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Dam Break Analysis of Sermo Dam

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ABSTRACT Sermo Dam is located in the Special Region of Yogyakarta and serves multiple purposes including providing drinking water, supplementing irrigation systems in the Kalibawang area, and flood control. According to data published by the World Commission, 60% of mitigation measures taken to overcome the impact of dam structure failures are unsuccessful. The simulation of dam failure serves as a crucial aspect of flood mitigation plans and strategies because it is more destructive than natural flood waves. This research used HEC-RAS 5.0.7 to examine the flood inundation mapping and simulate dam failure in two dimensions. However, Dam Break Analysis was adopted to provide a Dam Emergency Action Plan Guide to guide managers and the community. The overtopping scenario was adapted to model the failure of the Sermo Dam based on the frequent occurrence of heavy and extreme precipitation in the affected area. Data were analyzed using unsteady flow and PMF discharge with peak inflow discharge of 1276.6 m^3 s^{-1}, which result in an inundation area of 9394 hectares and a maximum flood height of 17 m. Dam failure-induced floods tend to potentially affect eight sub-districts including Kokap, Pengasih, Sentolo, Wates, Panjatan, Galur, Lendah, and Temon. The piping scenario is also considered based on the potential damage that tends to occur. In the piping scenario, the biggest flooding area was 5112 hectares with a maximum flood height of 13 m. About six sub-districts are potentially affected by dam failure-induced floods with Kokap and Sentolo being excluded from the list. Therefore, it is crucial to establish early warning systems and infrastructure to mitigate disaster risks. The results of this research can also inform evacuation planning, damage estimation, and post-flood rehabilitation efforts in the affected areas.

KEYWORDS Sermo Dam; Mitigation; Dam Failure; Flood Inundation Mapping; HEC-RAS 5.0.7

1 INTRODUCTION

Sustainable water management is becoming important due to population growth, hydrological drought, and limited water supplies. Building a dam is one of the most effective ways to ensure sustainable water delivery. Sermo Dam, located in the Special Region of Yogyakarta, serves multiple purposes including providing drinking water, supplementing irrigation systems in the Kalibawang area, and flood control.

Dams provide significant benefits for the public, but their construction also poses a large potential for danger. Major flooding can become an unavoidable disaster when a dam experiences structural failure. The water retained in the dam will flow uncontrollably, causing damage to the environment. Dam failure-induced floods are more destructive than natural floods and can cause casualties, material losses, environmental damage, active sediment transport, morphological changes, as well as deep psychological impacts and trauma to the affected areas. Floods account for about forty percent of the total deaths from natural disasters reported worldwide.

Historical records show that all types of dams are susceptible to failure. According to Costa (1985), embankment dams experienced failure due to overtopping (35%), piping (38%), foundation failure (21%), and other reasons (6%). About 31% and 22% of dam failures occurred between 1-5 years and 20-50 years, respectively, after inundation (Fread, 1984).

The performance of dams tends to change with time, and their damages can persist as well as cause problems at any point. According to the

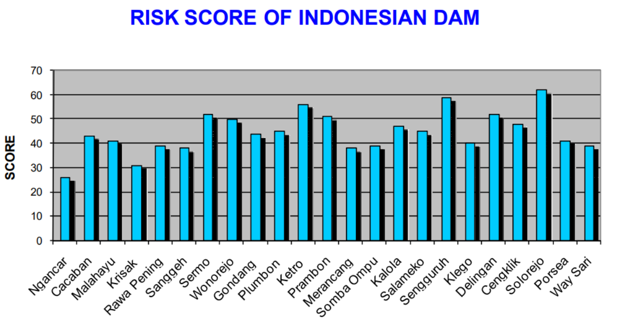


Figure 1 The Assessment of Dam Risk in Indonesia from Project implementation Plan for Dam Operational Improvement and Safety Project 2008 (Azdan and Samekto, 2008)

World Commission on Dams, 60% of the mitigation measures taken to overcome the impact of structural failures are unsuccessful (Azdan and Samekto, 2008).

Figure 1 shows the risk score of dam damage in Indonesia, which was obtained from the Project Implementation Plan for Dam Operational Improvement and Safety Project 2008. The assessment used two criteria as reference points: economic and physical risk. Based on these data, some major dams in the country, including Sermo and Wonorejo Dams, are classified as high risk for damage (Azdan and Samekto, 2008).

As part of the design and construction process, it is essential to consider flood mitigation and forecasting plans to minimize losses in the event of dam failure. Inaccurate predictions and poorly made decisions can have severe consequences, including significant economic losses and casualties (Peter, 2017).

Considering the risk factor and the impact of the Sermo Dam, it is necessary to analyze the potential failure. Dam failure-induced flood routing can be carried out using the dam break analysis method. The primary goal of this analysis is not to rebuild the dam to prevent collapse, but rather to assist in the formulation of disaster mitigation measures to minimize the damaging consequences.

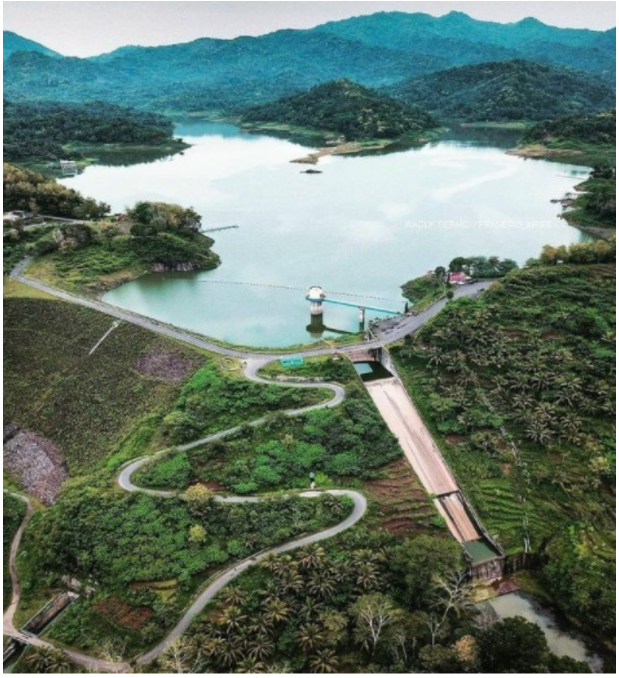
The accuracy of this method is essential for effectively managing floodplains and identifying flood-prone areas. This is because floods can be caused by a wide range of factors and are impacted by almost every aspect of the built and natural environment. While it can be challenging to completely forecast floods, a model that accurately represents the terrain characteristics, weather and precipitation patterns, hydrologic and hydraulic principles, as well as current regional and local conditions tend to greatly improve to build a strong forecasting.

The result of the dam break analysis provides a simulation of dam failure and its potential impact in the form of a map of the affected area. This map can be used as a data source to prepare an Emergency Action Plan (EAP). Based on the Director General for Water Resources (2010), every dam owner or management is required to have a Contingency Plan (CP) or Emergency Action Plan (EAP) that is publicly accessible and disclosed to relevant stakeholders. This research aims to assess the risk of inundation resulting from a potential failure of the Sermo Dam. To achieve this, a dam break analysis was conducted using HEC-RAS 5.0.7 model. The damaging consequences can be mitigated through effective planning and future development by accurate forecasting and systematically controlling floods and their magnitude. Therefore, this analysis tends to be used by local planning authorities to make informed decisions.

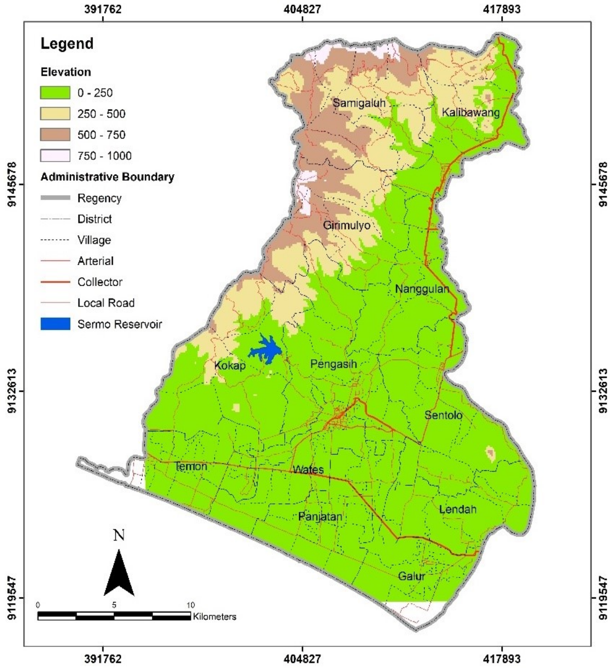
The research aims to determine the level of protection required, identify the areas that tend to be impacted by a potential flood, estimate its return period, and define the downstream and upstream flood zones.

2 RESEARCH METHODS

Flood routing is a key concept in hydrology used for flood forecasting and developing optimal flood management solutions (Styawan et al., 2018). In this research, statistical procedures were adopted to conduct hydrological analysis in Microsoft Excel. This analysis was used to obtain maximum rainfall estimates for different recurrence intervals and probable maximum precipitation (PMP). The maximum rainfall estimate and reservoir parameters were then used to simulate the surface runoff response from the drainage basin in HEC-HMS 4.9 to obtain a flood hydrograph. Furthermore, the SCS curve number (SCS-CN) approach was chosen for this research due to the limited availability of field data. The flood inundation area resulting from a potential dam failure was determined by simulating the results of the hydrolog-



(a) Sermo Reservoir



(b) Geographic location of the research area

Figure 2 Geographic info of Sermo Reservoir

ical analysis in two dimensions (2D) using HEC-RAS 5.0.7. Sermo Dam and the flow area were modeled by adopting Digital Elevation Model (DEM) in RAS Mapper on HEC-RAS. Inputs for dam break modeling included flood hydrograph, failure parameters, and dam failure scenarios. The output of the research was a dam failure-induced flood inundation map and analysis of the simulation results for floodwater depth, flood wave arrival time, flood inundation time, and flow velocity. Meanwhile, the resulting inundation was mapped using ArcGIS 10.8.

2.1 Research Site

This research focuses on Sermo Dam and its downstream region, particularly the Progo watershed. The dam is located in Sermo Lor Sub-Village, Hargowilis Village, Kokap District, Kulon Progo Regency, Special Region of Yogyakarta as shown in Figure 2b. Sermo Dam was constructed in 1994 by damming the Ngrancah River. It is a zoned rock-fill dam with an impervious core, measuring 58.6 meters, 190 meters, and 8 meters in wall height, length, and width respectively. Sermo Dam is equipped with an ogee spillway without a gate and a horseshoe-shaped tunnel in its middle, as shown in Figure 2a.

The dam covers an area of approximately 155 hectares and has a catchment area of 21.21 km^2, with a capacity of 25 million m^3 of water. There are various important towns and facilities, including Wates, which is located about 6 km away from the New Yogyakarta International Airport. This airport is the largest, located about 15 km away, and has various public facilities such as bridges and Wates Train Station, that support mobility to and from the Special Region of Yogyakarta. The downstream population has grown significantly over the years.

2.2 Data Collection

The accuracy and dependability of the data analysis are contingent on various factors including terrain, the quality of the satellite photos, and the rainfall record data. To provide essential physical information for the analysis, details about the dam are crucial. These include the structural dimensions of the dam, the capacity curve, contour details of the river downstream of the Sermo Dam, and alignment details of the river and dam. Primary information and data were collected through direct observation at the research site, while secondary data were obtained from the Serayu-Opak River Basin Agency.

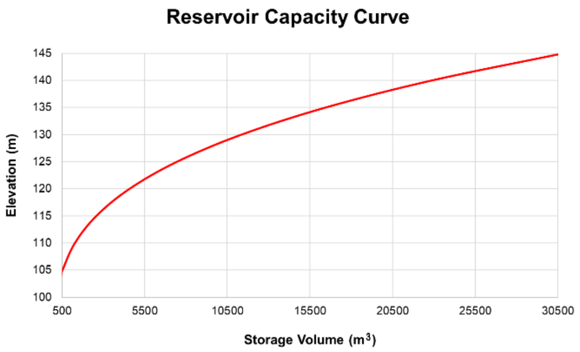


Figure 3 2014 Capacity Curve of Sermo Reservoir (2014, the Serayu-Opak River Management Office)

The primary inputs for the dam break analysis included a Digital Elevation Model (DEM), hydrological data, and dam-specific technical information. This research used daily precipitation data from the past 15 years (2006-2020) to determine the hydrological characteristics of the dam and obtain flood hydrographs. To accurately represent the Sermo watershed, three rain stations including Borrow Area, Plaosan, and Sermo Climatology were selected as the most appropriate sources of hydrological data.

An elevation-volume relationship was established to determine the features of the dam storage area. This relationship was used to calculate flood routing above the spillway and determine dam elevation during flooding. Furthermore, the dam capacity curve will be used to forecast the potential for dam failure in HEC-RAS. Due to a lack of available data, the capacity curve is based on the 2014 bathymetry survey collected by the Serayu-Opak River Basin Agency, as shown in Figure 3.

The DEMNAS map was used to delineate the Ngrancah watershed and determine its boundary, as shown in Figure 4b. Figure 4b shows that the next step is to simulate land use and determine the distribution of CN values in the watershed. The CN value represents the amount of runoff or infiltration resulting from present rainfall. This weighted CN value (land cover coefficient) serves as input data using the HEC-HMS software. As a result, the digitization process had a significant impact on the analysis of this research.

On-screen digitization was used based on the 2022 base map to obtain land cover data, as shown in Figure 4b. This resulted in five categories of land use: settlement (1.73%), forest (0.35%), water body/reservoir (7.18%), mixed farm (72.8%), and plantation (0.25%). From this information, it was determined that the percentage of open space and impervious cover was 90.85% and 9.15%, respectively.

2.3 Dam Failure Scenario

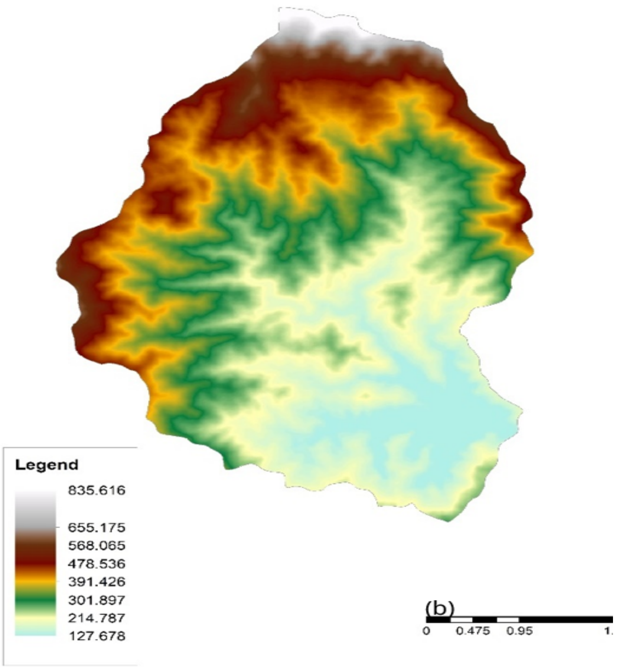
Earth embankment dam is one of the most well-known dams because of its suitability for all types of foundations, simple construction, and relatively low construction costs. However, earth embankment dams are more prone to collapse due to their less solid structure construction (Bharath et al., 2021).

The mechanism for the failure of a dam, whether it is an earth embankment or a concrete type, is not well understood. Undoubtedly, the processes that lead to the collapse of both types of dam are poorly known. It is commonly assumed that the dam would completely and instantly collapse when using mathematical models to simulate the flood waves caused by a dam failure (Brunner, 2016).

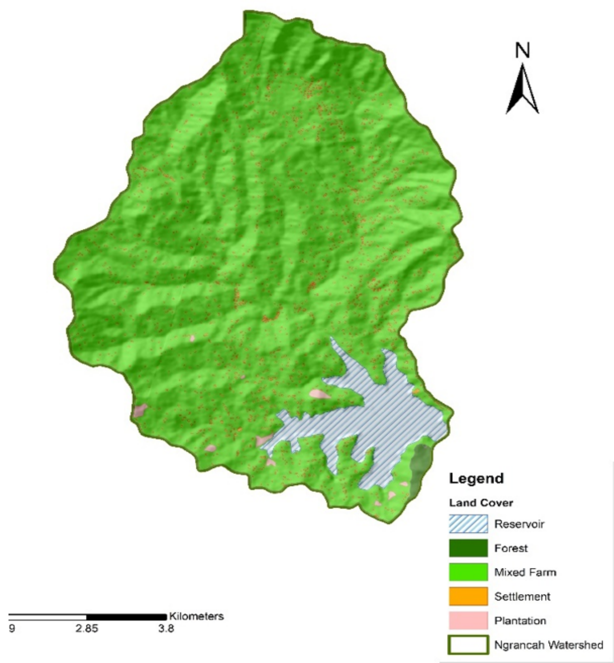
Overtopping and piping are common scenarios associated with earth embankment dam failures, while only overtopping applies to concrete dams. In this research, two scenarios including overtopping and piping were assumed for modeling the failure of the Sermo Dam.

Overtopping is believed to occur when the water level equals or exceeds the dam's elevation. This happens when the spillway capacity is inadequate or when there is extreme precipitation that exceeds the dam's design specifications (Khosravi et al., 2019). When a dam fails, water seeps through the material, creating larger holes that convey more water and materials. Piping can occur due to geological processes that produce mineral breakdowns in dams.

The conducted simulation was two-dimensional (2D), analyzing unsteady flow without considering sediment transport and observing the presence of transverse structures. Furthermore, the HEC-RAS 2D method was preferred over the one-dimensional (1D) because the latter cannot calculate multidirectional flood wave propagation. The two-dimensional (2D) simulation also pro-



(a) National DEM (DEMNAS)



(b) 2021 Land-use Map

Figure 4 Map scenario

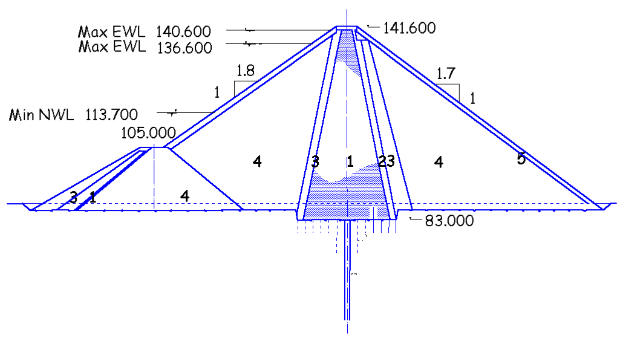


Figure 5 Dam cross section

vides more detailed results, including flow depth and velocity variations of each cross section (Urzică et al., 2021).

2.4 Failure Parameters

Estimation of average breaching width, breaking duration, and the type of failure is essential in predicting peak discharge, outflow hydrograph, and flood inundation downstream. Research has developed regression models that calculate failure factors including breaching width, breaking formation time, and crack slope angle using historical data from the past. Empirical equations proposed by Froehlich, MacDonald, Langridge-Monopolis (MLM), and Von Thun and Gillete (VTG) have been accepted by numerous investigations on dam failure (Initiative et al., 2013).

The Froehlich (1995*b*,*a*) method is considered to be reliable in determining dam failure parameters and dam failure-peak flow. Froehlich (2008) updated his breach equations based on the addition of new records, using 74 datasets of earth dams, zoned earth dams, earth dams with a core wall (i.e., clay), and rockfill to develop a set of equations to predict average breach width (B_{ave}), side slopes, as well as failure time (tf) (FEMA, 2013).

$$B_{ave} = 0,27 K_O V_W^{0,32} h_b^{0,04} \tag{1}$$

$$t_f = 63.2 \sqrt{\frac{V_W}{g H_b^2}} \tag{2}$$

K represents the constant (1.3 for overtopping and 1.0 for piping), VW represents the reservoir volume at the time of failure (m^3), Hb represents the final breach height (m), and g represents gravity (9.81 ms^{-2}).

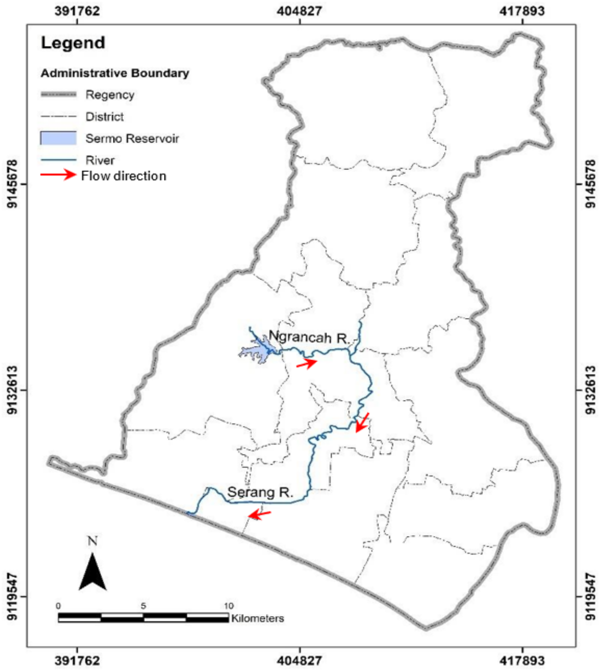


Figure 6 Water flow diagram for Sermo Reservoir

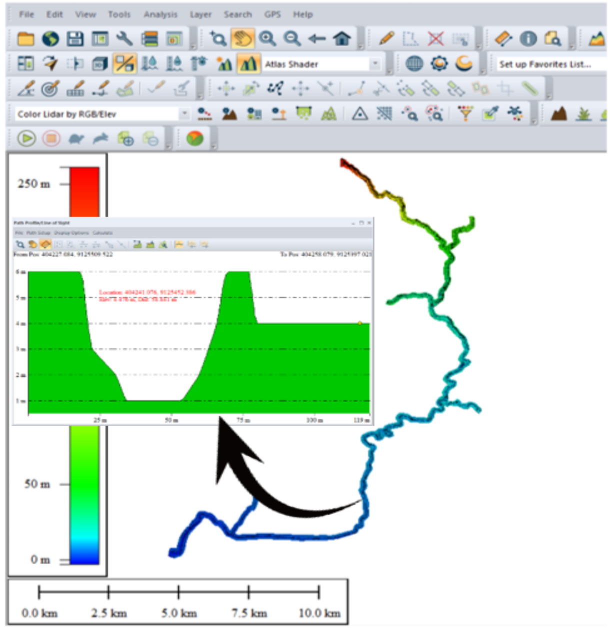


Figure 7 Serang River cross section was created using Global Mapper

Figure 5 depicts a cross-section of the Sermo Dam based on data acquired from the Serayu-Opak River Basin Agency.

Froehlich (2008) suggested an average side slope of 1H:1V and 0.7H:1V for overtopping and piping respectively. Although Froehlich failed to explicitly explain this, the height of the breach is typically estimated by assuming that it grows from the top of the dam to the natural ground surface at the breach location US Army Corps of Engineers Hydrologic Engineering Center (2014).

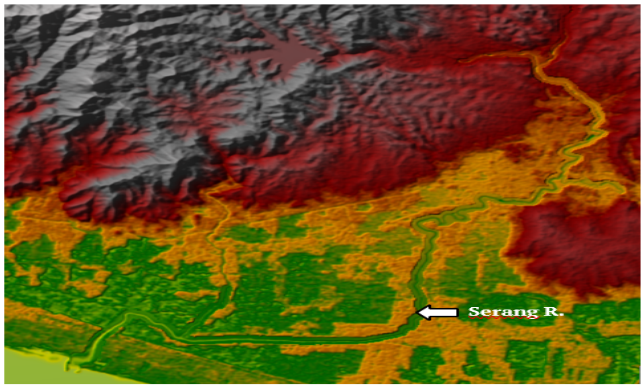


Figure 8 Hybrid DEM by combining DEMNAS Serang River contour

2.5 Sermo and Kulon Progo Watershed Characteristics

The Sermo Dam is located on the Ngancah River, and its downstream part connects to the Serang River through a spillway. This Serang River flows from north to south and reaches the Java Sea near Glagah Beach, as shown in Figure 6. The Serang River runs for approximately 25 kilometers from the dam downstream.

The river cross-sections downstream of the dam are the main input for river geometry data in HEC-RAS. A topographic survey was conducted to obtain accurate elevation records along the river channel from the dam outlet to the downstream. This methodology is very helpful in obtaining a broader and more accurate floodplain map, which is required for the analysis of the mitigation system (Bharath et al., 2021).

To produce an accurate terrain model, a hybrid DEM was created by combining National DEM (DEMNAS) and data from the results of a topographic survey of the cross-sections along the downstream such as the Serang River, as shown in Figure 8. More than 80 cross-sections were processed using Global Mapper 21.0 to create a new DEM, which has been converted into a projected one. Figure 7 depicts a river contour layout that has been converted into a DEM in the .tif format, based on the modeled research area in Global Mapper 21.0.

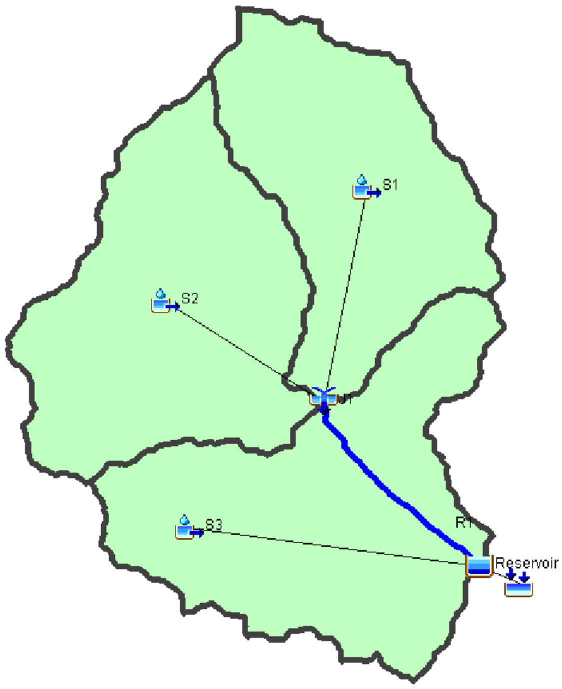


Figure 9 Simulation of the hydrological model of the Ngrancah Watershed

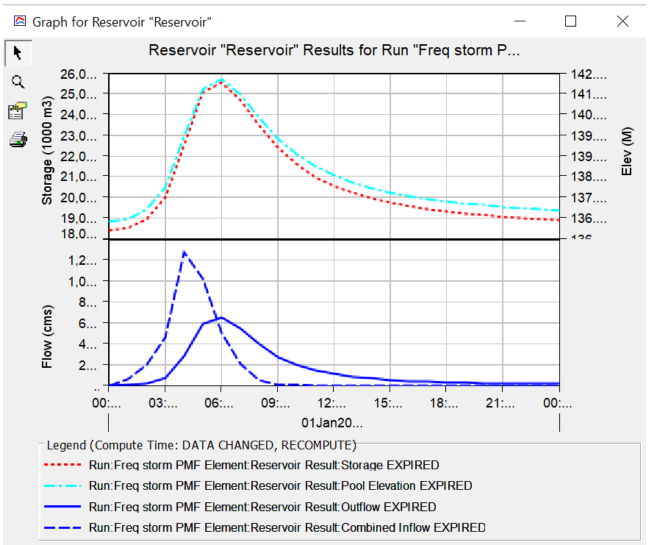


Figure 10 Flow hydrograph generated using SCS method

2.6 HEC-RAS Tools

US Army Corps of Engineers developed the HEC-RAS model to manage and regulate rivers, canals, ports, and other public infrastructure. This model has also collaborated with ArcGIS to enable the spatial display of hydraulic modeling results through GIS.

In its operation, HEC-RAS is a software application that combines a graphical user interface, hydraulic analysis, data management and storage,

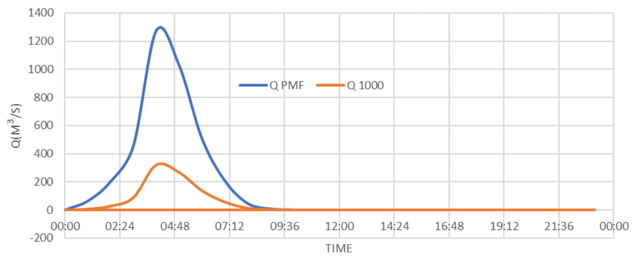


Figure 11 Sermo Dam flood hydrograph

graphics, as well as reporting functions (Istiarto, 2014). This research prefers to use the HEC-RAS model for flood simulation because it consistently produces accurate results and can handle complex channel geometry.

The HEC-RAS 5.0.1 (2D) Model is used to simulate flood-prone areas downstream of a dam. Furthermore, dam break analysis is performed using two-dimensional unsteady flow, which calculates the expected flood. This analysis used the Unsteady Flow Analysis technique with the Implicit Finite Volume algorithm and Wave Diffusion equations.

3 RESULT AND DISCUSSION

3.1 Hydrological Analysis Results

According to the Central Jawa map, the PMP value in the Sermo Dam area is estimated at 750 mm. The Hersfield value is lower at 590.279 mm when the PMP Arithmetic method is used to generate the PMP Isohyet. This PMP Isohyet value is used in the subsequent calculations.

Flood routing across the dam is the process of predicting potential outcomes resulting from the presence of a flood hydrograph. Furthermore, the objective of tracing floods is to estimate the water level that tends to exceed the spillway crest when a flood discharge passes through it.

The HEC-HMS model is capable of analyzing discharge and predicting flooding at the location of the control point for an early warning system. To simulate flood routing in the dam using HEC-HMS, the spillway component is added to the input for the Basin Model. The results of the hydrological simulation for the Ngrancah River drainage basin are shown in Figure 9. Meanwhile, Figure 10 displays the outflow hydrograph generated by the probable maximum precipitation (PMP), which is

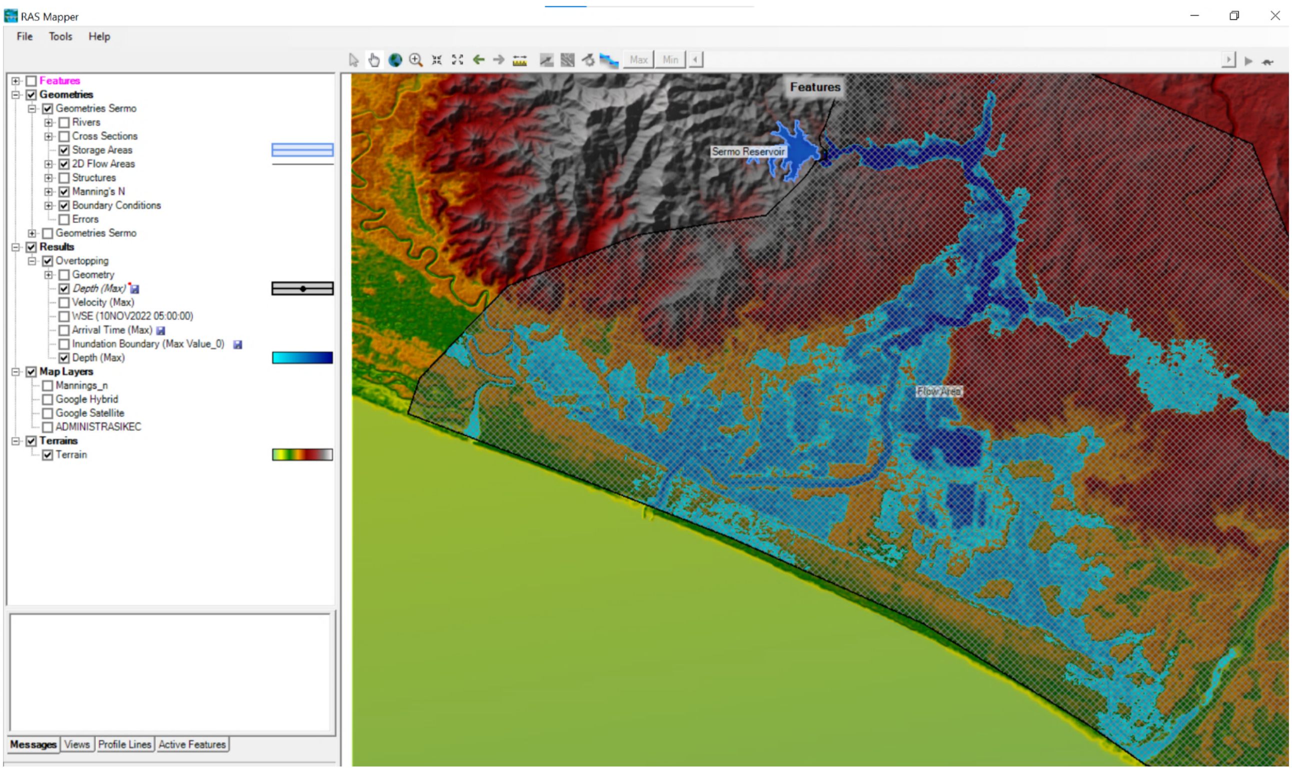


Figure 12 Simulation of geometric data, mesh, boundary condition inundation area

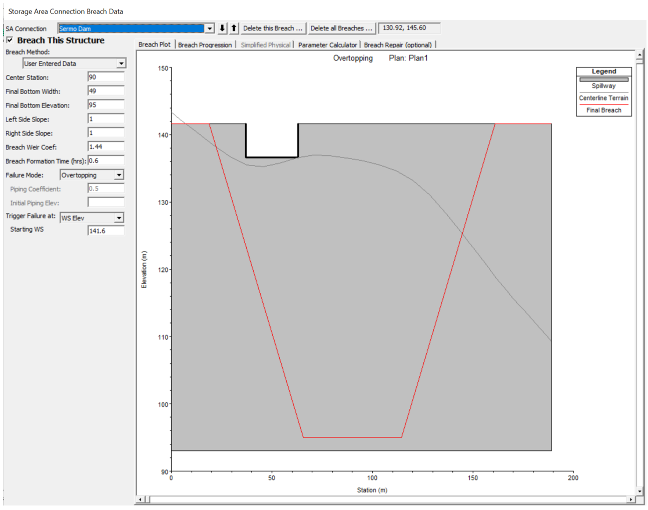


Figure 13 Overtopping failure scenario

also used to compute the 1000-year return period discharge.

According to the QPMF flood route results, as shown in Figure 10, the floodwater level reached a maximum height of +141.8 m, which exceeds the dam top elevation of +141.60 m, indicating the overtopping of the Sermo Dam. Consequently, it was determined that the overtopping and piping scenarios were appropriate for the Sermo dam-break modeling. This is because the overtopping and piping use the PMF flood flow and the 1000-year return period respectively. Table 1 provides a summary of the flood discharge design for the 1000-year return period and PMF, which is illustrated in Figure 11.

Table 1. Recapitulation of the Synthetic Unit Hydrograph Value

Synthetic Unit Hydrograph Method	Design Flood Discharge (m^3sec^{-1}) with a Certain Return Period	
	1000 years	PMF
SCS Unit Hydrograph	320.1	1276.6

3.2 Dam Break Analysis Results

The dam was modeled using two-dimensional HEC-RAS software, which represented it as a storage region with an elevation-storage curve. Furthermore, the lower reach area impacted by the dam failure was enclosed by a 2D flow area polygon that extended downstream from the dam outlet. The mesh covered the entire 2D flow area, which was sized according to the user's needs to represent the river and floodplain. To determine surface roughness, manning's coefficient (n) was cal-

Table 2. Recapitulation of dam failure parameters

Parameter	Breaking Scenario				Unit
	Overtopping	Piping			
		Base Piping	Middle Piping	Top Piping	
Shape of breach	Trapezoid	Rectangular	Rectangular	Rectangular	
Center Station	90	90	90	90	
Left Side Slope	1	0.7	0.7	0.7	
Rigth Slide Slope	1	0.7	0.7	0.7	
Breach Weir Coef	1.44	1.44	1.44	1.44	
Final breach height (Hb)	46.6	41.6	41.6	41.6	m
Average breach width (B_{ave})	95.36	73.02	73.02	73.02	m
Breach Formation Time (Tf)	0.60	0.67	0.67	0.67	hour
Final Bottom Width	49	44	44	44	m
Final Bottom Elevation	95	95	95	95	m
Failure Mode	Overtopping	Piping	Piping	Piping	
Piping Coefficient	-	0.5	0.5	0.5	
Initial Piping Elevation	-	136.6	121.6	106.6	m
Trigger Failure at	WS Elevation	WS Elevation	WS Elevation	WS Elevation	
Starting WS	141.6	136.6	136.6	136.6	m

Table 3. Simulation results of each scenario

Breaking Scenario	Number of Villages Affected	Inundation Area (Ha)	Inundation Volume (m^3)
Overtopping	8	9394	409603700
Top Piping	6	5108	100174680
Middle Piping	6	5103	99474130
Base Piping	6	5112	98957810

culated based on the land-use type at each potentially affected location. Figure 12 shows the simulation of geometric data, mesh, boundary conditions, and inundation area.

The dam was modeled in HECRAS using a line structure editor, which allowed the user to input embankment parameters and define the weir as well as gate openings such as radial and sluice. Figure 13 shows the failure parameter was inputted using the 'dam breach' option in the Inline Structure editor. Based on the dam failure parameters obtained using the Froelich equation, Table 2 displays the average breach width (B_{ave}), the final breach height (Hb), and the breach formation time (tf) for two scenarios: overtopping in PMF floods and piping (top, middle, and base piping). The upstream and downstream boundary conditions of the model were identified using the lines representing the flow hydrograph (discharge) for the upstream and the normal depth for the downstream.

A dam break simulation was conducted for 120 hours, and the results are displayed through an inundation map and a failure hydrograph. Furthermore, the inundation map can be analyzed to identify the flood hazard zones in crucial areas. Tables 3 and 4 show the analytical results.

3.3 Inundation Map

The potential threat to life and the extent of structural damage depends heavily on the speed and depth of the flood. Furthermore, the improvement in the speed and depth of the flood tends to increase the risk to both individuals and property (Derdous et al., 2015).

The maps were created using the worst-case sce-

Table 4. Simulation Results of each Scenario

Breaking Scenario	Maximum Flood Depth (m)	Total Peak Outflow Discharge (m^3 sec^{-1})	Breach Avg Velocity (m s^{-1})	Arrival Time (Hour)
Overtopping	17,163	32348,32	8,47	5,7
Top Piping	13,040	8909,83	6,52	8,0
Middle Piping	13,067	8909,83	12,28	8,0
Base Piping	13,075	8854,38	6,58	8,0

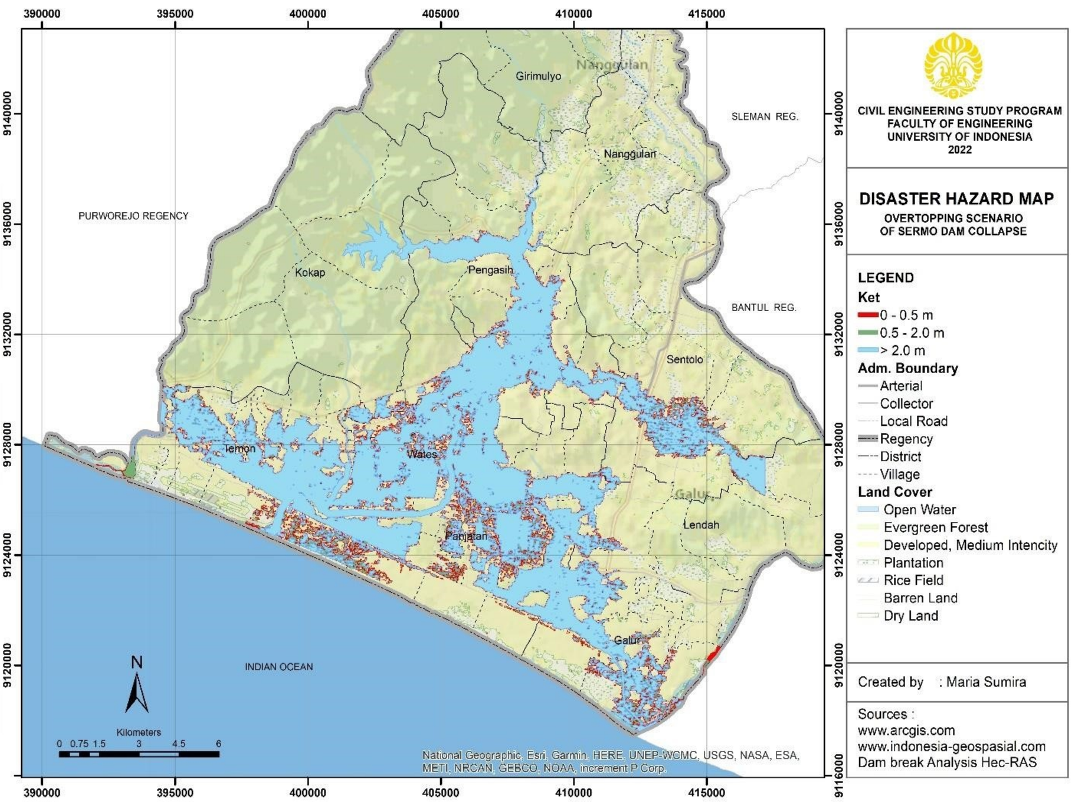


Figure 14 Map of inundation due to overtopping condition

nario to depict the principal locations that tend to be inundated. Figure 14 shows the overtopping scenario, while Figure 15 depicts the piping type.

According to the inundation map, the overtopping scenario tends to result in dam failure-induced floods affecting eight districts including Kokap, Pengasih, Sentolo, Wates, Pandatan, Galur, Lendah, and Temon, as shown in Figure 14. The intensity and frequency of floods may vary depending on factors such as slope and permeability. In the piping scenario, six districts tend to be affected by dam failure-induced floods with Kokap and Sentolo being excluded from the list shown in Figure 15. Land use and changes in land use over time, as well as urbanization and deforestation, can increase the number of impervious surfaces and surface runoff (Khalfallah and Saidi, 2018).

4 CONCLUSION

Dam failure is a complex and unpredictable event but disaster mapping and risk assessment are essential tools for developing effective mitigation and prevention strategies. Analyzing and simulating the potential failure of a dam is critical for identifying and minimizing risks. Additionally, an accurate assessment of flood levels and the forecasting of wave arrival times at critical locations downstream are necessary for developing efficient emergency action plans. The collapse of the Sermo

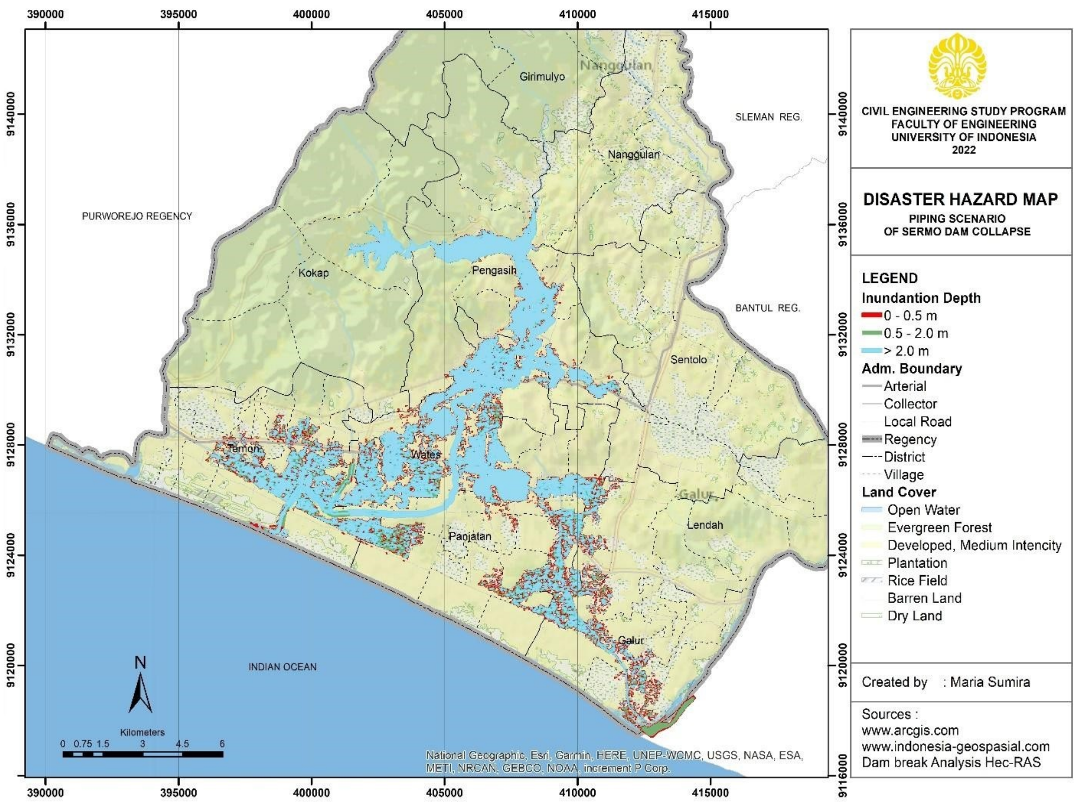


Figure 15 Map of inundation due to piping condition

Dam due to overtopping is the most significant hazard for downstream communities. Based on dam break analysis, flooding tends to potentially affect eight sub-districts including Kokap, Pengasih, Sentolo, Wates, Panjatan, Galur, Lendah, and Temon. Flood heights tend to range from 0 to 17 meters (QPMF), with flood wave velocities ranging from 0 to 8 meters per second, and an inundation area of 9349 hectares. Simulation results for the arrival time of flood waves suggest estimated evacuation times for QPMF range from 0-5.7 hours. In the piping scenario, six districts tend to be affected by dam failure-induced floods with Kokap and Sentolo being excluded from the list, and an inundation area of 5112 hectares. Simulation results were not calibrated in this research due to the lack of historical data on the Sermo Dam failures. Precisely predictions of inundation levels and flood wave arrival times are necessary to design effective emergency action plans for downstream areas.

DISCLAIMER

The authors declare no conflict of interest.

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