Journal of Engineering Science and Technology
Special Issue on INCITEST2025 Vol. 21, No. 1 (2026) 137 - 144

HAZARD ZONE ANALYSIS DUE TO THE FAILURE OF MUKA KUNING DAM IN BATAM

VITTA PRATIWI[1,*], HAROMI MA'MUN[1],
NILUFAR PARDA QIZI OMONOVA[2]

[1]Universitas Komputer Indonesia, Indonesia
[2]Chirchik State Pedagogical University, Uzbekistan
*Corresponding Author: vitta.pratiwi@email.unikom.ac.id

Abstract

The Muka Kuning Dam in Batam City plays a crucial role in raw water supply, yet its proximity to densely populated settlements render it highly vulnerable to failure risks. This study aims to analyse flood hazard zones resulting from potential dam failure scenarios and to identify priority areas for mitigation. Hydrological modelling using HEC-HMS was conducted to generate peak flood hydrographs under overtopping and piping scenarios, while two-dimensional hydraulic simulations with HEC-RAS 2D were employed to estimate flood depth, flow velocity, and arrival time. Results show that the overtopping scenario produces the highest peak discharge of 6,117.849 m^3/s, with a maximum inundation depth of 13.3 m and flow velocities up to 3.9 m/s. Flood hazard classification based on KPTS (2011), FEMA (2020), and UNESCO guidelines indicates that most downstream areas fall within high-risk zones and are inhabited by more than 7,785 people within a radius of less than 1 km from the dam, who are recommended for relocation. These findings provide a critical foundation for disaster mitigation planning and the protection of communities in densely populated areas.

Keywords: Dam breach, Flood hazard, HEC-HMS, HEC-RAS, Muka kuning dam.

1. Introduction

Riau Islands Province's economic hub Batam City is projected to have an increasing demand for clean water commensurate with population growth expected to reach 1.8 million by 2025 [1]. Under scarce water resource-limited conditions, dam development has become a strategic solution to secure the uninterrupted provision of raw water [2]. A dam is, however, inherently a high-risk infrastructure; despite its critical function, when the structures fail, the fallout can be life-threatening, devastating economically, and cause long-term environmental degradation [3]. For embankment dams, the most generally experienced failure mechanisms include overtopping, internal erosion (piping), and structural or foundation breakdowns [4].

Muka Kuning Dam is a major water system in Batam, situated in very close proximity to residential as well as industrial settlements at around 10 m from nearby built-up zones. The site's spatial situation ranks the dam as a high-risk level, since any rupture can, in principle, endanger the safety of the public and downstream infrastructure. To mitigate this risk, the Indonesian government imposed a minimum safety setback from the edge of the dam at 50 m through Ministerial Regulation of Public Works and Housing No. 7 of 2023.

Therefore, as failure of a dam can have potentially severe repercussions, extensive failure analysis is the essential consideration in densely populated areas [5, 6]. Hazard assessment mainly uses relevant hydraulic parameters including flood depth, flow velocity, and flood arrival time. This study seeks to present a quantitative and spatial flood hazard map to guide the mitigation planning and spatial policy creation of the downstream regions associated with high risk for the dam failure.

2. Methodology

A case study is done on Muka Kuning Dam surrounding Sungai Beduk District, Batam City, Riau Islands Province, Indonesia. The downstream areas comprising inexpensive rental housing along with many industrial areas raises the likelihood of flooding in the case of dam breakdown. Hydrological and hydraulic analysis had been analysed with primary and secondary data, as the main datasets were digital elevation model (DEM), topographic breaklines, and land use data retrieved from the INA-Geoportal platform [7, 8] (see Fig. 1 and Table 1).

Table 1. Technical data of Muka Kuning dam (Reservoir operation certification, 2022).

No.	Dam Component	Value
1	Watershed Area (km²)	9.78
2	Dam Type	Homogeneous Earthfill
3	Crest Elevation	28.75 m
4	Normal Water Level Elevation	25 m
5	Effective Storage	6.29×10^6 m³

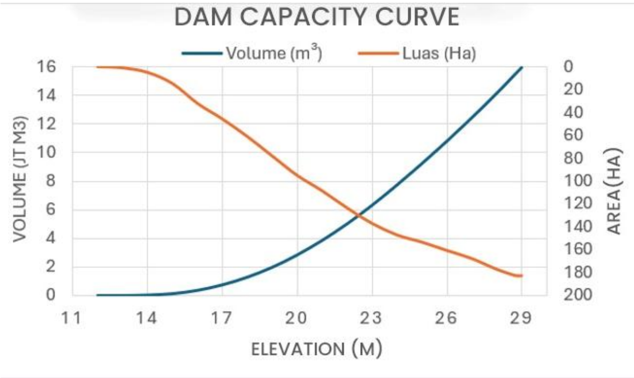

Fig. 1. Storage capacity curve of Muka Kuning dam.

Hydrological analysis was carried out using HEC-HMS. The design flood discharge was derived from three extreme rainfall scenarios, namely the 1,000-year return period, 0.5 Probable Maximum Precipitation (0.5 PMP), and PMP [9]. Return period rainfall was estimated through statistical frequency analysis using the Gumbel, Log-Normal, and Log Pearson Type III distributions in accordance with SNI 2415:2016, while PMP rainfall was calculated using the Hershfield method following SNI 7746:2012 as shown in Eq. (1-3). Surface runoff was computed using the Nakayasu, Snyder, and SCS Curve Number unit hydrograph methods, which are widely applied in Indonesia [10,11]. Dam breach modelling considered two failure scenarios, overtopping and piping. Breach parameters, including average breach width, breach height, side slope, and breach formation time, were determined using the Froehlich empirical method. This method was selected because it is based on 74 documented earthfill dam failure cases, representing construction characteristics comparable to those of the Muka Kuning Dam [7].

$$Bave = 0.27\,Ko\,Vw^{0.32}hb^{0.04} \tag{1}$$

$$B_{bottom} = B_{ave} - 2m\frac{hb}{2} \tag{2}$$

$$t_f = 63.2\sqrt{\frac{V_w}{g\,h_b^2}} \tag{3}$$

In this study, Bave represents the average breach width (m), Ko denotes the coefficient (1.3 for overtopping and 1.0 for piping), Vw is the dam volume (m^3), hb the water level within the dam (m), m the breach side slope, g the acceleration due to gravity (9.80665 m/s^2), and tf he breaches formation time (days). The study shows that, when looking at an overtopping scenario, the slope for a dam's side is assumed to be set to a ratio of 1H:1V, whereas for a piping scenario, is set to a slope ratio of 0.7H:1V. The Breach formation time for extreme failure scenarios was defined using the USACE classification to represent sudden structural failure and to obtain conservative estimates of peak discharge. Dam-breach generation was simulated with HEC-HMS due to its numerical stability, while downstream flood propagation was modelled using HEC-RAS to derive spatial patterns of maximum inundation depth, flow velocity, and flood arrival time for hazard classification [12-14].

Flood hazard assessment for potential failure of the Muka Kuning Dam is based on inundation depth, flow velocity, and flood arrival time. Hazard zoning was derived from numerical simulations following the Directorate General of Water Resources Decree No. 257/KPTS/D/2011 and FEMA (2020) and refined using the ADB-UNESCO-GIWP (2013) framework by incorporating debris, settlement distance, and exposed population (PenRis).

3. Results and Discussion

3.1. Hydrological analysis

Rainfall data were statistically analysed using Microsoft Excel to determine design rainfall through frequency analysis and PMP estimation, based on records from the Hang Nadim Rainfall Station, Batam, covering the 2004-2024 period. The Log-Normal distribution was selected after passing the Chi-Square and Kolmogorov-Smirnov tests at the 5% significance level and yielding the lowest error, producing a 1,000-year return period rainfall of 515.23 mm. PMP was estimated at 833.405 mm using the Hershfield method, and both values were adopted for subsequent hydrological analysis. Design flood discharges were then computed using HEC-HMS with three synthetic unit hydrograph methods, as presented in Figs. 2 and 3.

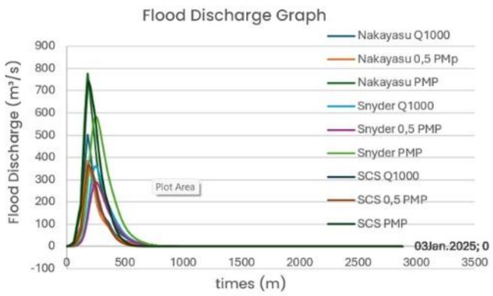

Fig. 2. Flood discharge simulation results using HEC-HMS.

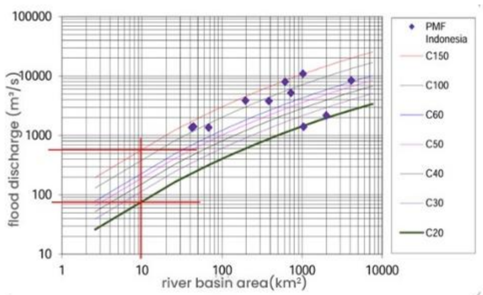

Fig. 3. Creager envelope curve.

Flood discharge results were evaluated using the Creager curve to verify consistency with watershed area characteristics. As shown in Fig. 3, the design peak discharge falls within the range of 75-595 m³/s. Among the three synthetic unit hydrograph methods, the Snyder method produced the highest peak discharge within this range and was therefore selected for the dam-break simulation.

3.2. Dam breach simulation results (HEC-HMS)

Scenario modelling was conducted by estimating the breach formation time using Equations (2) and (3) in conjunction with the USACE (1980) criteria, adopting a duration of 0.5–4 hours to generate conservative peak discharges under a worst-case scenario. Based on the flood discharge simulation performed with HEC-HMS, the failure-triggering elevation was defined at +27.663 m, corresponding to 1.337 m below the dam crest. This assumption reflects the fact that maximum reservoir water levels do not necessarily reach the crest and that premature failure may occur due to non-hydrological factors.

The crest of the Muka Kuning Dam is currently used as a traffic route, introducing dynamic loading and repeated vibrations that may lead to long-term deformation of the embankment. Residential activities located within approximately 20 m of the dam toe increase the risk of lateral pressure and seepage, particularly under suboptimal drainage conditions. Under extreme circumstances, seismic actions may further reduce the crest elevation as a result of dynamic consolidation, soil liquefaction, and significant structural deformation (see Table 2). Peak discharges for the overtopping and piping scenarios (top, mid, and bottom) were obtained from HEC-HMS dam-break simulations. Differences among scenarios arise from variations in breach formation rates, which directly control the volume of flow released from the dam (see Table 3).

Table 2. Dam breach parameters.

Parameter	Overtopping	Piping		
		Top	Middle	Bottom
Top Elevation (m)	29	29	29	29
Bottom Elevation (m)	12	12	12	12
Bottom Width	59.47	46.83	46.83	46.83
Left Slope (xH:1V)	1	0.7	0.7	0.7
Right Slope (xH:1V)	1	0.7	0.7	0.7
Piping Elevation (m)	-	24	19	14
Piping Coefficient	-	0.6	0.6	0.6
Development Time (HR)	0.5 - 4	0.5 - 4	0.5 - 4	0.5 - 4
Trigger Elevation (m)	27.663	27.663	27.663	27.663

Table 3. Dam breach simulation results using HEC-HMS.

Breach Time (hr)	Overtopping (m^3/s)	Piping Top (m^3/s)	Piping Middle (m^3/s)	Piping Bottom (m^3/s)
0.5	6117.849	5013.781	4720.367	5172.022
1.31	4355.685	3810.878	3282.44	3902.46
2	3348.438	3109.122	2695.81	3280.458
3	2336.23	2278.574	2088.254	2746.828
4	1785.992	1724.356	1717.699	2354.598

According to the simulation outcomes, the overtopping mechanism produced the greatest peak discharge 6,117.849 m³/s, surpassing the flows generated under all other dam-break scenarios. This elevated discharge is attributed to the more rapid onset of structural failure, which permits water to spill directly across the dam crest.

3.3. Flood modelling results (HEC-RAS 2D)

Flood propagation downstream of the dam was simulated using HEC-RAS version 5.0.7 with a two-dimensional (2D) modelling approach. The simulations were performed under unsteady flow conditions, with the peak discharge of 6,117.849 m³/s from the overtopping scenario applied as the model input (see Fig. 4).

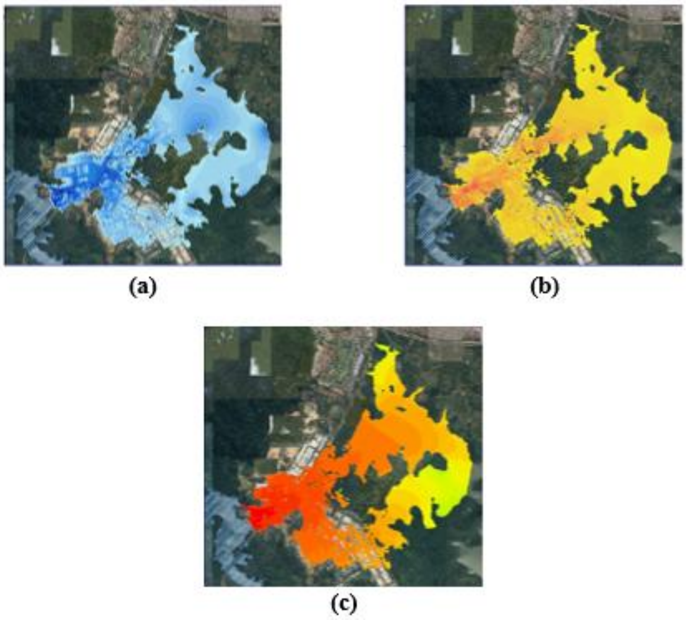

Fig. 4. Overtopping Scenario: (a) Maximum flood depth modelling result, (b) Maximum flow velocity modelling results, (c) Flood arrival time modelling results.

Simulation results indicate that failure of the Muka Kuning Dam produces a maximum inundation depth of 13.30 m and a peak flow velocity of 3.9 m/s, with the highest values occurring near the dam and along primary flow paths. Both depth and velocity decrease downstream as flood energy dissipates. The 2D HEC-RAS model estimates flood arrival times ranging from approximately 0.5 minutes to 2.8 hours across the study area.

3.4. Flood hazard classification

Flood hazard categories were evaluated using a 500 × 500 m spatial grid based on inundation depth, flow velocity, and flood arrival time. HEC-RAS simulation results presented in Fig. 5 illustrate the distribution of flood-prone areas according to the KPTS (2011), FEMA, and UNESCO models, enabling systematic comparison of risk zones under dam-failure scenarios.

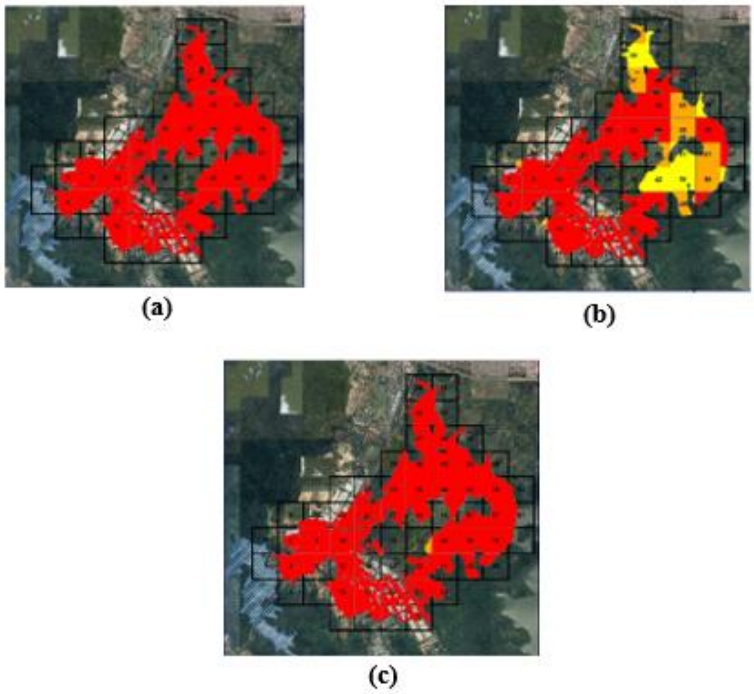

Fig. 5. Distribution of flood-prone areas: (a) Flood hazard zones based on KPTS 2011 classification, (b) Flood hazard zones based on FEMA guidelines, (c) Flood hazard zones based on UNESCO classification.

Flood hazard assessment based on KPTS (2011), FEMA (2018), and ADB-UNESCO-GIWP indicates that most downstream areas of the Muka Kuning Dam fall within high to very high-risk zones. HEC-RAS 2D simulations show inundation depths exceeding 2 m, flow velocities greater than 1.5 m/s, and flood arrival times of less than one hour in densely populated areas. Under the KPTS (2011) criteria, Muka Kuning Village, located less than 1 km from the dam and home to approximately 7,785 residents, is classified as an extreme hazard zone.

4. Conclusion

This study simulates the failure of the Muka Kuning Dam to evaluate flood characteristics and associated hazard levels. Hydrological analysis indicates a PMF discharge of 583.149 m^3/s with a water level reaching an elevation of 27.663 m, while the overtopping scenario represents the most critical condition, producing a maximum discharge of 6,117.849 m^3/s with a breach formation time of 0.5 h. The HEC-RAS 2D simulations yield a maximum inundation depth of 13.3 m, flow velocities of up to 3.9 m/s, and a minimum flood arrival time of 0.5 min. Hazard classification based on KPTS (2011), FEMA (2020), and UNESCO guidelines shows that most downstream areas fall within high-hazard zones, posing serious threats to human safety and critical industrial and commercial infrastructure. Accordingly, relocation of high-risk areas to safer zones is recommended as a primary mitigation measure.

References

1. Aulia, W.; Triweko, R.W.; Riyanto, B.A.; Adidarma, W.K.; and Yudianto, D. (2020). Analysis of Mukakuning and Duriangkang reservoir's capacity to fulfill the raw water demand of Batam City. *Jurnal Sumber Daya Air*, 16(2), 119-129.
2. Sumira, M.; Anggraheni, E.; and Prastica, R.M.S. (2023). Dam break analysis of Sermo Dam. *Journal of the Civil Engineering Forum,* 9(2), 127-138.
3. Phyo, A.P.; Yabar, H.; and Richards, D. (2023). Managing dam breach and flood inundation by HEC-RAS modeling and GIS mapping for disaster risk management. *Case Studies in Chemical and Environmental Engineering*, 8, 100487-100504.
4. Tessema, B.H.; Gebremedhn, A.Y.; and Getahun, Y.S. (2024). Dam breach analysis and flood inundation mapping of Dire Dam, using HEC-HMS and HEC-RAS models. *Sustainable Water Resources Management*, 10(2), 45-62.
5. Goh, S.E.G.; Zakaria, A.A.; Ahmad, M.F.; Zamir, M.; Ling, C.; and Maulana, H. (2024). The most likely flooded soil in Terengganu state during historically greatest rainfall intensity. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 41(2), 152-163.
6. Pratiwi, V.; Kusuma, M.S.B.; Kardhana, H.; and Farid, M. (2020). Experimental study of dam break flow generated by the flap gate in horizontal channel. *Geomate Journal*, 19(75), 19-26.
7. Ferrari, A.; Vacondio, R.; and Mignosa, P. (2023). High-resolution 2D shallow water modelling of dam failure floods for emergency action plans. *Journal of Hydrology*, 618, 129192-129207.
8. Maulana, H.; and Kanai, H. (2022). Potential agricultural land suitability visualization using augmented reality geographic information system (AR-GIS). *Journal of Engineering, Science and Technology*, 17(2), 1422-1435.
9. Yekti, M.I.; Adityananta, I.K.E.B.; and Pariartha, I.P.G.S. (2023). The Tamblang Dam break analysis using HEC-RAS 5.0.7 and PenRis hazard classification in Indonesia. *Arabian Journal of Geosciences*, 16(6), 365-378.
10. Hernadi, R.; Sulistiyono, H.; and Setiawan, E. (2021). Analisis dan dampak keruntuhan bendungan tiu kulit. *Media Bina Ilmiah*, 16(3), 6643-6654.
11. Turkel, A.O.; Zaifoglu, H.; and Yanmaz, A.M. (2024). Probabilistic modeling of dam failure scenarios: a case study of Kanlikoy Dam in Cyprus. *Natural Hazards*, 120(11), 10087-10117.
12. Kavosizadeh, A.R.; Barati, R.; Foroudi, A.; Saboorkazeran, H.; and Mahmoudi Moghadam, A. (2025). A framework for hydraulic simulation and risk analysis of embankment dam break. *Journal of Advanced Informatics in Water, Soil, and Structure*, 1(1), 15-33.
13. Tanne, Y.A.; Pratama, A.P.; and Rahardian, R. (2023). Analisis produktivitas operasi pemasangan balok baja (Studi kasus: Pembangunan kampus II Universitas Pasundan). *Media Komunikasi Teknik Sipil*, 29(2), 233-242.
14. Brunner, G.W. (2024). HEC-RAS HEC-RAS hydraulic reference. *US Army Corps Engineering*, 6, 1-477.