ANALYSIS OF DAM BREAK IMPACTS AND MITIGATION STRATEGIES USING HEC-RAS 2D MODELING

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Abstract: Dam failure is a critical hydrological hazard with potentially severe impacts on downstream communities and infrastructure. This study analyzes dam break impacts and mitigation strategies using two-dimensional hydraulic modeling with HEC-RAS 2D, integrated with Geographic Information System (GIS)-based spatial analysis, at the Kerinci Merangin Hydropower Dam in Jambi Province, Indonesia. Overtopping and piping failure scenarios were simulated to estimate peak discharge, inundation extent, flow velocity, and flood wave arrival time, which directly informed the design of a site-specific Emergency Action Plan (EAP). Simulation results indicate that a complete dam failure could generate a peak discharge of approximately 681.5 m³/s, with flood waves reaching high-risk downstream areas within only 15-20 minutes. GIS-based hazard mapping reveals that several critical access and evacuation routes are located within high-inundation zones, limiting conventional evacuation feasibility. A sensitivity analysis of key hydraulic parameters, including breach geometry and Manning’s roughness coefficient, demonstrates that small parameter variations significantly affect flood arrival time and evacuation lead-time reliability. The study’s contribution lies in demonstrating how sensitivity-informed dam break modeling can identify evacuation constraints and support the development of a highly localized, rapid-response EAP, moving beyond generic mitigation frameworks toward operationally feasible disaster preparedness.

Keywords: dam break; HEC-RAS 2D; GIS; sensitivity analysis; emergency action plan; flood modeling.

Abstrak: Kegagalan bendungan merupakan bahaya hidrologi yang kritis dengan potensi dampak yang serius terhadap masyarakat dan infrastruktur di wilayah hilir. Penelitian ini menganalisis dampak keruntuhan bendungan dan strategi mitigasi menggunakan pemodelan hidraulik dua dimensi dengan HEC-RAS 2D yang terintegrasi dengan analisis spasial berbasis Sistem Informasi Geografis (SIG), dengan studi kasus Bendungan PLTA Kerinci Merangin di Provinsi Jambi, Indonesia. Skenario kegagalan akibat overtopping dan piping disimulasikan untuk mengestimasi debit puncak, luas genangan, kecepatan aliran, serta waktu kedatangan gelombang banjir yang secara langsung digunakan sebagai dasar penyusunan Rencana Tindakan Darurat (Emergency Action Plan/EAP) yang bersifat spesifik lokasi. Hasil simulasi menunjukkan bahwa kegagalan total bendungan dapat menghasilkan debit puncak sekitar 681,5 m³/detik, dengan gelombang banjir mencapai wilayah hilir berisiko tinggi hanya dalam waktu 15-20 menit. Pemetaan bahaya berbasis SIG mengungkap bahwa beberapa jalur akses dan evakuasi kritis berada dalam zona genangan tinggi, sehingga membatasi kelayakan evakuasi konvensional. Analisis sensitivitas terhadap parameter hidraulik utama, termasuk geometri rekahan dan koefisien kekasaran Manning, menunjukkan bahwa variasi parameter yang relatif kecil dapat secara signifikan memengaruhi waktu kedatangan banjir dan keandalan waktu evakuasi. Kontribusi utama penelitian ini terletak pada demonstrasi bagaimana pemodelan keruntuhan bendungan yang mempertimbangkan analisis sensitivitas dapat mengidentifikasi keterbatasan evakuasi dan mendukung penyusunan EAP yang sangat terlokalisasi dan berorientasi pada respons cepat, melampaui kerangka mitigasi generik menuju kesiapsiagaan bencana yang lebih operasional dan realistis.

Kata kunci: keruntuhan bendungan; HEC-RAS 2D; SIG; analisis sensitivitas; rencana tindakan darurat; pemodelan banjir.

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Introduction

Dams are vital for water supply, irrigation, hydropower generation, and flood control. However, their failure can lead to catastrophic disasters, particularly in densely populated downstream areas. A dam break, a sudden and uncontrolled release of impounded water due to structural failure, poses serious risks to human lives, the environment, and economic assets (ICOLD, 2020). Recent incidents such as the failure of the Xe-Pian Xe-Namnoy Dam in Laos and the Sardoba Dam in Uzbekistan have highlighted the urgent need for improved assessment, early warning, and mitigation planning for dam-related hazards (Awal et al., 2024; Mo, et al., 2023)

The main causes of dam failure typically include overtopping, piping (internal erosion), structural instability, and seismic activity. Ortopping and piping are the most frequently modeled scenarios due to their prevalence and impact severity (Brunner, 2020; Awal et al., 2024; Darji & Patel, 2024). Overtopping occurs when flood inflow exceeds the spillway capacity, causing water to overflow and erode the dam crest, while piping refers to the internal erosion of embankment material due to uncontrolled seepage.

To assess such scenarios, the Hydrologic Engineering Center's River Analysis System (HEC-RAS), specifically its 2D hydraulic simulation module, has become a widely used tool for dam break modeling. HEC-RAS 2D enables accurate estimation of flood parameters such as peak discharge, inundation extent, flood depth, and travel time using the unsteady Saint-Venant equations (Brunner, 2020; Spero et al., 2022; Mattas et al., 2023). This modeling framework allows researchers and practitioners to simulate breach scenarios under varying hydraulic conditions and topographies, and to visualize flood propagation over time.

Recent research has demonstrated the significance of integrating HEC-RAS 2D with Geographic Information Systems (GIS) to improve spatial risk analysis and support decision-making. GIS facilitates the mapping of flood hazard zones, overlays on land use and population density, and identification of vulnerable assets (Abdelghani, 2024; Siswanto et al., 2019; Dahlia et al., 2025). For example, in a case study of the Logung Dam in Central Java, Indonesia, HEC-RAS 2D combined with GIS enabled accurate mapping of high-risk areas and the development of evacuation plans based on real-time inundation modeling (Siswanto et al., 2019).

In addition to physical modeling, many scholars emphasize the importance of incorporating community-based risk management and regulatory frameworks. The Indonesian Ministry of Public Works and Housing (PUPR) mandates the preparation of an Emergency Action Plan (EAP) for every dam, which must include hazard zonation, early warning systems (EWS), evacuation protocols, and stakeholder coordination mechanisms (GZA Engineering, 2023). Research has shown that EAPs developed based on technical simulations, rather than generic checklists are significantly more effective in minimizing casualties and improving community preparedness (GZA Engineering, 2023; Chan et al., 2023).

However, one of the persisting challenges in dam break modeling is parameter uncertainty, especially related to breach geometry, formation time, Manning's roughness coefficient, and DEM resolution. Sensitivity analysis has become essential in evaluating how these variables affect simulation outcomes, such as flood depth and arrival time (Khanal et al., 2025; Ansori et al., 2023). Failure to address these uncertainties can lead to under- or overestimating hazard exposure (Mattas et al., 2023).

This study aims to analyze dam break impacts and propose a comprehensive mitigation strategy for the Kerinci Merangin Hydropower Dam in Jambi Province, Indonesia. The methodology includes two-dimensional dam break simulation using HEC-RAS 2D, GIS-based flood hazard mapping, and development of an Emergency Action Plan that aligns with national disaster risk management guidelines. Integrating spatial modeling and policy frameworks is expected to contribute to a more resilient dam safety system and better preparedness for at-risk communities.

Literature Review

Dam break mechanisms and consequences

A dam break refers to the sudden structural failure of a dam, resulting in the rapid release of impounded water and often leading to catastrophic flooding, property loss, and fatalities, especially in densely populated downstream areas. Understanding the causes and consequences of dam failure is essential for risk assessment and mitigation planning.

Among the critical failure mechanisms, piping is a significant concern, an internal erosion process caused by uncontrolled seepage that compromises dam integrity over time. Brunner (2020) noted that this mechanism is difficult to detect, particularly in aging dams lacking modern instrumentation. Although concrete gravity dams like Kerinci Merangin are more resistant to such failures, they remain vulnerable to extreme hydrological loads, seismic activity, and poor maintenance (Kowsari et al., 2021; Mo et al., 2023).

The consequences of dam break events are especially severe due to the high flood volume and rapid propagation speed, often leaving minimal time for evacuation. Unlike seasonal floods, dam break floods have a steep hydrograph and can reach peak flow within minutes, complicating emergency responses (Spero et al., 2022; Chan et al., 2023). For example, Mohamed et al. (2023) showed that a breach at Mosul Dam could release 8,000 m^3/s and flood settlements with depths over 5 meters. Similarly, Mattas et al. (2023) warned that even partial breaches near urban zones could result in fatalities without robust early warning systems.

Secondary impacts, such as water contamination, infrastructure failure, and long-term economic disruption, are also common (Madhuri et al., 2021). Therefore, global guidelines from ICOLD (2020), FEMA, and USACE recommend dam break analysis and Emergency Action Plans (EAPs) as part of standard safety protocols. Tools like HEC-RAS 2D have become instrumental in simulating breach scenarios and supporting hazard-based planning (Abdelghani, 2024; Brunner, 2020).

HEC-RAS 2D in dam break modeling

HEC-RAS (Hydrologic Engineering Center's River Analysis System), developed by the U.S. Army Corps of Engineers, has become a widely accepted tool for simulating dam break scenarios due to its ability to model two-dimensional flow dynamics. Since version 5.0, the software solves the full Saint-Venant equations across a computational mesh, capturing complex flood behavior more accurately than traditional 1D models, particularly in irregular topographies (Brunner, 2020; Spero et al., 2022).

By incorporating high-resolution digital elevation models (DEMs), HEC-RAS 2D allows precise predictions of flood depths, velocities, and arrival times (Dahlia et al., 2025). Recent studies have validated its reliability in simulating both overtopping and piping scenarios. For example, Mohamed et al. (2023) successfully replicated historical flood behavior for Mosul Dam, while Abdelghani (2024) integrated model outputs with GIS to support emergency planning for the Taksebt Dam.

Standard workflows in HEC-RAS 2D involve setting breach parameters, applying inflow hydrographs, assigning Manning's roughness, and calibrating terrain data to simulate flood propagation. The RAS Mapper module enables outputs to be visualized over satellite imagery and is used to develop hazard maps and evacuation routes. Applications in Indonesia, such as at Logung and Jatibarang dams, have shown their effectiveness in local dam safety planning (Siswanto et al., 2019; Dahlia et al., 2025).

However, the accuracy of simulation results is highly sensitive to input parameters, including DEM resolution and breach geometry. Sensitivity analyses, such as Global Sensitivity Analysis (GSA), are crucial for improving model robustness and reducing uncertainty in flood risk assessments (e Silva et al., 2024; Mo et al., 2023; Khanal et al., 2025).

Overall, HEC-RAS 2D provides a validated and adaptable platform for dam break modeling, combining technical accuracy with practical decision-making support for disaster preparedness and emergency response.

GIS integration and flood risk zonation

Integrating Geographic Information Systems (GIS) with HEC-RAS 2D modeling has greatly enhanced spatial flood hazard analysis, particularly for dam break assessments. While HEC-RAS 2D provides detailed outputs such as flood extent, depth, and arrival time, GIS enables these results to be visualized alongside critical data like land use, population density, and infrastructure (Abdelghani, 2024; Dahlia et al., 2025). This integration supports targeted risk assessment and emergency response planning.

GIS is beneficial for identifying vulnerable zones by overlaying flood maps with socio-economic indicators. For instance, Abdelghani (2024) used GIS to classify risk zones for the Taksebt Dam, while Siswanto et al. (2019) and Dahlia et al. (2025) applied similar approaches in Indonesia to develop evacuation routes and hazard maps for the Logung and Jatibarang Dams.

Scenario-based mapping is another strength of GIS, allowing users to simulate various breach conditions and rainfall events, thus aiding in developing robust Emergency Action Plans (EAPs) as required by ICOLD (2020) and national regulations. Recent GIS technologies, such as web dashboards and mobile platforms, also improve public access to risk information, enhancing early warning systems and community preparedness (Chan et al., 2023).

The synergy between GIS and HEC-RAS 2D provides technical precision and operational value, making it essential for flood risk management and dam safety planning.

Emergency Action Plans (EAPs) and Community Preparedness

Emergency Action Plans (EAPs) are essential for minimizing the impacts of dam failure, comprising components such as hazard zoning, early warning systems, evacuation procedures, and inter-agency coordination. In Indonesia and many other countries, the development of EAPs is mandatory for large dams and must comply with national and international safety standards (Abdelghani, 2024; ICOLD, 2020).

Modern EAPs increasingly rely on simulation-based data from tools like HEC-RAS 2D, which provide precise flood extent, arrival time, and depth estimations. These data-driven plans allow for tailored evacuation routes and more targeted mitigation strategies, as GZA Engineering (2023); ICOLD, 2020) and

Dahlia et al. (2025) emphasized. Simulation-based EAPs are more responsive to actual hazard scenarios than generic templates.

Community preparedness is also a vital element. Effective implementation includes public education, early warning drills, and evacuation simulations. Madhuri et al. (2021) stress the need for accessible communication, particularly in rural or underserved areas. Integrating EAPs into local disaster frameworks ensures community members are informed and ready to act (Chan et al., 2023).

In Indonesia, EAP outcomes vary depending on the availability of technical resources and institutional capacity. For example, the Logung Dam project demonstrated improved planning outcomes through GIS-integrated simulations (Siswanto et al., 2019), whereas other cases struggled due to limited modeling data (Darji & Patel, 2024).

Emerging technologies, such as mobile-based alerts and real-time data integration, enhance the functionality of EAPs by delivering location-specific warnings via SMS and apps (Spero et al., 2022). Overall, robust EAPs that combine technical modeling with community engagement and modern communication tools are crucial for improving dam safety and emergency response readiness.

Methodology

This study employed a simulation-based approach to assess the impacts of dam break scenarios and formulate mitigation strategies by integrating HEC-RAS 2D modeling with Geographic Information Systems (GIS). The methodology comprised five sequential stages: data collection and preparation, breach scenario definition, hydrodynamic simulation, spatial hazard mapping, and developing a comprehensive Emergency Action Plan (EAP).

The research was conducted on the Kerinci Merangin Hydropower Dam, a concrete gravity dam in Jambi Province, Indonesia. With a storage capacity of 16.82 million cubic meters, the dam plays a key role in electricity generation for the region. The downstream area is a mixture of agricultural fields, residential settlements, and road infrastructure, making it particularly vulnerable to a sudden dam failure.

Various datasets were collected from both primary and secondary sources. A 10-meter resolution Digital Elevation Model (DEM) was used to construct the terrain for the simulation. Hydrological data, including peak inflow, design flood hydrographs, and reservoir characteristics, were obtained from the dam operator and local water agencies. Structural specifications such as dam height, width, crest length, and materials were derived from engineering reports. Additional geospatial datasets, including land use, road networks, and population distribution, were gathered to support GIS-based vulnerability analysis. All spatial data were projected in UTM Zone 48S and preprocessed using GIS software to maintain consistency in coordinate systems and resolution.

Two dam failure mechanisms were considered in this study: overtopping and piping. Breach parameters, such as breach width, height, and formation time, were estimated using empirical equations adapted from Abdelghani (2024), considering the dam type and volume. The breach was assumed to occur at the dam's centerline, the most likely initiation point for overtopping and internal erosion. Scenario variation was incorporated by adjusting breach dimensions and failure durations, allowing the simulation of a range of possible outcomes, including worst-case scenarios.

HEC-RAS 2D simulations were conducted by constructing a computational mesh from the DEM, with finer mesh refinement applied to populated areas, river corridors, and infrastructure. Manning's roughness coefficients were assigned based on land use classifications, ranging from 0.03 in urban zones to 0.08 in vegetated areas. An unsteady flow simulation was run using the Saint-Venant equations, with boundary conditions set as a constant reservoir level upstream and normal depth downstream. The model ran over a 6-hour post-breach, using 10-second time steps to capture rapid flood wave progression accurately. Output parameters included flood extent, depth, velocity, and arrival time, which were cross-validated against dam safety guidelines and expert judgement, given the absence of historic failure records. The key model inputs are summarized in Table 1.

Table 1. Technical parameters for HEC-RAS 2D simulation

Parameter	Value/Description
Digital Elevation Model (DEM)	10 m resolution DEM
Computational Mesh Cell Size	10–30 m (refined near river and urban areas)
Simulation Time Step	10 seconds
Simulation Duration	6 hours post-breach
Breach Type	Overtopping and piping
Breach Width	Estimated using Froehlich equations
Breach Formation Time	15–30 minutes (scenario-based)
Manning's Roughness Coefficient (n)	0.03–0.08 based on land use
Boundary Conditions	Upstream: constant water level; Downstream: normal depth
Hydrograph Type	Probable Maximum Flood (PMF)
Output Parameters	Flood extent, depth, velocity, and arrival time

Simulation results were exported to RAS Mapper and further processed in GIS for hazard analysis. Flood depth and velocity layers were overlaid with land use, population, and infrastructure data to determine exposure and classify hazard levels. Flood hazard zones were categorized into low (<0.5 m), moderate (0.5–2.0 m), and high (>2.0 m) based on water depth. These layers enabled the identification of critical areas, vulnerable communities, and bottlenecks along evacuation routes.

Based on the simulation outputs, an Emergency Action Plan (EAP) was formulated following national dam safety standards and international guidelines (Abdelghani, 2024). The EAP consists of four key elements: hazard zoning maps, optimized evacuation routes and shelter locations, a structured Early Warning

System (EWS), and command coordination protocols for emergency response. Stakeholder input, including from local disaster management authorities and community leaders, was incorporated to ensure contextual relevance and operational feasibility. The plan is designed to be adaptable, allowing real-time updates as new data or technologies become available. The overall methodological workflow employed in this study is depicted in Figure 1.

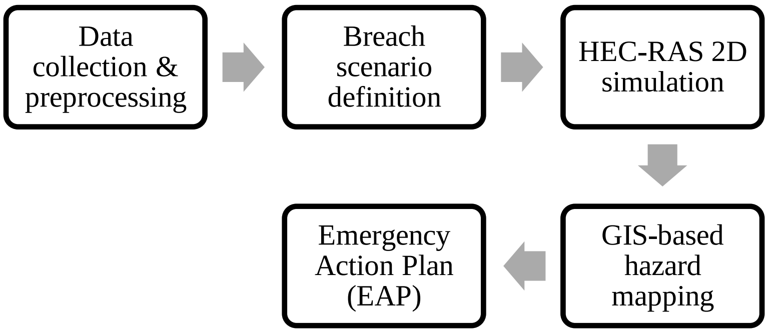

Figure 1. Methodological flowchart

Figure 1 outlines the full process from data collection, breach scenario definition, HEC-RAS 2D simulation, GIS-based hazard mapping, to formulating an Emergency Action Plan. This integrated, simulation-driven approach enhances dam safety management and supports disaster risk reduction through data-informed planning and spatially targeted interventions.

Results and Discussion

Flood Inundation Simulation Results

HEC-RAS 2D simulations reveal clear hydrodynamic contrasts between overtopping and piping failure scenarios. The overtopping scenario generated a peak discharge of 681.5 m³/s, with floodwaters reaching downstream settlements within 15-20 minutes, whereas the piping scenario produced a more gradual breach development and delayed flood arrival of approximately 30 minutes. This contrast highlights the strong influence of failure mechanisms on flood propagation speed and emergency response feasibility.

The simulated inundation covered approximately 3.42 km², affecting residential areas, agricultural land, and local road networks. Maximum flood depths reached up to 3.7 m in low-lying zones, while flow velocities ranged from 0.5 to 2.8 m/s, exceeding commonly reported thresholds for structural damage and human stability. These conditions indicate a high destructive potential, particularly for settlements located close to the river corridor.

Although flood depth and velocity ranges are broadly consistent with previous dam break studies (Abdelghani, 2024); Mohamed et al., 2023; Regmi & Baniya, 2025), the significantly shorter flood arrival time distinguishes the Kerinci Merangin case. This characteristic, driven by settlement proximity and confined valley morphology, demonstrates that evacuation feasibility is governed not only by flood magnitude but also by site-specific spatial and temporal constraints.

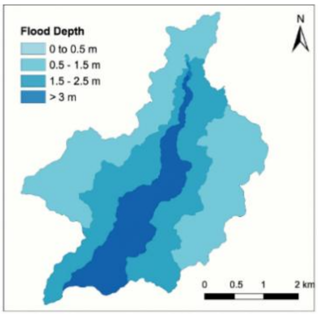

Figure 2. Flood depth distribution map

Figure 2 shows the spatial distribution of flood depths derived from HEC-RAS 2D simulations. Areas with inundation depths exceeding 3 m, particularly under the overtopping scenario, are concentrated along the main river channel and adjacent floodplains, identifying zones of high structural vulnerability that require priority consideration in emergency response and evacuation planning.

Flood Arrival Time and Risk Implications

Temporal analysis of flood arrival time provides a critical basis for evaluating evacuation feasibility and emergency response effectiveness. HEC-RAS 2D simulations indicate that high-risk downstream zones are inundated within 15-20 minutes following dam breach initiation, whereas peripheral areas experience delayed flood arrival of up to 8 hours. This pronounced variation in lead time highlights the spatially uneven nature of risk and the need for differentiated, location-specific evacuation strategies.

The extremely short arrival time in high-risk zones represents a severe operational constraint, leaving minimal opportunity for conventional warning dissemination and staged evacuation. Under such conditions, even short delays may determine evacuation success or failure, reinforcing the necessity for automated Early Warning Systems (EWS) and pre-defined rapid-response procedures in areas closest to the dam.

The flood arrival time map derived from HEC-RAS 2D maximum arrival time outputs spatially distinguishes zones of immediate and delayed inundation. This differentiation provides essential input for prioritizing warning dissemination, allocating emergency resources, and designing a localized Emergency Action Plan (EAP) tailored to time-sensitive risk conditions.

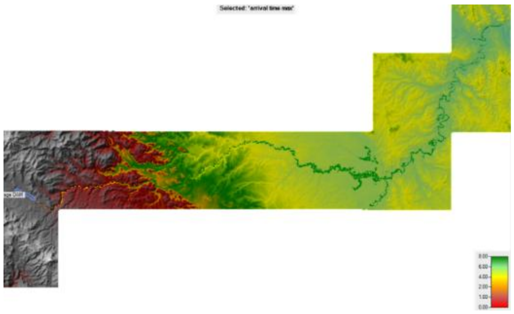

Figure 3. Flood wave arrival time map

Figure 3 presents simulated flood arrival times for downstream areas following a dam breach. Red zones indicate inundation within the first hour, reflecting critically limited response time, while green zones represent delayed exposure of up to 8 hours post-failure, supporting evacuation prioritization and emergency planning.

Flood Inundation Extent and Velocity Distribution

To complement the temporal flood analysis, Figure 4 presents the spatial extent of inundation and flow velocity distribution under the overtopping failure scenario. High flow velocities are concentrated near the breach location and progressively decrease downstream, reflecting rapid energy dissipation along the flood path. Areas exposed to high velocities are associated with elevated risks of structural damage, debris transport, and potential loss of life, particularly within settlement clusters along the main river corridor.

Spatial overlay analysis further indicates that several road networks and critical infrastructure elements intersect zones of high flow velocity, suggesting potential disruption to evacuation and emergency access during a dam failure event. This finding demonstrates that flood hazard severity is governed not only by inundation extent but also by the spatial coincidence of high-velocity flow and essential infrastructure. Similar velocity-driven risk patterns have been reported in previous dam break studies (Spero et al., 2022; Mattas et al., 2023), although the present case shows a more pronounced overlap between hazardous flow zones and evacuation corridors.

The combined analysis of inundation extent and velocity distribution provides a critical basis for prioritizing mitigation measures, optimizing evacuation route selection, and allocating emergency resources within the EAP, particularly under time-constrained response conditions.

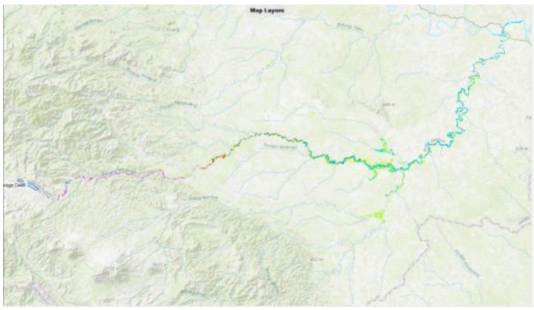

Figure 4. Simulated flood inundation extent and flow velocity distribution

Figure 4 shows the simulated spatial extent of flood inundation and flow velocity distribution resulting from an overtopping failure at the Kerinci Merangin Hydropower Dam. Higher velocities are concentrated near the breach and decrease downstream, highlighting affected settlements, agricultural land, and critical infrastructure relevant to emergency response and evacuation planning.

GIS-Based Hazard Zonation

Using HEC-RAS 2D outputs, flood hazard zones were classified through GIS analysis into low (<0.5 m), moderate (0.5-2.0 m), and high (>2.0 m) categories. The results indicate that approximately 27% of the inundated area falls within the high-hazard zone, primarily affecting low-lying residential areas such as Dusun Sungai Batu Gantih and adjacent agricultural land. These depth-based classifications provide a practical representation of flood severity relevant to structural damage and human safety.

Beyond hazard delineation, GIS overlay analysis reveals critical evacuation constraints, as the two main access routes serving downstream communities intersect zones of moderate to high inundation. This spatial coincidence substantially reduces evacuation efficiency and may cause severe delays during emergency response, a limitation that is not evident from hydraulic modeling alone. By integrating flood simulation results with population distribution, land use, and road network data, the analysis identifies localized risk patterns that directly inform EAP development.

The findings demonstrate that GIS-based hazard zonation functions not merely as a mapping exercise but as a decision-support tool linking technical flood modeling with operational disaster management. While similar GIS-integrated flood risk assessments have been conducted in Indonesia (Sideng et al. (2023), the present study places stronger emphasis on evacuation route feasibility under short flood arrival times, strengthening its relevance for time-critical emergency planning.

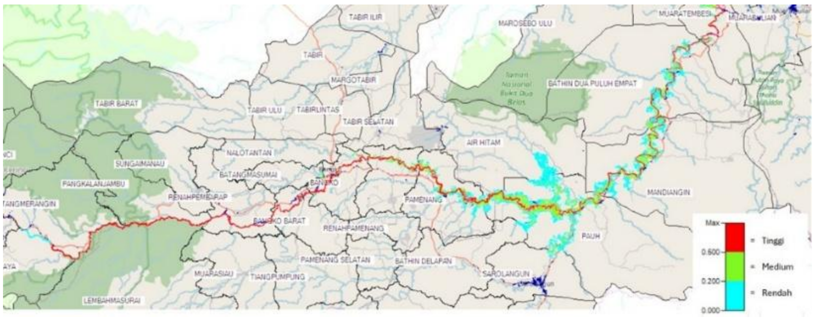

Figure 5. The GIS-based flood hazard classification map based on water depth thresholds

Figure 5 presents the spatial distribution of flood hazard zones classified by water depth thresholds. High-hazard areas (>2 m) are highlighted in red and show strong spatial correspondence with settlements and critical infrastructure, supporting targeted mitigation measures and evacuation planning.

Sensitivity Analysis of Key Hydraulic Parameters

A sensitivity analysis was conducted to evaluate the influence of key hydraulic parameters, particularly breach width and Manning's roughness coefficient, on flood arrival time and inundation characteristics. The analysis indicates that modest variations in breach geometry result in measurable changes in flood arrival time, while changes in surface roughness significantly affect flow depth and velocity in downstream areas. Although the overall inundation pattern remains consistent, these variations have important operational implications under short lead-time conditions, as even small delays may determine evacuation feasibility. This finding reinforces the need to incorporate parameter uncertainty into Emergency Action Plan (EAP) design rather than relying on deterministic simulation outputs.

Emergency Action Plan (EAP) Outcomes

Based on hydrodynamic simulations and GIS-based hazard zonation, a localized Emergency Action Plan (EAP) was developed to address the time-critical conditions in downstream areas. The plan is explicitly informed by flood arrival time, inundation depth, and evacuation route vulnerability, ensuring consistency between modeled hazards and operational response capacity.

Evacuation routes were revised using HEC-RAS 2D arrival time outputs, indicating that settlements inundated within 15-20 minutes cannot rely on conventional downstream evacuation and must instead move toward nearby higher ground and predefined assembly points. The EWS integrates manual sirens and SMS alerts to minimize dissemination delays under constrained lead-time conditions. A tiered coordination structure at village and district levels supports rapid decision-making and decentralized response.

The EAP outcomes demonstrate how integrating hydraulic modeling and spatial analysis can translate dam break simulations into actionable, time-sensitive emergency planning, advancing a more operational and context-specific approach to dam safety management.

Discussion

This study demonstrates that the integration of HEC-RAS 2D hydrodynamic modeling and GIS-based spatial analysis is particularly effective in revealing time-critical evacuation constraints in dam break scenarios. Unlike many previous studies that emphasize flood extent and depth, the present analysis identifies extremely short flood wave arrival times of approximately 15-20 minutes in high-risk downstream areas, which fundamentally limit the feasibility of conventional evacuation strategies.

The simulation of overtopping and piping failure scenarios enabled the identification of worst-case conditions and their direct implications for emergency response planning. While scenario-based modeling has been applied in other dam safety studies, such as the Mangla Dam case in Pakistan (Ahmad et al., 2023), the Kerinci Merangin Dam presents a more restrictive context due to the close proximity of settlements and confined downstream morphology. As a result, mitigation measures must prioritize automated, multi-channel Early Warning Systems (EWS) and pre-defined evacuation toward nearby higher ground rather than extended downstream evacuation routes.

The GIS-based hazard analysis further reveals that several critical access routes intersect inundation zones, compounding evacuation challenges under short lead-time conditions. This spatial coincidence between hazard intensity and infrastructure exposure explains why generic Emergency Action Plan (EAP) templates may be inadequate for this site. Instead, the findings support the development of a highly localized and time-sensitive EAP, emphasizing rapid warning dissemination and decentralized response coordination, consistent with recommendations by Ma et al. (2021).

Although the modeling framework is robust, uncertainty remains due to assumptions in breach geometry, surface roughness coefficients, and DEM resolution. Importantly, the sensitivity of flood arrival time to these parameters has direct operational consequences, as even minor deviations may determine evacuation success or failure. This reinforces the need to incorporate sensitivity-informed analysis into EAP design, rather than treating simulation outputs as deterministic predictions. Future integration of real-time rainfall and water level monitoring may further enhance the operational applicability of dam break risk assessments.

Conclusion

This study demonstrates how the integration of HEC-RAS 2D hydraulic modeling and GIS-based spatial analysis can reveal time-critical and spatially constrained risks associated with dam failure at the Kerinci Merangin Hydropower

Dam. Simulation results indicate that overtopping and piping failure scenarios may generate peak discharges of up to 681.5 m^3/s, inundate approximately 3.42 km^2, and impact high-risk downstream communities within 15-20 minutes, leaving extremely limited time for evacuation. GIS-based hazard zonation further identifies residential areas, agricultural land, and key access routes within moderate to high-risk zones, highlighting evacuation constraints that are not evident from hydraulic modeling alone. These findings directly informed the development of a localized Emergency Action Plan (EAP) that prioritizes rapid warning dissemination, evacuation toward nearby higher ground, and decentralized response coordination, rather than conventional downstream evacuation strategies. Although uncertainties remain due to assumptions in breach parameters, terrain resolution, and roughness coefficients, the sensitivity-informed analysis demonstrates that even small variations in model inputs can significantly affect flood arrival time and evacuation feasibility. Overall, the study underscores the importance of linking dam break simulations with spatial vulnerability analysis and operational planning, providing a practical and context-specific framework to enhance dam safety and emergency preparedness in regions with limited response lead time.

Conflict of Interest

The authors declare no conflict of interest. All authors contributed equally to the research and manuscript preparation. Limited assistance from AI was used solely for language refinement, not for content generation or analysis.

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