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EVALUATION OF TUKUL DAM SLOPE STABILITY IN PACITAN UNDER THE IMPACT OF CLIMATE CHANGE

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Abstract

This aim of this study is to evaluate the impact of climate change on the hydrological, hydraulic, and slope stability conditions of the Tukul Dam in the Kali Telu watershed, Pacitan. The methodology includes hydrological analysis using the Log Pearson Type III distribution, flood discharge estimation with the HSS Nakayasu method, and hydraulic simulation using HEC-RAS to determine maximum floodwater elevation. Slope stability was analyzed with Geostudio using the Bishop method to determine the factor of safety (FS). The results indicate that the maximum 1,000-year rainfall reaches 550.82 mm, generating a peak discharge of 1,152.26 m^3/s, exceeding the design discharge of 380.73 m^3/s. Hydraulic simulation showed a floodwater elevation of +183.59 meters, while slope stability analysis confirmed that all FS values remained above the safe limit of 1.30, ensuring dam stability. This study integrates updated hydrological data with geotechnical modeling to enhance understanding of dam resilience under extreme conditions. Recommendations include spillway capacity improvements, early warning systems, and continuous monitoring to mitigate future flood risks.

Keywords: Climate change, flood discharge, slope stability, HEC-RAS, Geostudio

Introduction

Indonesia, strategically located between two continents and two oceans, experiences a distinct climate that makes it highly vulnerable to climate change and extreme weather events. Rising global temperatures, sea level increases, and shifting rainfall patterns have intensified the frequency and severity of natural disasters, particularly flooding. Floods are among the most destructive hazards, causing significant damage to infrastructure, economic losses, and human casualties. For instance, in 2017 alone, Indonesia recorded 2,341 disaster events, resulting in 377 fatalities, the displacement of over 3.4 million people, and material losses amounting to trillions of rupiah (Helmi et al., 2019; Resosudarmo et al., 2013). Recent studies suggest that climate change will further exacerbate flood risks due to more erratic precipitation and rising sea levels (Kelly Levin et al., 2021). With over 60% of districts classified as flood-prone , the urgency for effective flood mitigation strategies has never been greater to safeguard communities and infrastructure against future disasters.

Pacitan Regency, situated in the southwestern part of East Java, is highly vulnerable to natural disasters due to its geographical and climatic conditions. It ranked fifth among disaster-prone areas in East Java in 2013, as reported (Nur Aini et al., 2018). Flooding is a particularly significant hazard, classified as high-risk with a score of 16.5 in the National Disaster Risk Index (Badan Nasional Penanggulangan Bencana, 2018). The region also faces risks from landslides and tsunamis due to its mountainous terrain and proximity to coastal fault lines (Karnaji et al., 2024; Nugraha Putra et al., 2021; Nurjannah et al., 2019). To address these challenges, the Indonesian government has initiated infrastructure projects like the Tukul Dam in Pacitan. These efforts aim to mitigate flood risks and improve water resource management. Such measures are crucial for reducing disaster impacts and enhancing community resilience(Nugraha Putra et al., 2021; Nurjannah et al., 2019).

The Tukul Dam, located in Karang Gede Village, Arjosari District, East Java, has faced increasing climate resilience challenges since its operation began in 2020, primarily due to discrepancies between its original hydrological design—based on pre-2011 rainfall data—and more recent environmental shifts. Updated data from the Nawangan Station indicate a rise in maximum rainfall from 105 mm (2007–2011) to 151 mm (2012–2016), raising concerns about the dam's flood storage capacity, water elevation thresholds, and slope stability (BMKG Jawa Timur, 2016). Additionally, since 2021, watershed erosion hazards have surged by 44%, with 18% of the area now classified as "very heavy" erosion zones, accelerating sedimentation rates to 3.55 mm/year and reducing the reservoir's projected lifespan to just 28 years (Gunawan et al., 2024). Over the past 34 years, regional temperature increases exceeding 1.21°C, with 2016 marking peak anomalies in both rainfall intensity and extreme heat, have further exacerbated hydrological uncertainties and flood risks (Ananta et al., 2024). The combined pressures of land-use changes (Gunawan et al., 2024; Muharis & Utamaningsih, 2023) and climatic volatility necessitate an urgent reassessment of the dam's flood discharge capacity (Ananta et al., 2024; Huseiny et al., 2024), water level thresholds, and slope stability protocols using updated climate models and real-time sedimentation monitoring (Petkovsek, 2023) to ensure its long-term safety and operational sustainability (Mosaid et al., 2024).

Recent studies underscore the critical role of accurate hydrological evaluations and stability assessments in dam safety management, particularly through comprehensive risk analysis frameworks (Gabriel-Martin et al., 2019; D. Yang et al., 2024). The Nakayasu Synthetic Unit Hydrograph (HSS Nakayasu) method has demonstrated reliability in estimating flood discharge for river basins with moderate hydrological conditions, as evidenced by applications in Indonesian watersheds (Arafat et al., 2020; Hidayat et al., 2022; Safarina, 2012). Hydraulic modeling tools like HEC-RAS enable precise flood elevation predictions, which are vital for assessing overflow risks and structural integrity (Ansori, 2023; Ansori et al., 2024). HEC-RAS was chosen due to its capability to accurately model unsteady flow dynamics and its established credibility in hydraulic and dam safety analyses. Furthermore, slope stability analyses using advanced computational methods contribute to evaluating dam resilience under extreme hydrological scenarios, supported by integrated risk assessment approaches (M. Eddleston, 2012; Psarropoulos et al., 2024; H. Yang et al., 2025).

This study is essential in addressing the emerging risks posed by climate change to the Tukul Dam's stability. By integrating updated hydrological data with advanced hydraulic and geotechnical modeling, it offers a more comprehensive and realistic evaluation of the dam's safety and effectiveness in flood mitigation under evolving climatic conditions. The novelty of this research lies in this integrative approach, which enables a multidimensional assessment of structural resilience—beyond what static or outdated models typically provide. The findings are expected to serve as a critical reference for future dam safety evaluations and climate-adaptive disaster mitigation planning in Indonesia.

Research Methods

This research employs a quantitative approach with a case study design to analyze the stability of the Tukul Dam under the influence of climate change. The study was conducted in Pacitan, East Java, utilizing updated hydrological data from Nawangan and Kerti rainfall stations, covering the period from 2003 to 2020. These data were used to estimate maximum rainfall intensity and design flood discharges for return periods up to 1,000 years. Hydrological analysis was performed using the Nakayasu Synthetic Unit Hydrograph method, while hydraulic simulations were conducted with HEC-RAS, based on design inflow and outflow discharge estimates derived from extreme rainfall events. Slope stability analysis was conducted using GeoStudio 2021, particularly the SLOPE/W module. Eight representative cross-sections of the main dam were modeled to evaluate the dam's structural integrity under extreme flood conditions. The analysis was performed under static loading and drained conditions, appropriate for long-term slope stability assessment where pore pressures dissipate gradually, with the Mohr-Coulomb failure criterion applied to represent soil behavior. Geotechnical parameters used in the analysis were sourced from direct shear tests documented in the official design reports of the Tukul Dam, prepared by PT. Global Parasindo Jaya. These parameters are presented in the following table.

Table 1. Summary of Geotechnical Parameters Used in Stability Modeling

No	Material Type	Unit Weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)	Permeability (m/s)
1	Impervious Core	16.94	25.20	18.23	3.98×10^{-9}
2	Random Fill	17.03	4.41	36.87	3.60×10^{-4}
3	Filter Layer	17.72	7.55	37.10	5.05×10^{-6}
4	Rock Toe	21.52	1,071.57	32.74	5.00×10^{-4}
5	Foundation	20.36	1,071.57	32.74	1.00×10^{-7}

The model incorporated a piezometric line representing flood-induced pore water pressures, based on maximum water surface elevations derived from hydraulic simulations using HEC-RAS. Slip surfaces were generated using the Entry and Exit method, and the Factor of Safety (FS) was calculated for both upstream and downstream slopes across multiple depth ratios (Y/H = 1.00, 0.75, 0.50, and 0.25). The calculated FS values were evaluated against the minimum safety requirement of 1.30, in accordance with SNI 8460:2017.

Research Results and Discussion

The hydrological, hydraulic, and slope stability analyses of Tukul Dam were conducted to assess the impact of climate change on rainfall patterns, flood discharge, water flow behavior, and structural stability within the Kali Telu watershed. The hydrological analysis utilized rainfall data from Nawangan and Kerti stations, the only stations within the watershed boundary, to determine rainfall characteristics and flood potential. Using the Thiessen Polygon method, the highest recorded rainfall was found to be 254 mm in 2017. The Log Pearson Type III method projected a maximum rainfall of 550.82 mm for a 1,000-year return period. This result confirmed a sharp increase in extreme rainfall events that may significantly influence flood risks. This pattern corresponds with prior research indicating that recent climatic shifts have increased rainfall variability and the frequency of extreme precipitation events, increasing the likelihood of severe flooding (Risal Ardiansyah Putra et al., 2021; Tabari, 2020; Wasko & Sharma, 2017).

Figure 1 illustrated the increasing trend in maximum rainfall across different return periods, demonstrating a marked rise in extreme precipitation events. This trend suggested that future flood events could exceed the dam's original design capacity. Rainfall intensities increased sharply at shorter return periods and gradually stabilized at longer intervals, reinforcing concerns about the influence of recent climatic variability on hydrological extremes. These findings on intensified rainfall patterns and return period behavior aligned with global studies, which indicated that warmer atmospheric conditions enhanced moisture retention and intensified storm events (Westra et al., 2014). With projected increases in peak rainfall, dam safety assessments must incorporate updated hydrological models and adaptive flood mitigation strategies (Gabriel-Martin et al., 2019; Petrovic et al., 2022).

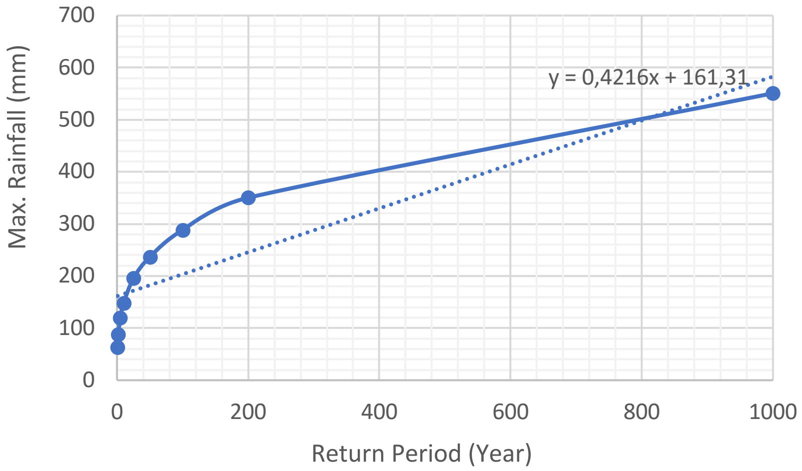


Figure 1. Maximum Design Rainfall Across Different Return Periods

The flood analysis, conducted using the Nakayasu Synthetic Unit Hydrograph (HSS Nakayasu) method, estimated peak flood discharges based on key watershed characteristics, including an area of 47.8 km², a main river length of 17.5 km, and a runoff coefficient of 0.85. The analysis showed that peak discharges vary across return periods, with a 1-year return period resulting in a peak discharge of 132.66 m³/s, a 10-year return period at 308.74 m³/s, a 100-year return period at 603.03 m³/s, and an extreme 1,000-year return period reaching 1,152.26 m³/s—far exceeding the original dam design capacity of 380.73 m³/s. Figure 2, the Nakayasu flood discharge hydrograph, highlights that flood peaks occur within the first five hours, emphasizing the need for rapid flood management responses to prevent structural overload (Ansori, 2023; Idfi et al., 2020; Indriani et al., 2021).

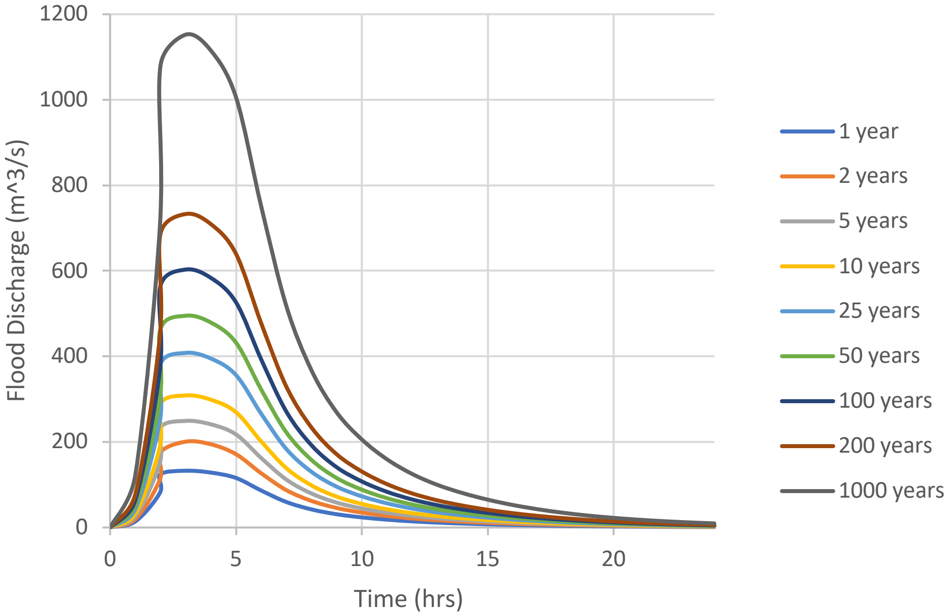


Figure 2. Nakayasu flood discharge hydrograph

The hydraulic analysis, conducted using HEC-RAS, provided detailed insights into flow behavior and structural response under extreme flooding conditions. DEMNAS data were incorporated to generate river cross-section models, while Manning's roughness coefficients were set at 0.035 for river sections and 0.014 for the dam structure. The simulation for the 1,000-year return period produced a maximum water surface elevation of +183.59 meters. This elevation exceeded the dam's current spillway threshold, indicating an increased risk of overtopping and associated structural stress (Aksoy et al., 2016; Ogras & Onen, 2020; Peker et al., 2024).

The slope stability analysis conducted across all modeled cross-sections of the Tukul Dam confirmed that the dam remains structurally stable under extreme flood scenarios, with all Factor of Safety (FS) values exceeding the minimum requirement of 1.30 in accordance with SNI 8460:2017. The area of greatest concern was identified on the downstream side of Section 8, where the lowest FS value—2.403—was recorded at a slip surface depth ratio of Y/H = 1.00. Despite being the lowest, this value remains well above the safety threshold. In contrast, the highest FS value of 3.870 was found on the upstream slope at Y/H = 0.25, indicating that shallower slip surfaces tend to exhibit greater stability.

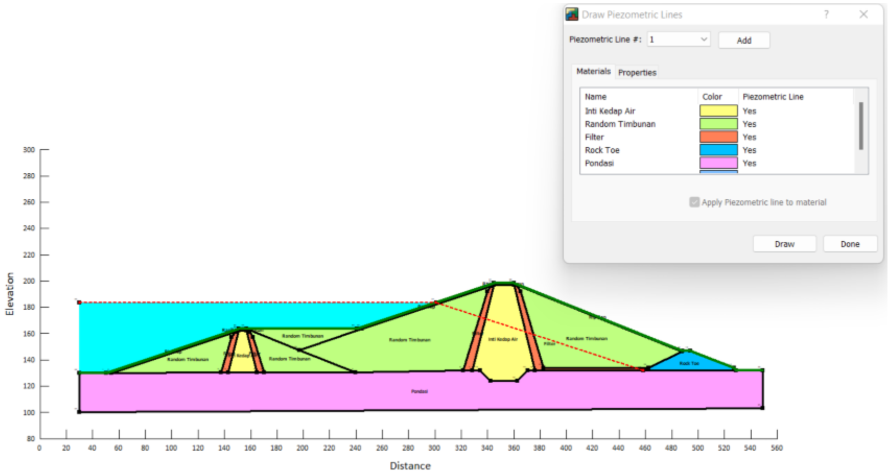
Table 1. Factor of Safety for Cross-Section 8 Under Extreme Flood Conditions

No	**Section**	**y/H = 1**	**y/H = 0.75**	**y/H = 0.50**	**y/H = 0.25**
1	Upstream	2.713	2.830	3.025	3.870
2	Downstream	2.403	2.409	2.684	3.756

Across all modeled sections, downstream slopes consistently exhibited lower FS values compared to upstream slopes, suggesting greater susceptibility to instability. A comparative analysis of FS values under pre- and post-climate change flood conditions revealed a significant reduction in safety factors, particularly on downstream slopes. This decrease is attributed to elevated pore water pressures resulting from increased flood elevations, which reduce soil shear strength and, consequently, slope stability over time (Kar & Roy, 2021; Mouyeaux et al., 2023).

Although the slope stability simulations in this study were performed under extreme flood conditions representing post-climate change scenarios (e.g., 1,000-year flood levels), no explicit baseline simulations were conducted for pre-climate change or normal operational water levels. However, comparative interpretation is still possible by evaluating the resulting Factor of Safety (FS) values against standard expectations. For example, FS values such as 2.403 at Y/H = 1.00 on the downstream slope of Section 8, although above the safety threshold of 1.30, indicate a significant reduction compared to what would typically be expected under dry or non-flooded conditions (often FS > 3.0). This suggests that increased pore water pressures caused by elevated flood levels have indeed diminished slope stability margins. The consistent pattern of lower FS on downstream slopes under these flood-induced pressures reinforces the need to reassess slope design criteria under evolving hydrological regimes (Hutama & Farichah, 2024).

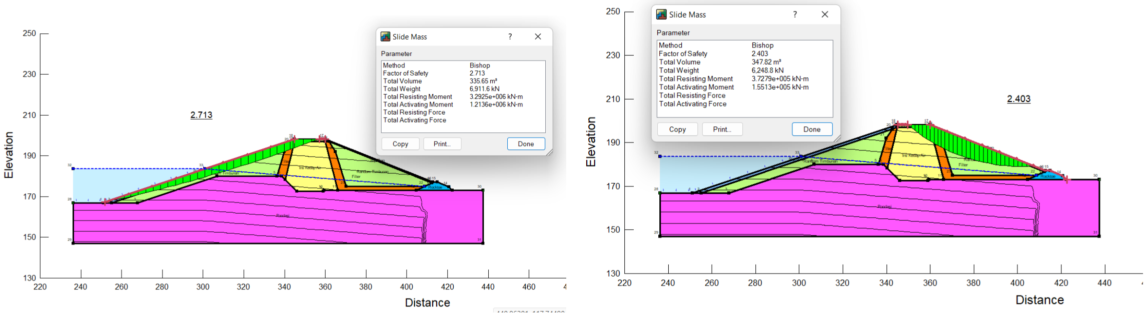
This behavior is further illustrated by the piezometric line simulation presented in Figure 3, which depicts the distribution of internal pore water pressure throughout the dam body under extreme flood conditions. The elevated water table generates higher pore pressures that reduce soil shear strength and increase the likelihood of slope failure.



Piezometric Line #: 1

Name	Color	Piezometric Line
Inti Kedap Air	🟨	Yes
Random Timbunan	🟩	Yes
Filter	🟧	Yes
Rock Toe	🟦	Yes
Pondasi	🟪	Yes

Figure 3. Piezometric Line Showing Internal Pore Water Pressure Distribution During Extreme Flood Conditions



Parameter	
Method	Bishop
Factor of Safety	2.713
Total Volume	335.65 m³
Total Weight	6,911.6 kN
Total Resisting Moment	3.2925e+006 kN-m
Total Activating Moment	1.2136e+006 kN-m
Total Resisting Force	
Total Activating Force	

Parameter	
Method	Bishop
Factor of Safety	2.403
Total Volume	347.82 m³
Total Weight	6,248.8 kN
Total Resisting Moment	3.7279e+005 kN-m
Total Activating Moment	1.5513e+005 kN-m
Total Resisting Force	
Total Activating Force	

(a) (b)

Figure 4. Failure Surface Visualization for Cross-Section 8: (a) Upstream Slope; (b) Downstream Slope

Failure mode visualizations for Section 8, shown in Figure 4, highlight the shape and location of critical slip surfaces. These results demonstrate the direction of potential movement and help identify structural zones most affected by hydraulic loading. These findings align with prior studies emphasizing the impact of pore pressure and flood elevation on embankment performance

(Gholamzade & Khalkhali, 2021; Pelascini et al., 2022; Wu et al., 2021). They underscore the need for proactive structural reinforcements, including spillway expansion, slope stabilization measures, and real-time pore pressure monitoring systems. The integration of updated flood forecasting models and early warning systems into dam operations is essential to ensure long-term safety and resilience in the face of increasing hydrometeorological extremes.

Conclusion

This study concluded that changing climatic conditions had significantly altered the hydrological and hydraulic characteristics of the Kali Telu watershed, particularly by increasing rainfall intensity and flood discharges; however, these changes did not substantially compromise the structural stability of the Tukul Dam's main embankment. The maximum flood discharge for the 1,000-year return period was calculated at 1,152.26 m^3/s, exceeding the original design capacity, while HEC-RAS simulations estimated a peak floodwater elevation of +183.59 meters. Despite these extreme conditions, slope stability analysis confirmed that all factor of safety (FS) values remained above the requirement, ensuring dam stability. These findings emphasize the need for continuous monitoring, adaptive flood management, and structural reinforcements to maintain long-term safety. Future research should incorporate real-time climate projections, assess sedimentation impacts on slope stability, and refine mitigation strategies. Practical implications include optimizing spillway design, strengthening early warning systems, and implementing adaptive maintenance to enhance the dam's capacity to withstand future hydrometeorological extremes.

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