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ECONOMIC LOSS ANALYSIS DUE TO THE FAILURE OF PAMUKKULU DAM IN TAKALAR, SOUTH SULAWESI, INDONESIA

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ABSTRACT: Every dam has the potential to fail due to disasters like earthquakes or other unforeseen events. Dam failures caused by extreme weather are particularly difficult to predict, which can lead to casualties and significant economic losses. This study aims to analyze the potential economic losses resulting from the failure of the Pamukkulu Dam, located in Takalar Regency, South Sulawesi Province, Indonesia. Extreme weather is considered the primary factor causing failure, projecting the worst-case scenario. The Probable Maximum Precipitation (PMP), the maximum rainfall that can occur in an area, was calculated using the Hershfield method, while the inflow discharge analyzed was the Probable Maximum Flood (PMF). The Synthetic Unit Hydrograph (SUH) was selected using the Creager method, resulting in ITB-1b being chosen. Dam failure and flood inundation simulations were conducted using HEC-RAS 6.6 software, based on two failure scenarios: overtopping and piping. The overtopping scenario produced the highest peak discharge, reaching 33,247.67 m^3/s, which was used to calculate economic losses for the most extreme condition. The simulation results showed that the inundated area due to dam failure under the overtopping scenario reached 110.79 km^2. Economic loss analysis was performed using the ECLAC method, based on the inundation area, land cover types, flood depth, combined with unit replacement values and damage factors. The estimated economic loss from the Pamukkulu Dam failure under the overtopping scenario is approximately IDR 1.12 trillion. The findings of this study are expected to support post-disaster recovery efforts and serve as a reference for developing flood risk management strategies.

Keywords: Dam Failure, Probable Maximum Precipitation, Probable Maximum Flood, Inundation Area, Economic Loss Analysis

1. INTRODUCTION

Pamukkulu Dam is a multifunctional infrastructure that offers various benefits, including flood control, raw water supply, irrigation, and tourism. However, behind these advantages, dam failure can trigger a massive flash flood that creates a serious disaster risk for downstream areas, including threats to human lives and property damage [1]. The occurrence of a flood disaster can significantly disrupt and cause substantial losses in the economic sector [2]. Naturally, the Pamukkulu Dam in Takalar Regency is no exception.

The failure of the Pamukkulu Dam would cause significant losses to Takalar Regency as well as to the surrounding regencies that are potentially affected. This is because Takalar Regency serves as one of the buffer zones for Makassar City. Dam failure can be caused by several factors, including earthquakes, extreme rainfall, structural damage to dam components, and terrorist attacks [3-5]. Dam failure due to extreme discharge (Probable Maximum Flood) is difficult to anticipate and is considered a natural cause of dam failure that commonly occurs [6]. Therefore, in this study, dam failure is modeled by considering the Probable Maximum Flood scenario.

Numerical modeling is one of the effective methods for analyzing and predicting dam failure [7]. Flood distribution analysis in the inundation area is a crucial aspect of dam failure studies. To simulate the flood spread in the inundated area, two-dimensional (2D) modeling using HEC-RAS 6.6 software can be employed. In this study, dam failure simulation is carried out using two scenarios: overtopping and piping. The scenario that produces the highest peak discharge will be used to simulate flood inundation to represent the most extreme condition. Beyond the scenarios applied in this study, it is also important to recognize that dam-break modeling and economic loss estimation methods have undergone significant advancements in recent years.

In recent years, dam-break modeling has advanced considerably with the application of more sophisticated methods to improve flood simulation accuracy. In addition to HEC-RAS 2D, other software such as BASEMENT, Iber, and TELEMAC-2D have been widely used to represent two-dimensional flood flows and even support probabilistic analyses for dam safety assessments [8]. At the same time, economic loss estimation methods have also progressed, including the use of locally calibrated depth–damage functions, probabilistic risk analysis, and sensitivity testing to capture uncertainties [9]. However, such approaches are still rarely applied in Indonesia. Therefore, this study provides added value by integrating dam-break modeling and economic loss estimation within the Indonesian context.

In this study, the analysis focused on the Probable Maximum Flood (PMF) scenario, as it is internationally recognized as the most conservative representation of extreme hydrometeorological conditions. PMF is defined as the largest flood that could theoretically occur within a given catchment and is widely adopted in dam safety design as a worst-case scenario [10-11]. While other types of extreme weather events, such as seasonal storms or design floods with specific return periods (e.g., Q1000), are relevant, they typically produce substantially smaller peak discharges compared to the PMF [11]. Therefore, to assess the consequences of dam failure under the most critical conditions, this study restricted the analysis to the PMF scenario. Based on the PMF scenario, the next step of this study is to evaluate its potential impacts through flood inundation simulation and subsequent economic loss analysis.

The flood inundation simulation results are then used to analyze economic losses using the ECLAC method. This method has been widely applied in various studies [12] and can assess losses caused by flood inundation [13]. The economic loss analysis is expected to accelerate the post-disaster recovery process and serve as a reference in developing flood risk management strategies.

The remainder of this paper is structured as follows: Section 2 explains the research significance, the Pamukkuu Dam's role, and the methods used to estimate potential economic losses due to dam failure. Section 3 describes the study area, dam and watershed characteristics, and the methodology, including hydrological analysis, reservoir routing, and flood propagation modeling. Section 4 presents the result discussion, including flood propagation, inundation, and economic impact analysis. Section 5 concludes the study, summarizing the dam failure simulation, flood inundation, estimated economic losses, and implications for disaster mitigation and planning recommendations.

2. RESEARCH SIGNIFICANCE

This study holds strategic importance in supporting disaster risk mitigation and dam failure impact management in Indonesia. The Pamukkulu Dam is vital for irrigation, flood control, and water supply. However, its failure due to extreme events like Probable Maximum Flood (PMF) could lead to significant economic losses. By employing HEC-RAS simulations and the ECLAC method, this research provides quantitative estimates of financial impacts. The results are expected to assist policymakers and technical agencies in developing effective, data-driven risk management strategies, while also contributing to scientific literature on dam failure loss analysis.

3. MATERIALS AND METHOD

3.1 Study Area

Pamukkulu Dam is located in the upstream area of the Pappa River in Takalar Regency, South Sulawesi Province, with coordinates at 5°23'58.43"S and 119°35'42.03"E. Takalar Regency covers an area of 566.51 km², consisting of ten districts and one hundred villages, with a population of 292,183 people according to data from the Directorate General of Population and Civil Registration (Dukcapil), Ministry of Home Affairs of Indonesia. The study area map is shown in Fig. 1.

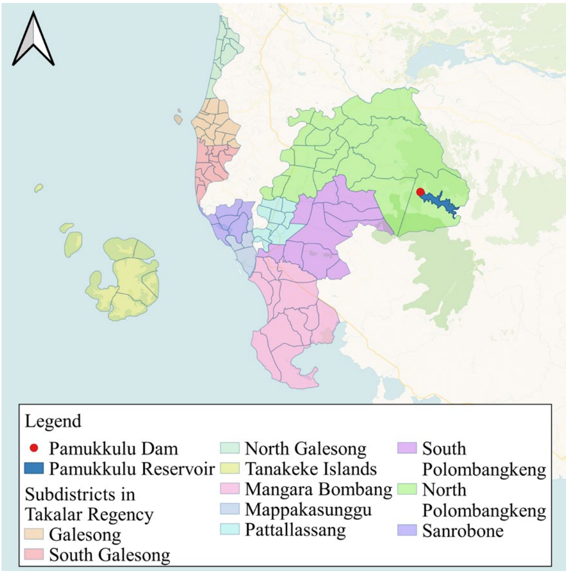

Fig. 1 Map of the Study Area

3.2 Dam Watershed Characteristics

The topographic data used in this study were obtained from the Digital Elevation Model (DEM) imagery provided by the Geospatial Information Agency (BIG) of Indonesia, with a spatial resolution of 0.27 arcseconds. Through topographic data analysis processed using QGIS, the Pamukkulu Watershed (DAS) was found to have an area of 89.49 km², a river length of 23.31 km, a river length to the centroid point of 12.51 km, and a river slope of 0.04.

Meanwhile, land cover data were sourced from the Indonesian Ministry of Environment and Forestry (KLHK). Based on land cover classification, the Pamukkulu Watershed is predominantly covered by mixed dryland agriculture, accounting for 57.77% of the total study area. Additionally, hydrologic soil group data were obtained from the Global Hydrologic Soil Groups database. The Pamukkulu Watershed is predominantly classified as soil group type D, which indicates high runoff potential. This group is characterized by soils with less than 50% sand and more than 40% clay content, covering 54.55% of the study area. The Pamukkulu Watershed map is shown in Fig. 2, the land cover map in Fig. 3, and the hydrologic soil group map in Fig. 4.

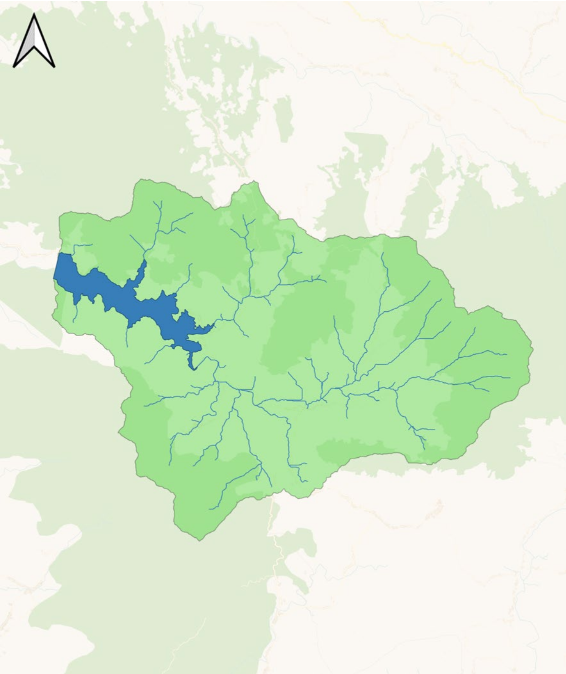

Fig. 2 Pamukkulu Watershed Map

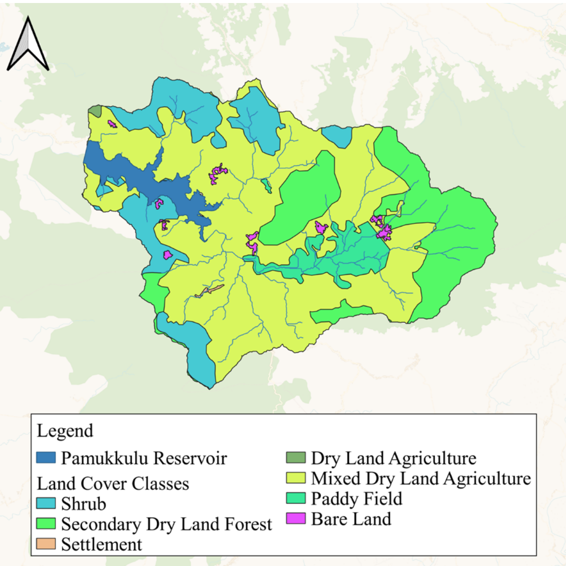

Fig. 3 Land Cover Map of the Pamukkulu Watershed

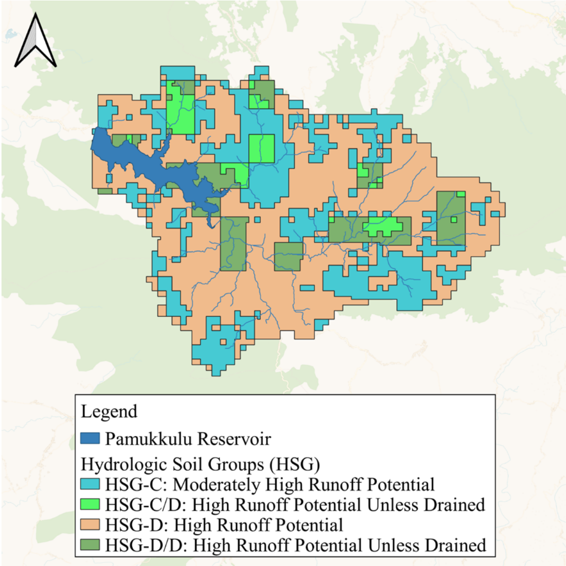

Fig. 4 Hydrologic Soil Group Map of the Pamukkulu Watershed

3.3 Methodology

The first stage of this study is the hydrological analysis, which was conducted using 20 years of rainfall data (2001-2020) to obtain the value of Probable Maximum Precipitation (PMP). Subsequently, the calculation of the Probable Maximum Flood (PMF) discharge was carried out using topographic data, hydrologic soil group information, and land cover data. The next stage involves dam failure analysis, including failure simulation and flood inundation modeling using HEC-RAS 6.6 software.

HEC-RAS is an open-source software developed by the US Army Corps of Engineers and has been widely used in various studies for hydrologic simulation and hydraulic modeling [14]. This software allows users to perform two-dimensional (2D) unsteady flow modeling, which is based on the 2D Saint-Venant equations and solved using the finite difference method. In addition to model selection, the adequacy of hydrological data length is another critical factor influencing the reliability of flood estimation.

In general, long-term datasets (≥30 years) are recommended to capture long-term climate variability. However, in Indonesia, the official guideline SNI 2415:2016 stipulates that a minimum of 20 years of data is required for flood discharge estimation, using either rainfall or streamflow records (if available). This standard specifically employs Annual Maximum Daily Rainfall (AMDR) as the basis for design rainfall determination.

In this study, we followed this guideline by utilizing 20 years of rainfall data (2001-2020). To enhance reliability, station data were supplemented with GPM satellite data, which were bias-corrected and validated through outlier, trend, stability, and independence tests in accordance with the SNI. Moreover, the Hershfield method applied in the PMP estimation is conservative, ensuring that the resulting PMF values adequately represent worst-case conditions despite the limited dataset length. Nevertheless, future studies are encouraged to utilize longer datasets or climate reconstructions (e.g., reanalysis data) to capture multi-decadal variability.

Building upon the hydrological and hydraulic analyses, the subsequent step involves assessing the socio-economic consequences of the simulated dam-break scenario. The flood inundation simulation results serve as the basis for the economic loss analysis. Economic losses are calculated using the ECLAC method, supported by spatial analysis using QGIS software to identify flood-affected areas.

3.4 Hydrology Analysis

Rainfall data for the hydrological analysis in this study were obtained from the Pamukkulu Station. However, due to data limitations at the station, satellite-based rainfall data from the Global Precipitation Measurement (GPM) were also utilized. Before being used, GPM data must be corrected against ground station data [15]. One commonly used correction method in satellite rainfall analysis is bias correction. To evaluate the quality of the corrected satellite rainfall data, one of the parameters used is the correlation coefficient [16]. A correlation coefficient value between 0.8 and 1.0 is considered to indicate a very strong relationship [17].

Before correcting the satellite rainfall data (GPM), the data from the Pamukkulu Station (ground station) must first undergo a validation test. This step is essential to ensure that the reference station provides high-quality data suitable for bias correction. The validation tests in this study refer to the Indonesian Standard Guidelines, which include outlier, trend, stability, and independence tests. Based on the results, the data from the Pamukkulu Station meet all validation criteria and are therefore considered suitable for use as a reference in the bias correction of the GPM data.

Subsequently, the GPM data were corrected against the rainfall data from the Pamukkulu Station using the bias correction method. The correction results yielded a correlation coefficient of 1.0, indicating a very strong relationship between the corrected GPM data and the observed data. The corrected GPM data were then revalidated, showing that they passed all validation tests and were therefore considered suitable for use in the subsequent analyses.

The subsequent rainfall data processing refers to SNI 2415-2016 concerning the Procedures for Calculating Design Flood Discharge [18]. Probable Maximum Precipitation (PMP) is a widely used concept among water resources experts for determining the Probable Maximum Flood (PMF). The PMP analysis was conducted using the Hershfield method, based on SNI 7746-2012, and utilized the corrected daily maximum rainfall data from GPM.

The obtained PMP value was then multiplied by the Areal Reduction Factor (ARF). ARF is used to convert point rainfall estimates into average areal rainfall estimates and serves as a crucial component in conventional flood risk assessments. This approach is widely applied in hydrologic and hydraulic modeling, particularly in flood hazard applications such as inundation mapping and flood risk mitigation [19]. Each region has a different ARF curve, which is derived from the Indonesian Standard Guidelines for hydrological analysis. Based on the analysis results, the PMP value for the Pamukkulu Watershed (DAS) is 610.90 mm.

In addition, the Indonesian Standard Guidelines also provide several types of rainfall distributions for hydrological analysis purposes. In this study, the rainfall distribution used is PSA-007 with a rainfall duration of 6 hours. Effective rainfall serves as the input required for calculating the Probable Maximum Flood (PMF) discharge. It is obtained by subtracting rainfall losses due to infiltration from the total precipitation.

Infiltration is calculated using the Soil Conservation Service Curve Number (SCS-CN) method. The Curve Number (CN) method was selected due to its high accuracy and ease of application [20]. A study conducted [21] also showed that the CN method provides the highest level of accuracy compared to other infiltration estimation methods.

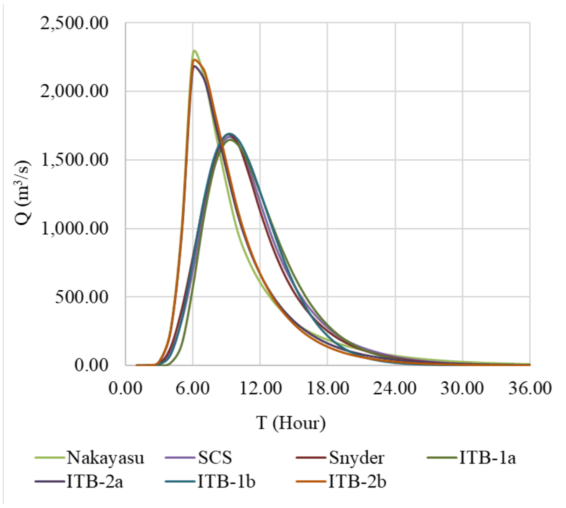

Fig. 5 PMF Discharge (Q_{PMF}) of Pamukkulu Dam

Infiltration calculations consider land cover conditions and hydrologic soil groups as the primary parameters. In addition, land cover data were also used to determine surface roughness values (Manning's n), as flood propagation is highly influenced by the type of land cover [22]. Based on the analysis results, the Curve Number (CN) value for the Pamukkulu Watershed is 83.94.

Next, to determine the inflow discharge of the Probable Maximum Flood (PMF), a Synthetic Unit Hydrograph (SUH) approach was used. The SUH methods applied in this study include Nakayasu (Alpha = 2.0), SCS, ITB-1a (Exact), ITB-2a (Exact), ITB-1b (Exact), and ITB-2b (Exact). The hydrograph calculation results from the Synthetic Unit Hydrograph methods are presented in Fig. 5.

The Envelope Curve method is one of the approaches used in dam safety planning and the Creager method is one of the most widely used Envelope Curves in the literature [23]. Accordingly, this study adopts the Creager method to estimate the maximum discharge that may occur in the Pamukkulu Watershed. The equations for the Creager method are presented in Eqs (1)-(2).

$$q = (46\ x\ 0.02832)\ C\ (0.3861\ x\ A)^{a} \quad (1)$$

$$a = 0.894\ (0.3861\ x\ A)^{-0.048} \quad (2)$$

Where: q is the peak discharge (m³/s), A is the watershed area (km²), and C is the Creager coefficient.

Based on the Water Inventory Study conducted by PLN Indonesia, the Creager coefficient (Q_{PMF}) used for the Sulawesi region is 90. The closer the modeled discharge to the maximum discharge according to the Creager curve, the more accurate the model is considered to be. However, the peak discharge from the Synthetic Unit Hydrograph (SUH) calculations must not exceed the upper limit defined by the Creager curve. Among the SUH methods analyzed, the ITB-1B method was selected as it produced the peak discharge value closest to the Creager curve. A comparison diagram between the results of the SUH methods and the Creager curve is shown in Fig. 6.

In line with these results, this study employed the ITB-1B Synthetic Unit Hydrograph (SUH) because its results showed the closest agreement with the Creager curve, which is internationally recognized as a reference for extreme flood estimation [24]. Comparisons with other methods, such as ITB-2a-b, Nakayasu, ITB 1-a, SCS, and Snyder indicated larger deviations from the Creager curve. Therefore, since the objective of this research was to analyze Probable Maximum Flood (PMF) scenarios, ITB-1B was selected as the most representative method.

In this study, the ITB-1B method was adopted as it complies with the hydrological guidelines currently applied in Indonesia, where this method is recommended for synthetic unit hydrograph analysis in design flood estimation. In addition, its peak discharge results are consistent with the Creager coefficient for the Sulawesi region (90), ensuring that the flood estimates remain within acceptable design limits. Therefore, the selection of ITB-1B is considered appropriate and aligned with national standards, even though this study does not provide statistical metrics or sensitivity analysis among different SUH methods.

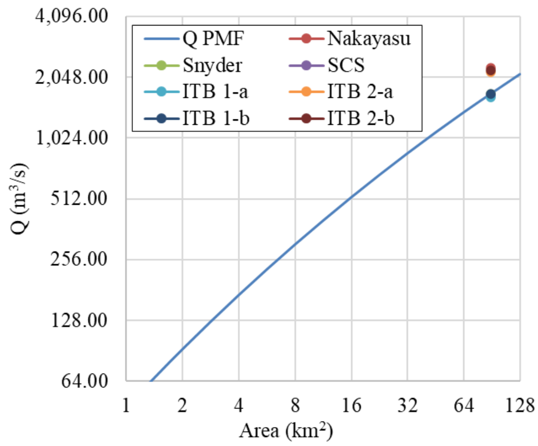

Fig. 6 Comparison Diagram Between SUH Results and the Creager Curve

As no historical flood peak observations were available at downstream gauges to serve as a benchmark, the PMF analysis in this study was carried out using the Creager method. This method is officially recommended in Indonesian hydrological guidelines for synthetic unit hydrograph analysis in design flood estimation. The results indicate that the peak discharge obtained using the ITB-1B method shows only a very small deviation from the Creager coefficient for the Sulawesi region (C = 90), ensuring that the flood estimates remain within acceptable design bounds. Furthermore, the Creager curve is widely applied internationally as a reference for extreme flood estimation, which provides additional confidence in the validity of the adopted approach.

3.5 Reservoir Routing

In this study, the reservoir routing process was modeled using HEC-RAS 6.6 software, with dam failure parameters considered as the primary input. These parameters were developed based on the technical data of the Pamukkulu Dam obtained from PT WIKA–DMT (KSO). The failure scenarios analyzed include two primary mechanisms: overtopping and piping, with variations in breach location at the base, middle, and top of the dam body.

Overtopping is a condition in which the water volume in a dam exceeds its capacity, causing water to overflow through the top or sides of the dam and

Table 1. Parameters Used in the Pamukkulu Dam Failure Simulation

Parameters	Scenario				Units
	Overtopping	Bottom Piping	Middle Piping	Top Piping	
Breach Side-Slope Ratio H:V	1H:1V	0.7H:1V	0.7H:1V	0.7H:1V	
Average Breach Width	99	79	79	79	m
Piping Coefficient	-	0.6	0.6	0.6	
Piping Elevation	-	85	100	115	
Breach Formation Time	1.15	1.15	1.15	1.15	hour
Trigger Elevation	129.2	129	129	129	m

flow downstream [25]. Meanwhile, piping occurs when water flows through cracks or voids in the soil or materials around the dam foundation, leading to internal erosion and potentially causing structural damage [26].

The dam failure parameters in this study were calculated using empirical formulas developed by [27], which include the side-slope ratio, average breach width, and breach formation time. The regression equations used are presented in Equations (3) and (4).

$$B_{ave} = 0.27 K_0 V_w^{0.32} h_b^{0.04} \tag{3}$$

$$T_f = 63.2 \sqrt{\frac{V_w}{g h_b^2}} \tag{4}$$

Where B_{ave} is average breach width (m), K_0 is constant (1.3 for overtopping and 1.0 for piping conditions), V_w is reservoir volume (m³), h_b is breach height (m), T_f is breach formation time (s), and g is acceleration due to gravity (9.81 m/s²).

This study employed the empirical equations proposed by [27], which remain among the most widely used and validated methods for estimating embankment dam breach parameters. These equations were developed from a large dataset of historical dam failure cases worldwide, making it a standard reference in many dam-breach modeling studies. Recent studies continue to adopt Froehlich's equations due to their robustness and relatively simple data requirements, which is particularly relevant under data-limited conditions such as those at Pamukkulu Dam.

Although newer formulations are available and multi-method comparisons could help reduce uncertainties, the scope of this study was focused on simulating representative dam-break scenarios for economic loss estimation rather than performing sensitivity analyses of different breach prediction methods. Accordingly, the use of Froehlich's equations is considered appropriate for this context, while sensitivity analyses using alternative breach equations are recommended for future research. In this regard, several dam failure parameters need to be specified to support the simulation process.

Dam failure parameters such as breach location, dimensions, and development time are critical in dam failure modeling [28], as they significantly influence the estimated peak outflow discharge from the dam [29]. Table 1 presents the parameters used in the Pamukkulu Dam failure simulation.

3.6 Flood Propagation Model

The two-dimensional (2D) flood propagation in this study was modeled using HEC-RAS 6.6 software. This modeling is based on a mathematical representation known as the Saint-Venant equations. These equations consist of the continuity equation (principle of mass conservation) and the momentum equations (principle of momentum conservation). The mathematical form of these equations is presented in Eqs. (5)-(7).

Continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{5}$$

Momentum x-direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} - g(So_x - Sf_x) = 0 \tag{6}$$

Momentum y-direction:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y} + u\frac{\partial v}{\partial x} + g\frac{\partial h}{\partial y} - g(So_y - Sf_y) = 0 \tag{7}$$

Where h is water depth, u and v are the velocity of the x- direction and y-direction respectively, g is the gravitational acceleration, So_x and So_y are the depth gradient for the x-direction and y-direction respectively, and Sf_x and Sf_y are energy grade lines for the x-direction and y-direction. To ensure model stability, the time step is estimated based on the Courant-Friedrichs-Lewy (CFL) condition, as shown in Eq. (8).

$$Cr = \frac{c\Delta t}{\Delta x} = \frac{\sqrt{gh}\Delta t}{\Delta x} \leq 1 \quad (8)$$

Flood propagation in this study was modeled using the Shallow Water Equations (SWE), as these equations can represent rapid water flow, such as in dam break scenarios [30]. To enhance model reliability, detailed modeling was performed, particularly in the 2D Flow Area, by incorporating breaklines to ensure that topographic features are accurately represented in the model. The grid size in the 2D flow area was set to 100 × 100 meters, while a finer grid of 25 × 25 meters was applied along the breaklines to improve the accuracy of flow propagation, especially along river cross-sections. Since the downstream boundary of the model directly discharges into the sea, tidal boundary conditions were required. In this study, tidal data were obtained from the Indonesian Geospatial Reference System (SRGI).

4. RESULT AND DISCUSSION

4.1 Flood Propagation and Inundation

Flood routing in the dam failure simulation was carried out to determine the maximum outflow discharge for each analyzed scenario. The most extreme peak discharge value from these simulations was then used as the basis for modeling the flood inundation extent, representing the worst-case scenario. Based on the routing results, the highest outflow discharge occurred in the overtopping scenario, with a peak discharge of 33,247.67 m³/s. A summary of the flood routing results for all Pamukkulu Dam failure scenarios is presented in Table 2. This outcome guided the selection of the scenario to be used for subsequent analysis.

In this study, several dam failure modes were modeled, including overtopping and piping at different elevations. The simulation results indicated that the overtopping scenario produced the largest peak discharge compared to other modes. Therefore, the inundation analysis and economic loss estimation were based on the overtopping scenario. This selection was made because the primary objective of the research is to evaluate the worst-case consequences of dam failure, ensuring that the analysis represents the most critical condition relevant to dam safety and risk assessment. To place these findings in a broader perspective, it is useful to consider past dam failures that have occurred in Indonesia. In the Indonesian context, several significant dam failures have historically occurred due to various causes. For example, the failure of the Situ Gintung Dam in 2009 was triggered by a combination of factors, including the aging embankment, inadequate spillway capacity, and operational issues. Meanwhile, the failure of the Way Ela Dam in Central Maluku in 2013 occurred as a result of increased water pressure inside the dam, which suddenly caused the embankment to collapse. According to records from the Indonesian National Disaster Management Authority [31], these cases indicate that overtopping and piping are the two most critical dam failure mechanisms in Indonesia.

In line with this, the present study models these two mechanisms (overtopping and piping) under the Probable Maximum Flood (PMF) condition, which represents the most extreme hydrometeorological scenario. Thus, the analysis not only reflects historically relevant failure mechanisms in Indonesia but also evaluates them within a conservative framework consistent with international practices in dam safety assessments.

Table 2. Recapitulation of Peak Discharge from Pamukkulu Dam Failure Scenarios

Scenario	$Q_{outflow}$ (m³/s)
Overtopping	33,247.67
Top Piping	27,415.01
Middle Piping	28,594.90
Bottom Piping	28,509.73

The modeling results indicate that the dam-break scenario due to piping produced a peak discharge of approximately 85% compared to the overtopping scenario. This value remains physically reasonable, as demonstrated in a two-dimensional modeling study of the Mangla Dam, where the peak discharge resulting from piping failure was reported to reach up to 98% of that of the overtopping scenario [32]. Accordingly, the subsequent analysis focused on flood inundation patterns associated with the overtopping scenario.

Based on the results of flood inundation modeling, the flood-affected area from the Pamukkulu Dam failure under the overtopping scenario reached approximately 110.79 km², inundating six sub-districts and 45 villages. To evaluate the spatial distribution of flood impacts on land use and settlements, an overlay analysis was performed using QGIS software by integrating the flood extent map, land cover map, and administrative boundary map. The analysis revealed that, under the overtopping scenario, inundated paddy fields covered 7,903.64 hectares, representing 71.34% of the total flooded area, as summarized in Table 3. The schematic of the HEC-RAS model is provided in Fig. 7, while the corresponding flood depth distribution map is shown in Fig. 8. Although these modeling results deliver valuable insights into the potential extent and severity of flooding, it remains essential to critically examine their reliability given the absence of empirical dam failure data.

Table 3. Land Cover Classes in Takalar Regency and Distribution of Flooded Areas

Land Cover	Land Cover Area (Ha)	Land Cover Percentage
Shrub	68.80	0.62%
Mangrove Forest	243.39	2.20%
Residential	902.12	8.14%
Mixed Dryland Agriculture	249.34	2.25%
Paddy Field	7,903.64	71.34%
Fishpond	1,711.49	15.45%
Bare Land	0.06	0.001%

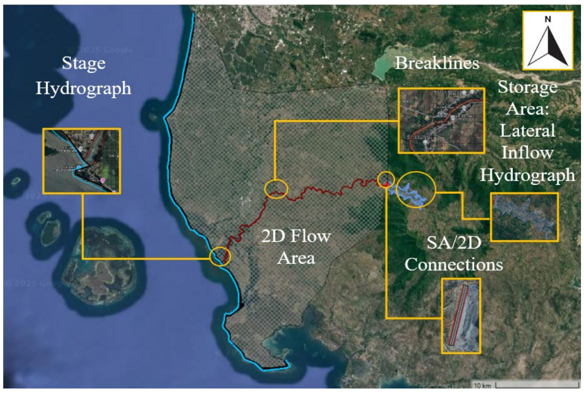

Fig. 7 HEC-RAS Model Scheme

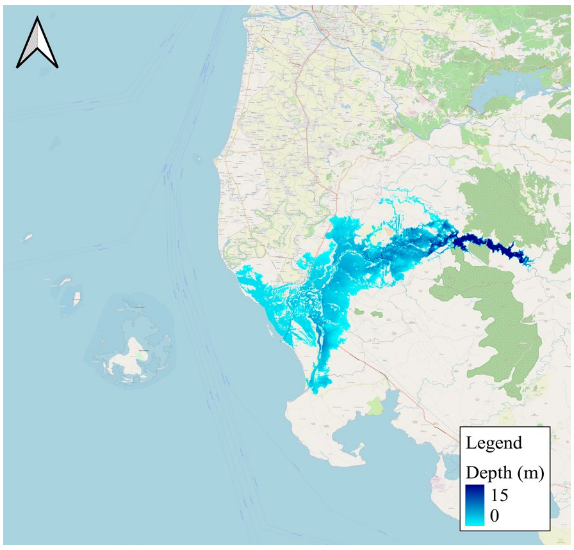

Fig. 8 Inundation Depth Map

Direct validation of the simulated inundation extent (110.79 km² with 45 affected villages) could not be performed since the Pamukkulu Dam has not experienced any failure. Nevertheless, the model was developed using HEC-RAS 2D, which has been widely applied and validated in numerous dam-break and flood studies. The simulated inundation pattern follows the natural downstream river morphology, and the affected villages correspond to settlements located within the floodplain. Moreover, the inundation extent is consistent with the reservoir storage capacity and the peak discharge under the PMF scenario, which specifically represents the worst-case condition. To further enhance the representativeness of the simulation, Manning's roughness coefficients were adjusted according to actual land-use conditions, following the HEC-RAS guidelines, rather than using uniform default values. Therefore, the simulation results are considered representative.

4.2 Economic Analysis

Economic losses resulting from dam failure include damage to residential, agricultural, commercial, industrial, and other affected areas, but do not cover the loss or damage of the dam itself or other structures associated with the dam's intended functions [33]. In this study, the method used to estimate economic losses due to dam failure involves calculating direct damage caused by inundation, using the ECLAC (Economic Commission for Latin America and the Caribbean) approach.

Economic loss analysis using the ECLAC method can assist the government in budgeting and planning for rehabilitation and reconstruction phases [34]. The economic losses are calculated based on the extent of inundation and the flood depth within the study area. The flood extent obtained from dam failure modeling is combined with replacement unit values and vulnerability factors to estimate the economic losses in each affected land-use category. To maintain clarity and focus, the analysis emphasized only the essential variables, while other aspects were excluded from the modeling scope.

In this study, parameters such as flood arrival time, duration, and evacuation time requirements were not included in the simulations, as the primary objective was to estimate the potential economic losses from a hypothetical failure of the Pamukkulu Dam. For this purpose, the key variables required were flood depth and inundation extent derived from the HEC-RAS 2D modeling. Other hydrodynamic variables, such as flood arrival time, inundation duration, and evacuation requirements, would be more relevant in studies focusing on dam failure risk assessment or the development of emergency action plans. Thus, the economic loss estimation relied primarily on flood depth, inundation extent, and land cover data to quantify potential damages.

In the ECLAC method, economic losses due to flooding are influenced not only by the extent of inundation but also by the distribution of flood depth and land cover in the affected area [35]. The land cover serves as a key parameter in the depth-damage function, which is used to analyze the level of damage caused by flooding. The land cover data used in this economic analysis is based on 2024 satellite imagery obtained from Sentinel-2. According to the analysis, Takalar Regency is predominantly covered by paddy fields, accounting for 48.77% of the total area.

The spatial distribution of flood depth and the extent of inundated areas are important to consider, as these factors determine the variation in damage levels for each land use class, which ultimately has a significant influence on the total economic loss values.

Depth-damage functions are generally derived through two methods. The first method is based on empirical data from past flood events, while the second method involves a hypothetical analysis that considers land cover patterns, object types, questionnaire surveys, and other relevant sources. The latter is known as the synthetic stage-damage function approach [36]. In this study, the replacement unit values, and vulnerability curves (depth-damage functions) were adopted from the study conducted by [37-38]. The replacement unit values were developed based on expert meetings and workshops, using fuzzy cognitive mapping to define the relationship between land classes and economic exposure. These values represent the maximum economic exposure per hectare for each land class. The maximum economic exposure values are presented in Table 4.

Meanwhile, the depth-damage functions were formulated through a series of expert meetings to define initial functions, followed by validation workshops, and synthesized using fuzzy cognitive mapping to produce the final curves. These curves indicate the damage fraction as a function of inundation depth for each land cover class. The depth-damage function curves are shown in Fig. 9. Open space refers to natural vegetation areas that are not intensively cultivated, such as shrublands and bare land. Residential indicate settlement areas. Agriculture includes all types of agricultural land, including paddy fields and mixed dryland farming. Meanwhile, Swamp and Pond is used to classify areas such as fishponds and mangrove forests that are utilized for aquaculture or represent brackish water ecosystems.

The damage fractions at each inundation depth were determined using depth-damage functions derived from the ECLAC framework and adapted to Jakarta-specific vulnerability curves. These curves were developed by [37-38] through a series of expert meetings to formulate the initial functions, followed by validation workshops for refinement, and synthesized using fuzzy cognitive mapping to establish the final curves. The functions are represented as empirical non-linear curves that relate flood depth to asset damage percentages, with different saturation thresholds depending on land use categories.

In this study, the conversion of replacement unit values from USD to Indonesian Rupiah was carried out using the reference exchange rate from Bank Indonesia (JISDOR) as of June 25, 2025, which was IDR 16,292 per USD. The use of the current exchange rate ensures that the economic values used in the analysis reflect actual conditions in the analysis year. Based on the results, the estimated

Table 4. Maximum Economic Exposure per Land Cover Class

Land Use Class	Maximum Economic Exposure Value (Thousand USD/Ha)
Government Facility	301
Industry	517.9
Commercial and Business	517.9
Residential	150.6
Agriculture	1.6
Swamp and Pond	3.8
Open Space	3.1

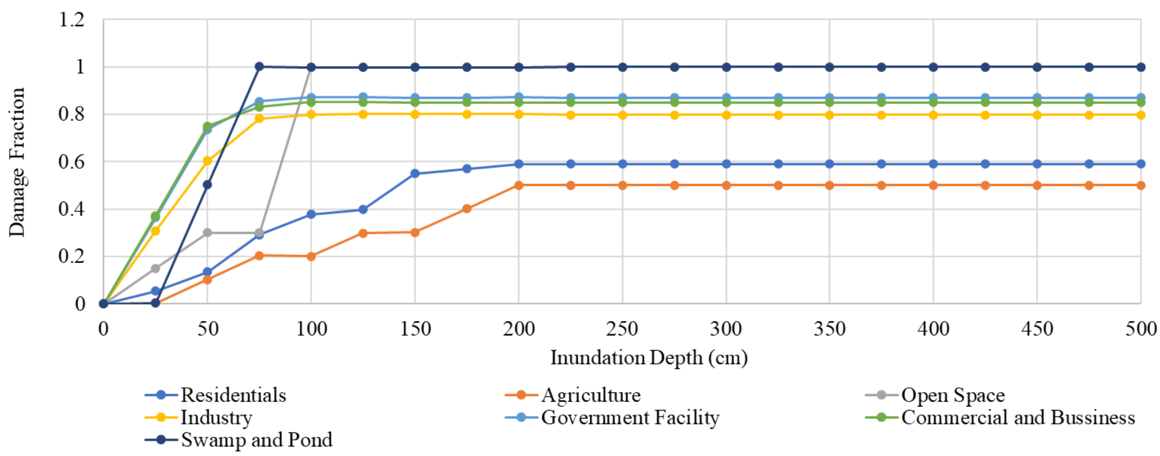

Fig. 9 Depth-Damage Function

economic loss due to the failure of Pamukkulu Dam under the overtopping scenario is approximately USD 68.64 million or IDR 1.12 trillion. The detailed results are presented in Table 5.

Table 5. Inundation Area and Economic Loss Value

Land Use Class	Inundation Area (Ha)	Economic Loss (Thousand USD)
Shrub	68.80	185.79
Mangrove Forest	243.39	862.07
Residential	902.12	56,291.98
Mixed Dryland Agriculture	249.34	137.87
Paddy Field	7,903.64	4,934.26
Fishpond	1,711.49	6,226.83
Bare Land	0.06	0.19

5. CONCLUSION

This study simulated the failure of Pamukkulu Dam to estimate the resulting economic losses. The simulation is based on several failure scenarios, developed using the dam's technical parameters to generate the corresponding outflow discharges. Subsequently, two-dimensional numerical modeling was used to simulate flood inundation, with the scenario producing the highest discharge selected to represent the most extreme condition.

Based on the simulation results, the flood inundation area caused by the failure of Pamukkulu Dam under the overtopping scenario reached 110.79 km², affecting 6 sub-districts comprising 45 villages. The estimated economic loss for this scenario is approximately USD 68.64 million or IDR 1.12 trillion.

In this study, the economic loss estimation was carried out using the ECLAC method, which by design produces a single point estimate. This approach is consistent with the official ECLAC guidelines, which emphasize that the primary purpose of the method is not to achieve maximum quantitative precision but to provide a timely and comprehensive estimate to support post-disaster decision-making. A similar application was also demonstrated in [35] in the case of economic losses due to the failure of the Saguling-Cirata-Jatiluhur cascade dams, where the results were reported as single-value estimates for each affected region without presenting minimum-maximum ranges. Therefore, although a sensitivity analysis was not performed, the estimated loss of IDR 1.12 trillion obtained in this study remains valid within the ECLAC framework and is consistent with recent research practices in Indonesia.

The analysis results indicate that the magnitude of economic losses is strongly influenced by the extent of inundation, flood depth distribution, and land cover in the affected areas. This study provides essential information for the effective formulation of disaster mitigation plans. In addition, the findings can serve as recommendations for policymakers, particularly in regional development such as residential area planning, prioritizing locations that are not affected or have low flood exposure.

To reduce or prevent economic losses resulting from the failure of Pamukkulu Dam, it is recommended to carry out regular inspection and maintenance of the dam structure to identify and address potential structural damage at an early stage. Additionally, the economic loss analysis conducted in this study is expected to accelerate post-disaster recovery efforts and serve as a reference in the development of future flood risk management strategies.

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