capacity, adequate freeboard maintenance, and reinforced downstream structures are proposed to mitigate the risks of overtopping and catastrophic failure. Early warning systems, emergency action plans, and effective catchment management are essential non-structural strategies that can further safeguard communities vulnerable to flooding [47, 48]. Furthermore, examining historical case studies, like the Situ Gintung Dam failure in Indonesia and the Vajont Dam disaster in Italy reveals critical lessons regarding the importance of thorough risk assessments, community awareness programs, and proactive geological evaluations during dam design and operation [49]. In summary, the simultaneous equation and multiple regression analyses elucidate the robust relationships between the dam characteristics and flood inundation risks, underscoring the need for comprehensive management strategies prioritizing the structural integrity and community safety.

IV. CONCLUSION

This study has developed the first comprehensive empirical model linking the reservoir storage volume to downstream flood inundation area for multiple dam-break scenarios in Indonesia. By examining 12 representative earthfill dams across diverse regions and hydrological settings, the research addresses a critical knowledge gap: previously, there were no empirically based inundation models applicable to more than a single dam in the Indonesian context. The methodology combined detailed hydrological and hydraulic simulations using HEC-RAS with regression analysis, deriving volume–area relationships that apply to overtopping and piping failure scenarios. This multi-dam modeling approach is novel, as earlier studies in Indonesia were mainly limited to individual case studies or theoretical analyses. Integrating structural variables, such as dam height and reservoir capacity, with hydrological factors, like catchment size and extreme inflows, into a unified regression framework is a key contribution of this work, yielding a practical empirical model for predicting the flood extent from the reservoir volume.

The results confirm that the dam characteristics, especially dam height and reservoir size, strongly influence the magnitude of flood inundation. In the performed analysis, taller dams with larger storage volumes tend to produce significantly more extensive downstream flooding when they fail. The derived volume–area relationships indicate that the initial reservoir storage can explain a substantial portion of the variance in the flood inundation area. The model showed a moderate-to-strong correlation between the reservoir volume and inundated area for overtopping failure conditions, while a similar trend was observed for piping-induced failures. These findings underscore that while the reservoir volume is a dominant predictor of the flood extent, other factors, such as downstream topography, breach formation dynamics, and floodplain characteristics, also affect the exact inundation footprint. Nonetheless, the study successfully demonstrates an empirical means to estimate the flood-inundation areas across different dam sites, which marks a significant step forward in dam-break flood modeling for Indonesia. This contribution is especially noteworthy given the range of dam sizes and catchment environments considered, reinforcing the model's relevance across various scenarios.

The practical implications of this work are substantial for the dam safety management and policy. The new volume–area model can be directly applied in dam safety assessments to rapidly gauge potential downstream flood hazards based on a dam's reservoir capacity, improving the risk evaluation for existing and planned dams. This empowers engineers and decision-makers to identify high-risk dams, such as large earthfill reservoirs, and to design more effective early warning systems by linking real-time reservoir levels to predicted inundation zones. Communities downstream of large dams could receive timelier alerts and better evacuation planning, as the empirical relationships help translate the reservoir conditions into expected flood impacts. On a national infrastructure level, these findings provide evidence-based guidance for policymakers: the results can inform updates to Indonesia's dam safety regulations and emergency action protocols, ensuring they account for the scale of potential inundation revealed by a dam's storage volume. In summary, the study's multi-dam empirical modeling approach leveraging HEC-RAS simulations and regression across numerous sites offers a novel and valuable tool for improving the resilience of dam infrastructure. It fills a crucial gap in Indonesian water-resources engineering by providing a data-driven relationship between the reservoir size and flood impact, strengthening the foundation for safer dam design, more effective emergency preparedness, and informed national water infrastructure policy.

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