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Terrain-Driven Flood Risk Modeling of a Levee Breach Scenario along the Jeneberang River: Implications for Urban Housing in Buyang Village, Makassar, Indonesia

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Abstract Flooding caused by levee breaches remains a significant hazard in urban environments, particularly in low-lying regions exposed to intense rainfall and characterized by geomorphological vulnerability. This study assesses the flood risk to Buyang Village, Makassar, in case of a hypothetical levee failure at the Patompo Embankment along the Jeneberang River. Using a Probable Maximum Flood (PMF) hydrograph as input, the simulation was carried out with HEC-RAS 1D unsteady flow modeling, enhanced by high-resolution GPS-based topography, DEM generation, GIS integration, and terrain analysis via TOPAZ. The model incorporated a 300-meter lateral breach with outflow peaking at 86 m^3/s. Results indicate that floodwaters are diverted toward Sambung Jawa and Balang Baru due to natural elevation barriers, leaving the Rusunawa housing site in Buyang Village unaffected under worst-case conditions. Model validation was conducted by comparing simulated pathways with known flood-prone areas, while calibration involved sensitivity testing of Manning's roughness coefficients, breach parameters, and inflow variations. These tests confirmed that the protective influence of terrain—and the resulting safety of Buyang Village—remained consistent across all scenarios. The findings highlight the pivotal role of terrain in flood mitigation and underscore the utility of integrating hydrodynamic simulation with geospatial analysis in urban flood risk assessments. This study offers critical input for disaster risk reduction, urban zoning, and infrastructure planning in flood-prone Indonesian cities.

Keywords Levee Breach, Hydrodynamic Simulation, Terrain Analysis, HEC-RAS, Flood Risk Validation, Model Calibration, Sensitivity Analysis, Urban Flood Modeling, Makassar

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1. Introduction

Flooding remains among the most frequent and destructive natural disasters globally, particularly in riverine and low-lying urban areas. In Indonesia, floods are predominantly triggered by intense rainfall during the wet season; however, structural failures such as embankment breaches or dam collapses represent equally severe threats, often resulting in high-velocity flows that cause rapid and extensive inundation, structural damage, and loss of life.

In recent years, flood disasters resulting from levee failures have gained increasing attention in the scientific community, as they often occur without warning and have devastating impacts. The severity of flood impacts from embankment breaches is influenced by the velocity, depth, and duration of floodwaters, as well as the vulnerability and preparedness of the affected population [1, 2]. Even relatively shallow yet fast-moving water—such as 30 cm depth flowing at 4.45 m/s—can exert forces equivalent to wind speeds strong enough to knock down people and damage lightweight structures [3].

Hydrodynamic modeling tools, particularly the HEC-RAS software developed by the U.S. Army Corps of Engineers, have become standard for assessing flood hazards associated with structural failures. Recent advances in HEC-RAS—especially 2D modeling and unsteady flow simulations—have enhanced model resolution, improved terrain integration, and increased real-time applicability for disaster preparedness [4-6]. These tools are increasingly integrated with Digital Elevation Models (DEMs), remote sensing, and Geographic Information Systems (GIS), enabling more accurate predictions of flood extents and depths in complex urban landscapes [7, 8]. Recent studies emphasize the importance of integrating high-resolution topographic surveys with predictive simulations to inform flood mitigation strategies in urbanizing areas. For example, Hidayat et al. [8] successfully applied HEC-RAS to simulate flood behavior in Jakarta's Ciliwung River corridor. Hazard classification and dam breach modeling are utilized to develop early warning systems [9,10]; these efforts underscore the importance of robust simulations in planning resilient infrastructure in flood-prone areas.

Buyang Village in Makassar, South Sulawesi, is a rapidly developing urban area near the *Jeneberang* River. The *Patompo* Embankment protects the surrounding community and is a critical infrastructure asset. The planned construction of a low-cost vertical housing complex (*Rusunawa*) in this region makes assessing the flood risk during an embankment failure essential. Although the area has not historically experienced catastrophic flooding, changes in climate patterns and land use necessitate a reassessment of its vulnerability.

This study aims to estimate the spatial extent and characteristics of inundation that may result from a hypothetical levee breach at the *Patompo* Embankment. Using HEC-RAS 3.1.2 and GPS-based topographic inputs, the simulation incorporates a Probable Maximum Flood (PMF) scenario, high-resolution DEMs, and GIS-based floodplain mapping. The objective is to determine whether the *Rusunawa* housing site in *Buyang* Village remains safe under a worst-case failure scenario and to provide actionable insights for flood mitigation, spatial planning, and infrastructure development in the *Makassar* metropolitan area.

This study integrates terrain-informed hydrodynamic modeling with systematic validation and calibration, demonstrating that natural elevation buffers protect Buyang Village from levee-breach flooding and offering a replicable framework for flood risk assessment in rapidly urbanizing Indonesian cities.

2. Methodology

2.1. Overview

This study utilized a hydrodynamic modeling approach to simulate potential inundation resulting from a levee breach at the *Patompo* Embankment on the *Jeneberang* River, Makassar, as seen in Figure 1. The methodology consisted of two main stages: 1) Levee breach modeling, to estimate outflow hydrographs from the failed embankment; and 2) Flood plain inundation modeling, to simulate the extent and depth of flooding in surrounding areas, particularly *Buyang* Village.

The hydrodynamic simulations were performed using the HEC-RAS 3.1.2 software developed by the U.S. Army Corps of Engineers. This tool can simulate unsteady flow conditions and floodplain-river interactions during extreme hydrological events.

2.2. Data Collection and Preparation

Several types of spatial and hydrological data were collected and processed for model input: 1) Topographic Data, a detailed GPS-based field survey was conducted using UTM Zone 50 and WGS 1984. The resulting coordinate data (X, Y, Z) were used to construct the study area's Digital Elevation Model (DEM); 2) Aerial Imagery, high-resolution orthophotos were utilized for land-use mapping and alignment of model features with real-world conditions; 3) Land use map, a digitized land-use map (scale 1:50,000) was prepared to assign Manning's roughness coefficients in the hydrodynamic model based on surface types, as seen in Figure 2; 4) River cross sections, cross-sectional data along the *Jeneberang* River, particularly near the potential breach location in *Parangtambung* Village, were acquired to define channel geometry; and 5) Hydrological Data, a Probable Maximum Flood (PMF) hydrograph was used to represent the peak inflow scenario. Discharge values were adopted from previous (Table 1).

Land-use data were digitized to enhance modeling accuracy and simulate realistic flood behavior, thereby assigning spatially variable Manning's roughness coefficients. This approach is consistent with recent work by Rahman et al. [4] and Yekti et al. [9], who have demonstrated the effectiveness of land classification in enhancing the resolution of 2D flood models.

The Probable Maximum Flood (PMF) hydrograph was adopted from previous national studies and applied as the inflow boundary condition. Similar to the approach in Saleh et al. [11], the PMF represented a worst-case scenario, allowing planners to assess flood behavior under maximum hazard potential.

2.3. Levee Breach Modeling

The river embankment was modeled as a lateral structure (i.e., a weir-type boundary) in HEC-RAS to simulate the levee breach. Two types of failure mechanisms are typically considered in such simulations: overtopping and piping. For this study, a simplified geometric breach was assumed, with the following characteristics: Breach length: 300 meters; Side slopes: 1:1 on both sides; Breach elevation: Initiated at +12 m, ending at +6 m; and Peak breach outflow: Estimated at 86 m^3/s. This outflow hydrograph was then used as lateral inflow to simulate downstream flooding.

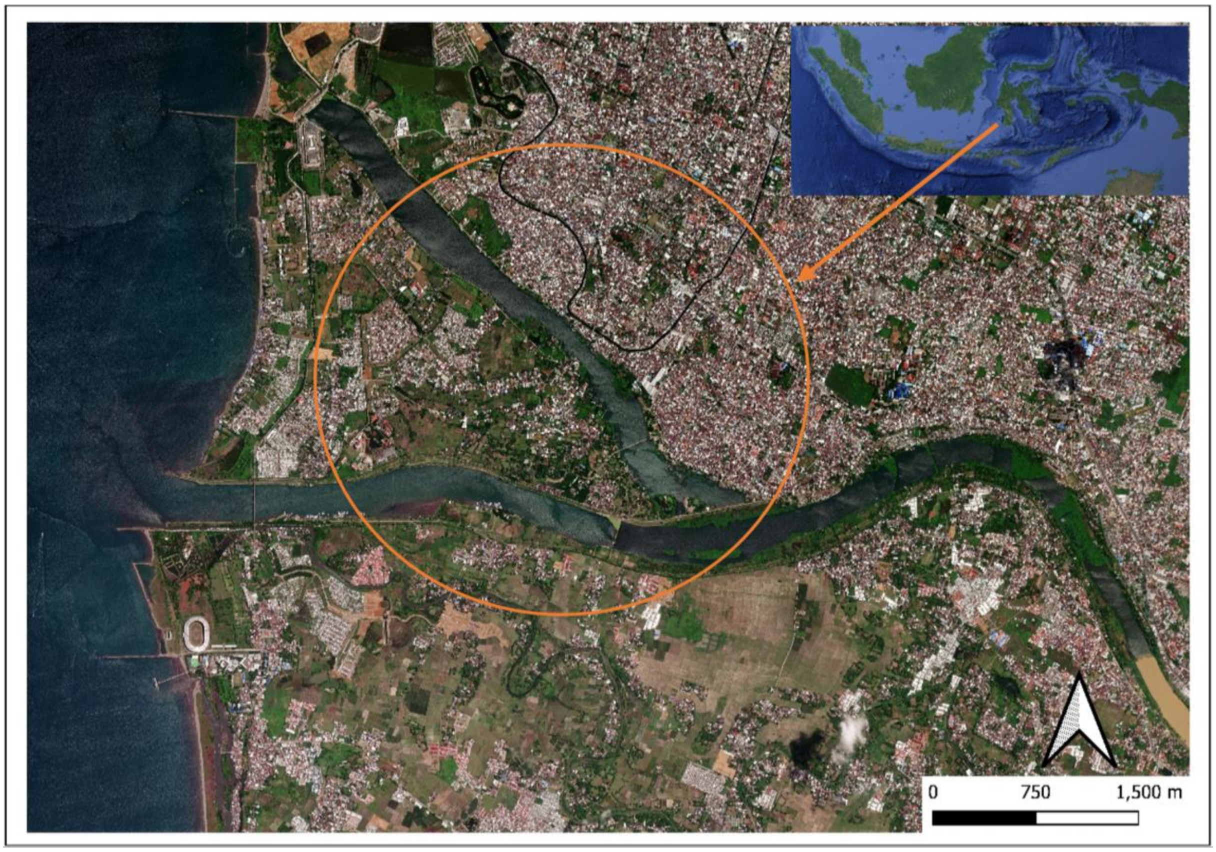

Figure 1. Study location of levee breach at the *Patompo* Embankment on the *Jeneberang* River

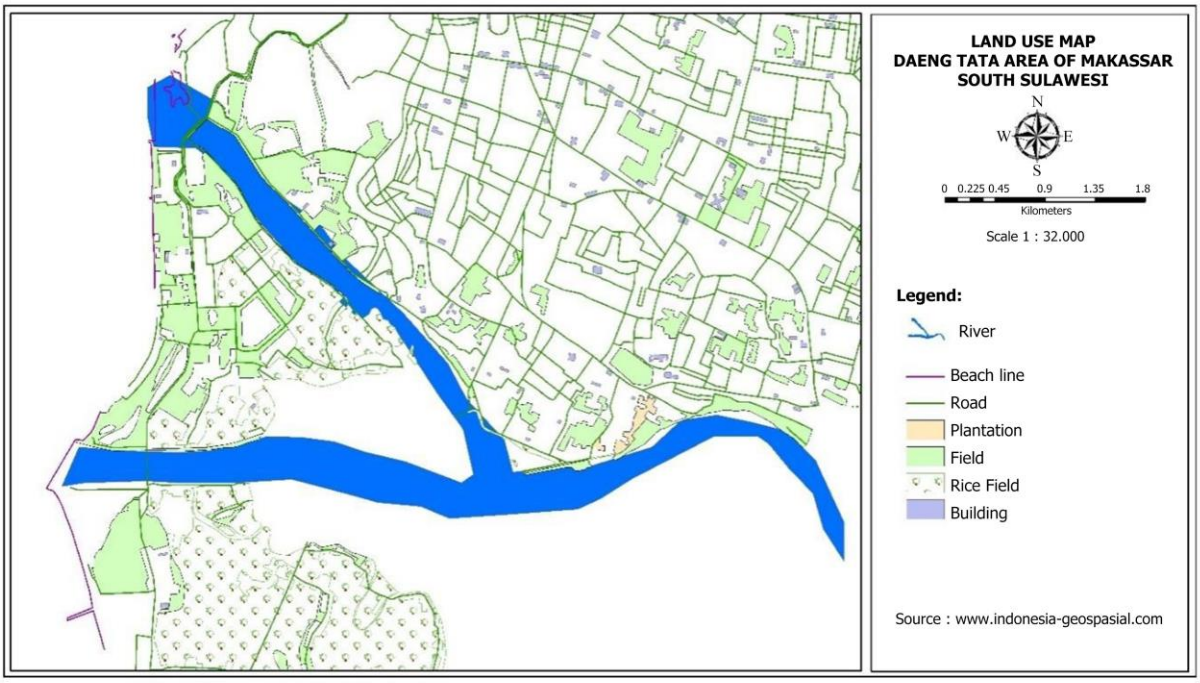

Figure 2. Land Use of West Makassar

Table 1. PMF Discharge, After Saleh et al. [11]

T (hours)	Discharge PMF (m^3/sec)	T (hours)	Discharge PMF (m^3/sec)	T (hours)	Discharge PMF (m^3/sec)	T (hours)	Discharge PMF (m^3/sec)
0	0.00	*26*	625.00	*51*	232.01	*76*	113.64
1	150.00	*27*	500.00	*52*	227.27	*77*	108.90
2	275.00	*28*	475.00	*53*	222.54	*78*	104.17
3	562.50	*29*	437.50	*54*	217.80	*79*	99.43
4	1687.50	*30*	412.50	*55*	213.07	*80*	94.70
5	2500.00	*31*	400.00	*56*	208.33	*81*	89.96
6	3250.00	*32*	387.50	*57*	203.60	*82*	85.23
7	4250.00	*33*	375.00	*58*	198.86	*83*	80.49
8	4750.00	*34*	312.50	*59*	194.13	*84*	75.76
9	4500.00	*35*	307.77	*60*	189.39	*85*	71.02
10	4250.00	*36*	303.03	*61*	184.66	*86*	66.29
11	3812.50	*37*	298.30	*62*	179.92	*87*	61.55
12	3687.50	*38*	293.56	*63*	175.19	*88*	56.82
13	3250.00	*39*	288.83	*64*	170.45	*89*	52.08
14	3000.00	*40*	284.09	*65*	165.72	*90*	47.35
15	2562.50	*41*	279.36	*66*	160.98	*91*	42.61
16	2250.00	*42*	274.62	*67*	156.25	*92*	37.88
17	2062.50	*43*	269.89	*68*	151.52	*93*	33.14
18	1750.00	*44*	265.15	*69*	146.78	*94*	28.41
19	1562.50	*45*	260.42	*70*	142.05	*95*	23.67
20	1375.00	*46*	255.68	*71*	137.31	*96*	18.94
21	1250.00	*47*	250.95	*72*	132.58	*97*	14.20
22	1125.00	*48*	246.21	*73*	127.84	*98*	9.47
23	1000.00	*49*	241.48	*74*	123.11	*99*	4.73
24	875.00	*50*	236.74	*75*	118.37	*100*	0.00
25	600.00						

2.4. Levee Breach Simulation

Following standard practice in breach modeling [11, 12], a lateral breach structure was introduced along the right embankment of the *Jeneberang* River. The breach was assumed to have a trapezoidal cross-section with 1:1 side slopes, extending 300 meters in length. The geometry of the breach adhered to standard configurations outlined in U.S. Army Corps of Engineers guidelines and recent 2D studies conducted across Southeast Asia [4].

2.5. GIS-Based Floodplain Delineation

To define the flow direction from the breach point, the TOPAZ terrain analysis module was used in conjunction with WMS 7.1, mirroring methods in studies by Mustamin et al. [5] and Yekti et al. [9]. This step ensured that floodwaters were routed according to actual topographic flow paths, thereby helping identify vulnerable zones.

2.6. Visualization and Mapping

Final inundation results (flood depth, extent, and velocity) were visualized by overlaying model output onto georeferenced aerial imagery using GIS. Flood depth maps and water surface profiles were generated to determine whether floodwaters would reach the planned *Rusunawa* housing site.

2.7. Model Validation and Calibration

Validation and calibration procedures were applied to ensure the reliability of simulation outcomes. Model validation was done by comparing the simulated flood pathways with available historical references and remote sensing imagery of past flood events in the Jeneberang River basin. Although Buyang Village has not experienced significant inundation in recent records, flood-prone areas such as Sambung Jawa and Balang Baru—identified in the simulation as primary flow receivers—showed consistency with documented flood-prone zones. This agreement indicates that the model captures realistic flood routing behavior.

Calibration was performed through sensitivity testing of key hydraulic and breach parameters. Manning's roughness coefficients, assigned according to land-use categories, were adjusted within a ±20% range to assess their effects on water surface elevations and flood extents. Similarly, breach geometry parameters were varied, including breach width (200–400 m) and depth (±2 m). Results showed that while local water depths and velocities changed slightly, the overall flood routing pattern remained consistent, with Buyang Village protected by natural terrain barriers.

Additional calibration was conducted by adjusting the Probable Maximum Flood (PMF) inflow hydrograph by ±10%. The results confirmed the robustness of the model: even under increased inflow scenarios, floodwaters were consistently diverted away from the Rusunawa housing site. This indicates that the conclusion—that Buyang Village remains unaffected under a worst-case breach event—is stable under reasonable uncertainty ranges.

3. Results and Analysis

3.1. Hydrological Data and PMF Hydrograph

The simulation employed a Probable Maximum Flood (PMF) hydrograph derived from national-level studies to represent the worst-case inflow scenario [13]. The hydrograph spans a 100-hour duration, peaking at 4750 m^3/s during the 8th hour (Figure 3). This input served as the upstream boundary condition in the HEC-RAS model, driving the breach flow dynamics.

3.2. Terrain and Topographic Survey

A GPS-based topographic survey covering coordinates from 5.10°S to 5.22°S latitude and 119.375°E to 119.515°E longitude was conducted. Using UTM Zone 50 and WGS 1984 as projection references, the collected (X, Y, Z) points were interpolated into a high-resolution Digital Elevation Model (DEM) (Figure 4). This DEM established the geometric foundation for hydrodynamic modeling and was crucial in detecting the lowest elevation corridors for potential flood routing.

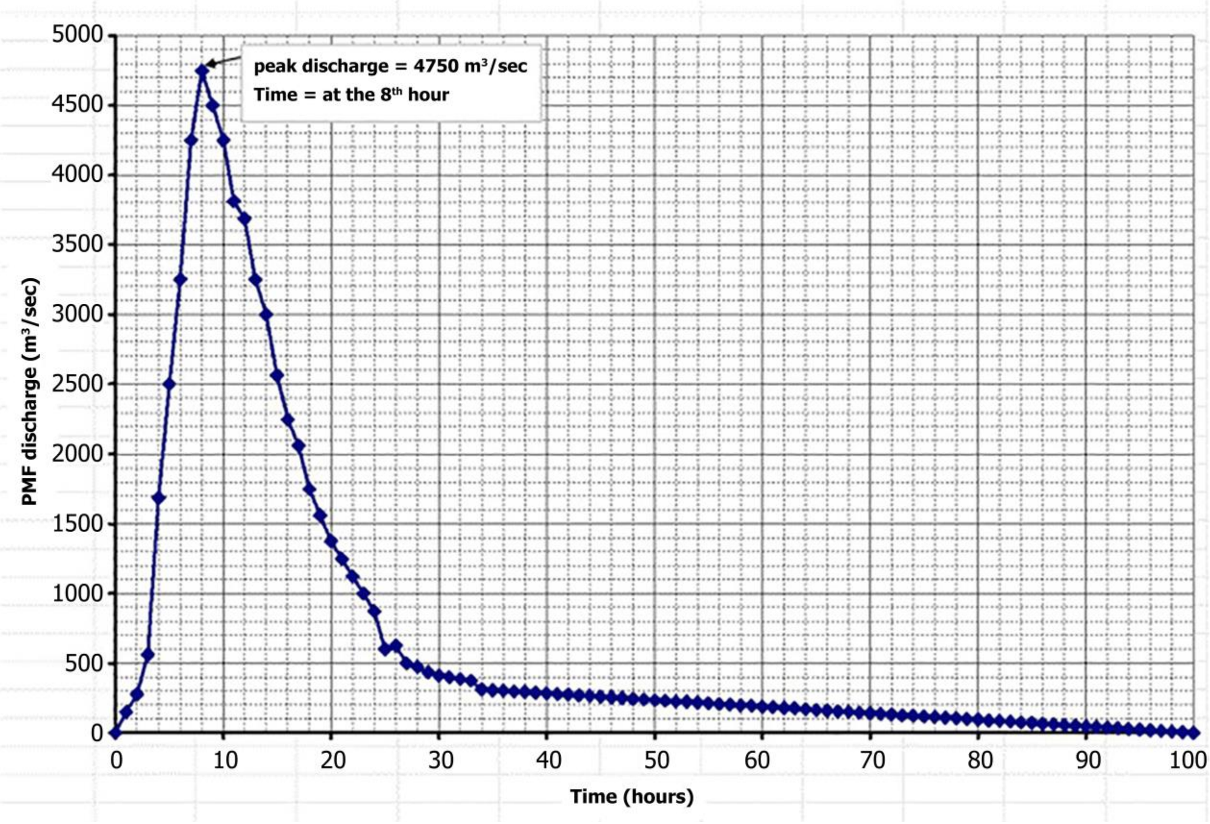

Figure 3. PMF hydrograph

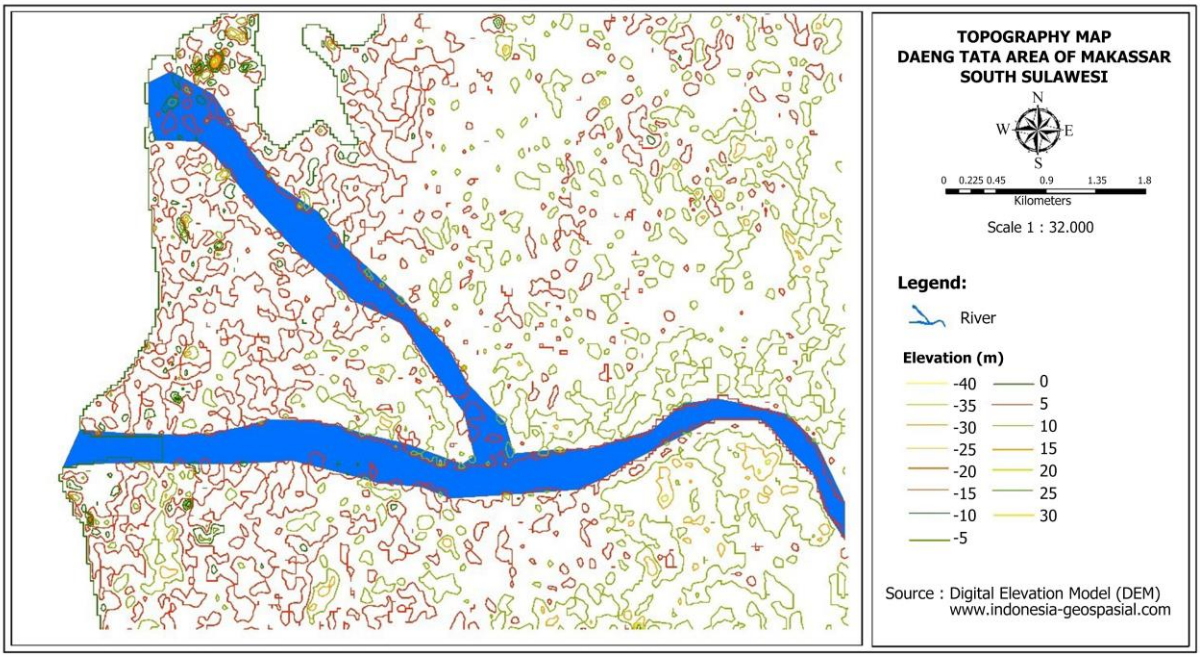

Figure 4. DEM as the result of GPS plotting on a topography map

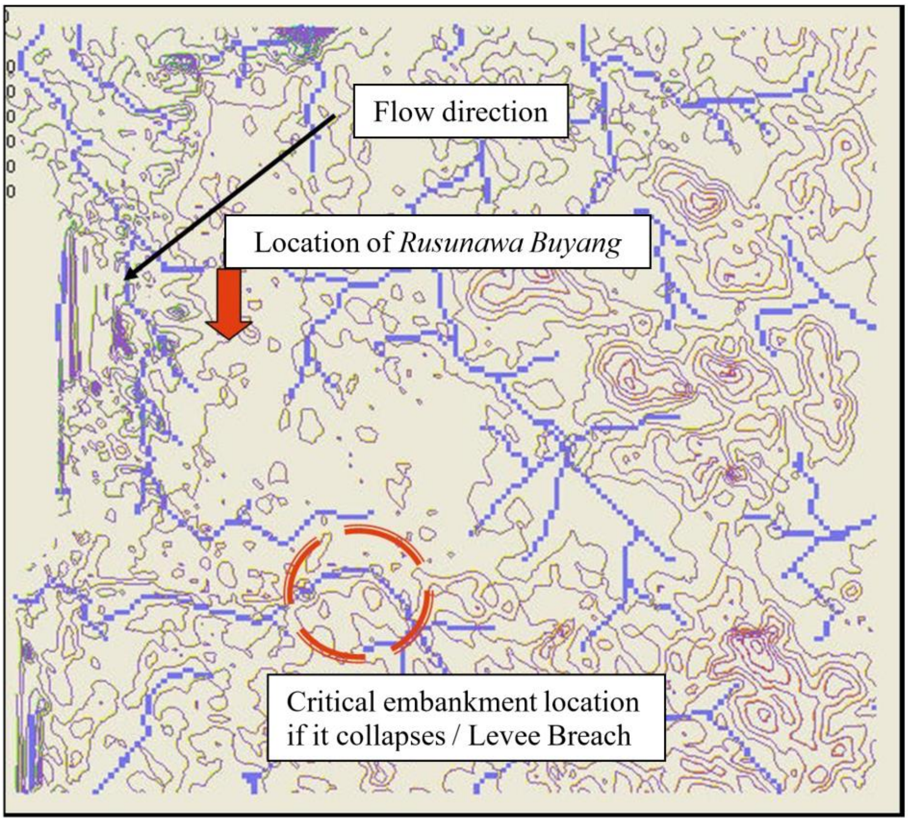

Figure 5. The Critical section of *Patompo* Dam and flow direction

3.3. Flow Path Analysis and Critical Breach Location

TOPAZ terrain analysis, integrated with WMS 7.1, was applied to derive natural flow paths based on surface slope and elevation. The analysis pinpointed a high-risk breach segment on the right bank of the Jeneberang River near Parangtambung Village. This section was designated as the model's primary failure point for levee breaching (Figure 5).

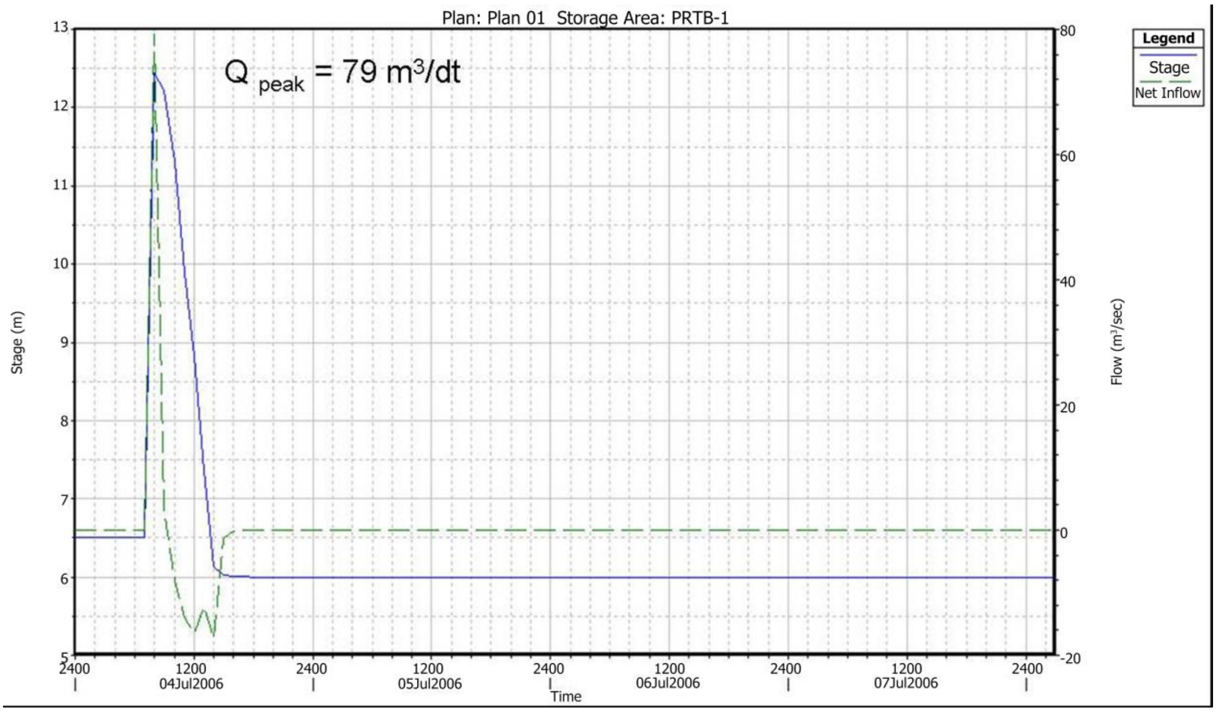

Figure 6. Stage –Hydrograph as a result of Levee Breaching Analysis

3.4. Levee Breach Simulation with HEC-RAS

A trapezoidal breach, 300 meters wide, with 1:1 side slopes and crest elevations descending from +12 m to +6 m, was implemented in the model. The breach outflow, simulated as a lateral inflow boundary condition, peaked at 86 m^3/s. The resulting hydrograph (Figure 6) characterizes the time-dependent discharge feeding into the downstream floodplain area labeled “Buyang Storage.”

3.5. Inundation Analysis and Flow Characteristics

Using the terrain-driven gradient, the unsteady flow simulation propagated the breach outflow across 25 modeled cross-sections. Water surface elevation plots (Figures 7 and 8) indicate that floodwaters primarily travel southeast toward Sambung Jawa and Balang Baru. DEM-guided routing and boundary friction coefficients limited the spread toward Buyang Village. Three-dimensional visualization (Figure 9) reveals that topographic high points shield the Rusunawa site from significant inundation. Velocity profiles (Figure 10) show peak flow speeds at constriction zones and drainage depressions, ranging from 1.2 to 2.7 m/s.

The simulation results show that the main flood flow is directed toward *Sambung Jawa* and *Balang Baru* villages, bypassing *Buyang* Village. While minor sheet flow may occur in low-lying areas, the *Rusunawa* housing site remains unaffected under the modeled breach scenario.

3.6. Final Flood Inundation Map

The final inundation extent map (Figure 11), overlaid on georeferenced aerial imagery, confirms that the floodwaters do not encroach upon the planned Rusunawa site. The simulation outcomes validate that the natural elevation buffer surrounding Buyang Village effectively diverts flow toward lower basins. Despite extreme PMF input, the housing area remains dry.

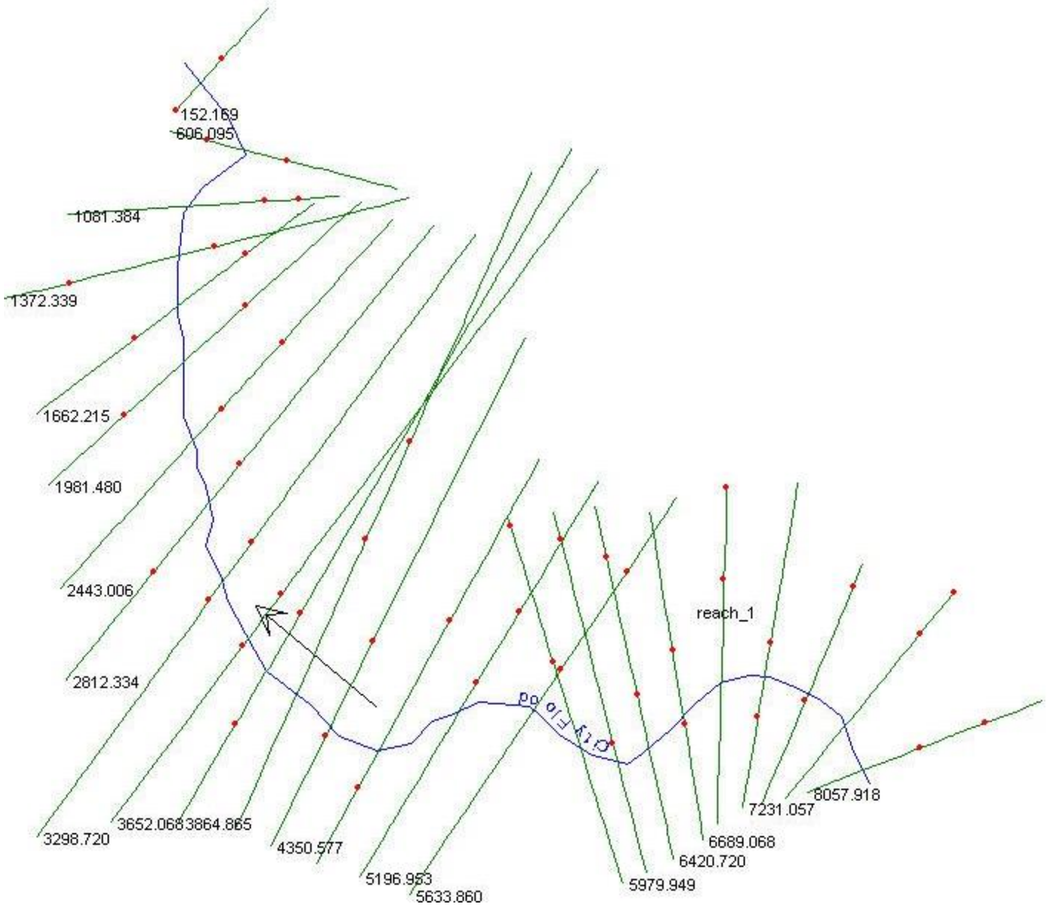

Figure 7. Schematic of the model in the HECRAS program

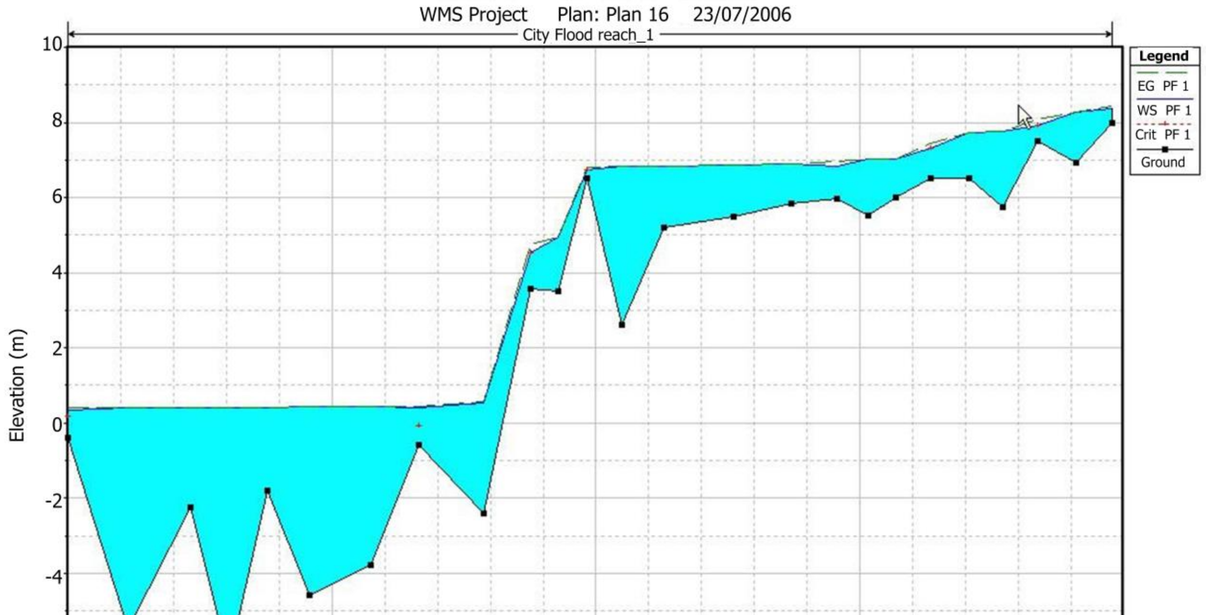

Figure 8. Long Section of Flood Declination

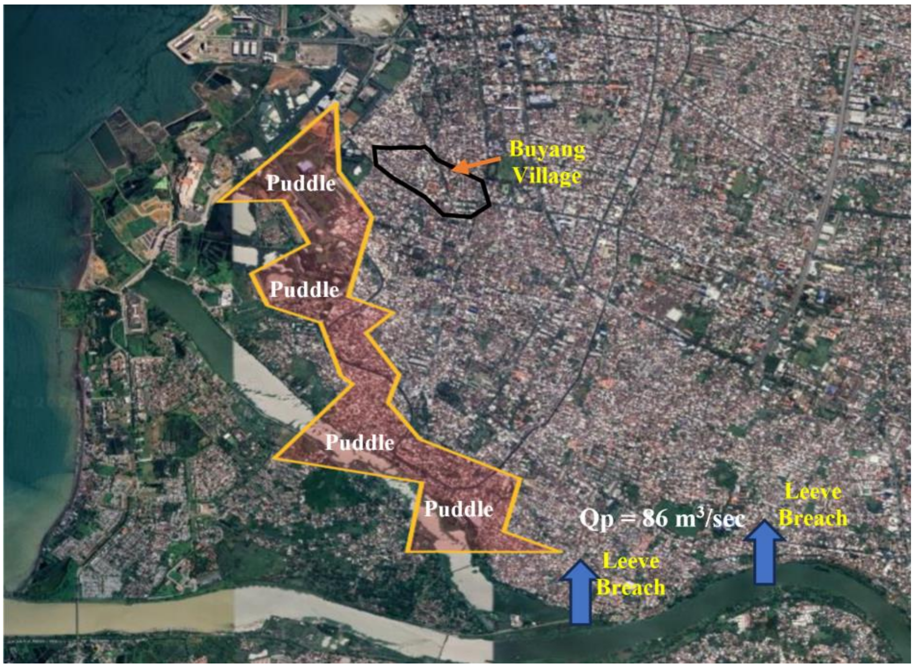

Figure 9. XYZ plot perspective

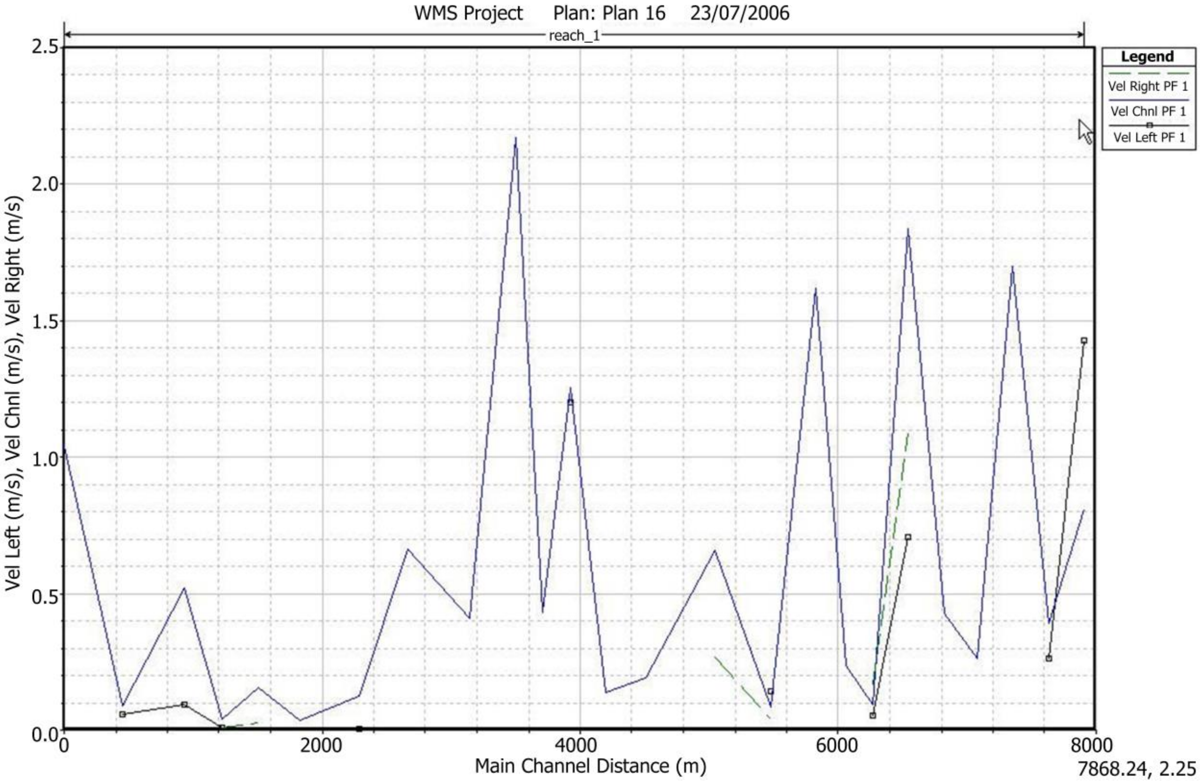

Figure 10. Flood flow velocity graph

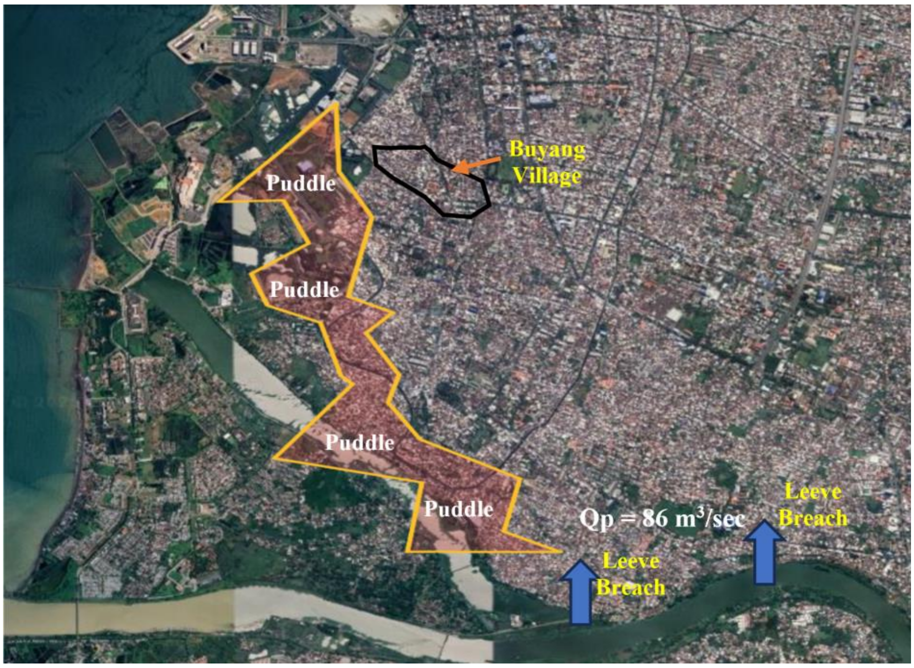

Figure 11. Flooding area caused by a levee breach

4. Discussion

This study employed a terrain-informed HEC-RAS 1D model integrated with GPS-based DEM data, WMS, and TOPAZ terrain analysis to evaluate the flood hazard caused by a hypothetical breach of the Patompo Embankment. The simulation findings indicate that the Rusunawa housing site in Buyang Village is shielded from breach-induced flooding due to protective elevation gradients.

The influence of terrain on flood propagation is demonstrated. The deflection of flow toward Sambung Jawa and Balang Baru is consistent with findings by Yekti et al. [9] and Saleh et al. [11], who emphasized the critical role of terrain analysis in accurate floodplain delineation. The study supports the use of high-resolution DEMs in flood modeling for urban planning and hazard mitigation.

Breach geometry is another key factor in predicting flood extent. The 300-meter trapezoidal breach produced an outflow of 86 m^3/s. The sensitivity of flood models to breach width, slope, and elevation underlines the need for context-specific breach parameterization [4, 12]. The implications for emergency preparedness are significant: models must account for variations in breach dimensions and multiple possible failure points.

In terms of modeling tools, the combination of HEC-RAS, WMS, and TOPAZ proved effective even under a 1D unsteady flow framework. Although 2D modeling offers higher spatial resolution, the current study demonstrates that accurate terrain-informed routing in 1D can still produce robust flood predictions. This is supported by Mustamin et al. [5], Lee and Kim [7], and Sharma and Katiyar [14], who validate the performance of similar configurations in Southeast Asian River Basins.

However, the study presents limitations, as it only considered a deterministic scenario. Future simulations should integrate probabilistic modeling approaches incorporating breach uncertainty and climate-adjusted inflow variability [13-16]. In addition, a sensitivity analysis should be conducted to examine flood responses under alternative breach lengths (e.g., 400 m) and DEM perturbations.

Lastly, urban expansion remains a latent threat, as increasing land development, impermeable surfaces, and climate shifts could alter the characteristics of runoff. Thus, the current flood-safe status of Buyang Village must be re-evaluated periodically. Risk maps should be updated with infrastructure development [8, 16].

This study demonstrates that flood resilience planning in Indonesian cities requires integrating spatial analysis, terrain modeling, and robust hydrodynamic tools. It recommends that policymakers consider terrain-based flood zoning to guide resilient housing development. To further elevate the scientific contribution and applicability of this study, several improvements are recommended: conduct ensemble modeling using multiple breach locations and varying widths (300–500 m); incorporate long-term land-use and rainfall projections to anticipate future flood risk; validate simulation outcomes using historical flood events or remote-sensing-derived inundation maps; and transition from 1D to 2D HEC-RAS [17,18] for complex urban terrain modeling. The discussions and synthesis are summarized in Table 2. These additions would increase the predictive reliability and practical relevance of the model outcomes for infrastructure and disaster preparedness planning in Makassar and similar flood-prone regions.

Table 2. Summarized discussions and synthesis of the current study

Theme	This Study	Supported By	Key Implication
Terrain Influence	Sloped terrain protects Buyang	Xie et al. [1], Hidayat [8]	Terrain should guide development zoning
Breach Parameters	300 m trapezoidal breach	Rahman [4], Yekti [9]	Site-specific breach modeling is critical
Modeling Framework	HEC-RAS 1D, WMS, TOPAZ	Mustamin [5], Latif [2], Aprizal [12]	Terrain-informed routing improves accuracy
Urban Planning Impact	The *Rusunawa* site is safe	Lee & Kim [7], Sharma [14]	Flood planning must consider urban expansion and climate change
Future Modeling Strategy	Deterministic, single breach	Peter et al. [13], Arxiv discussions [6]	Adopt probabilistic breach and uncertainty modeling

Validation and Calibration Summary

The simulation results were validated against historical flood-prone areas and remote sensing imagery, showing agreement in routing floodwaters toward Sambung Jawa and Balang Baru. Through sensitivity testing of Manning's roughness coefficients, breach dimensions, and PMF inflow variations, calibration confirmed that minor parameter adjustments did not alter the main finding: Buyang Village, including the Rusunawa site, remains outside the inundation zone. This consistency under varying assumptions reinforces the robustness of the model outcomes.

5. Conclusions

This study investigated the potential flood hazard in Buyang Village, Makassar, resulting from a hypothetical levee breach at the Patompo Embankment on the Jeneberang River. By integrating high-resolution GPS-based DEM data, HEC-RAS 1D unsteady flow simulations, and terrain analysis via WMS and TOPAZ, the flood propagation was modeled under a Probable Maximum Flood (PMF) scenario. The results confirm that, due to favorable topography and flow path divergence, the Rusunawa site in Buyang Village remains outside the inundation zone—even under a worst-case breach event. The breach outflow of 86 m^3/s was routed toward lower elevation zones, specifically Sambung Jawa and Balang Baru, while natural terrain buffers protected Buyang Village.

Validation against observed flood-prone areas and calibration through sensitivity testing of roughness coefficients, breach parameters, and inflow variations further support the robustness of this conclusion. Across all tested scenarios, the protective role of local terrain was consistently observed, reinforcing the reliability of the model results.

This study underscores three main points: (1) terrain exerts a dominant influence on flood distribution and should be prioritized in urban planning; (2) even 1D unsteady flow models can produce reliable insights when supported by accurate topographic inputs; and (3) deterministic analysis provides valuable first-order understanding but should be complemented by probabilistic approaches and multi-scenario simulations in future research. Expanding to 2D hydrodynamic solvers, integrating land-use change projections, and testing multiple breach configurations are recommended to further strengthen the predictive capability.

The findings are replicable for other urban settlements across Indonesia facing flood risks due to climate change and rapid urbanization. Adopting terrain-based flood zoning and aligning infrastructure development with dynamic hazard assessments is essential for policymakers and planners to enhance resilience.

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