Dam Failure Model to Predict Inundation Hazard Map for Emergency Plan

Juliastuti, Sofia Alisjahbana, Dadang Ma'soem, Oki Setyandito, Made Suangga

Abstract: ***The construction of dams can offer many advantages, but their failure could result in major damages, including loss of life and property destruction. The research aims to model dam failure for Mapping Hazard area including inundation height and arrival time. A key scenario for dam failure is partial breach of embankment dam: overtopping and piping. The overtopping shape modeling was simulated in triangle and trapezoidal shapes. The piping failure modeling is simulated as orifice with rectangular shape. This study was conducted by using the integration of hydraulic modeling, which used a numerical method with Navier-Stoke solver and Geographic Information System (GIS) to assess the risks that could be cause by any damages on Dam failure. Flow simulation of the dam break was performed by using ZhongXing HY-21 software and the results were mapped by using the GIS. The result of the research is overtopping failure was selected for the model with peak discharge maximum (Q_{max}) is 2089 m^3/sec. The fastest arrival time is 0.4 hours (24 minutes). Several villages catagorized as a high-risk area. This inundation hazard map is very important for emergency plan which determines the evacuation routes and coordination scheme with local disaster agency.***

Keywords**: *dam, failure, inundation, hazard, emergency.***

I. INTRODUCTION

Most dams are heavy structures that may lead to failure, posing risks to human life [1], property, and the environment. Therefore, in accordance with Indonesian regulations [2] and the regulations of the International Committee on Large Dams (ICOLD) [3], dam safety requires that an Emergency Action Plan (EAP) is in place for each dam and every 5 years, licensees must be update and refile the plans [4]. The purpose of EAP is to minimize the risk of life and property at downstream area due to dam failure. The focus of an EAP is disaster management based on Flood Inundation Mapping (FIM). Identifying the flood risk zones are the primary steps for formulating flood management strategy [5] including depth and time travel, hazards map preparation, evacuation route, early warning system, and disaster response. According to ICOLD standard, the hazard classification is based on the potential damage at downstream areas including human and infrastructure risk [6]. A survey in the inundation area should determine the potential damage [7,8]. By using the depth of inundation, the evacuation requirement can be determined to reduce the hazard [9]. The study of dam failure is important for stakeholders to minimize flood hazards including how to communicate the people to do during and after disaster [10,11,12].

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II. LITERATURE REVIEW

Hydraulic Engineering Center-River Analysis System (HEC-RAS) software is widely used for dam break analysis model [13]. Honghai Qi et al. [14] developed a realistic two-dimensional flood simulation using HEC-RAS for classified layers using GIS including zoning layer. The test result was validated by using HEC-FDA software. Salajeghah et al. [15] studied the Polasjan river basin in Iran for floodplain analysis using HEC-RAS and GIS. The output model was developed by integrating both HEC-RAS and ArcGIS software. This methodology has many advantages such as being user-friendly because it can update the floodplain maps when hydrological and hydraulics conditions change. Zope et al. [16] studied the Oshiwara River in Mumbai, India using HEC-HMS hydrological-GeoHMS GIS Module to investigate the impact of land use change on urban flooding. The result is that the model can be used for flood mitigation and evacuation management. The outcome of Emergency Action Plan (EAP) in agriculture area surround Sathanur Dam, India were utilized to identify the economic loss faced by the farmers who live in a highly affected village [17]. The flood inundation map was developed using HEC-GeoRAS.

III. RESEARCH DESIGN

A. Methodology

The methodology used in this research follows the flow as seen in Figure 1. Both ArcGIS and Navier-Stoke solver using ZHONG XING HY-21 flood simulation model [18] were used in this research project (see Fig.1). The first step is to acquire data by preprocessing of special data using Digital Elevation Model (DEM) for dam break simulation using Zhong Xing HY21 and preparation of layer using ArcGIS. The next stage is integrated between the result from dam break simulation and layer data using ArcGIS for identified flooded area.

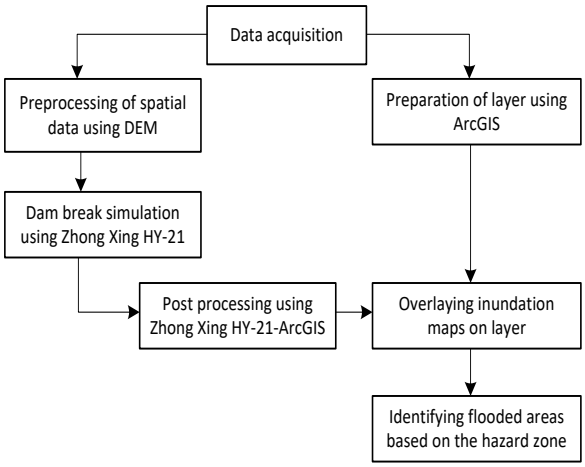


Figure 1. Flood modeling methodology [17]

B. Dam Break Assumption

The assumption of sudden dam failure is usually made in dam breach modeling. The breaching could break the dam suddenly [19, 20]. But another research study [21] found that the cause of the dam failure was partial breach and can occur suddenly.

The breach assumption is the basis of mathematical modeling for dam failure [22, 23]. For concrete arch dam, the assumption is total breach, and for the embankment dam is partial breach. The models of partial failure for Malahayu dam were overtopping and piping.

The modeling that caused overtopping was simulated in triangle and trapezoidal shapes (see Fig. 2).

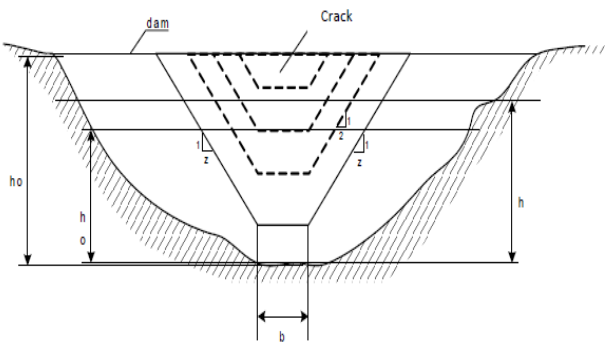


Figure 2. Overtopping

The parameter Z is slope (1: Z) and b is length. The range of z is 0 < Z < 2.
The equation is:

$$b = b_{bar} - 0{,}5Zh_d \qquad [1]$$

Where:
b = length
z = slope
hd = elevation

The piping failure modeling is simulated as orifice. The shaped is rectangular (see Fig. 3).

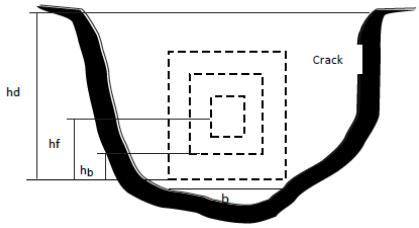


Figure 3. Piping

The equations to solve the failure model were the mass conservation and momentum flow in two-dimensional (2D) governing equation of shallow water or 2D Shallow Wave Equation from the Navier-Stokes 3D equations [24]. These equations could describe the flow of incompressible fluids are the fundamental partial differentials equations. By using the rate of stress and rate of strain tensors, it can be shown that the components of a viscous force (*F*).

The Navier-Stokes equations was entered the continuity equation of fluid flow, the equation became four equations in four unknowns (namely the scalar and vector u). The Navier-Stokes equation consisted of mass conservation, momentum, and energy and mass conservation was included the continuity equation. The continuity equation was:

$$\frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = S^h \qquad [2]$$

Or

$$\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = S \qquad [3]$$

The momentum equation in x direction:

$$\frac{\partial p}{\partial t} + \frac{\partial F}{\partial x}\left(\frac{p^2}{h} + \frac{gh^2}{2}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -gh\frac{\partial Z_b}{\partial x} + \qquad [4]$$

$$\Omega q + \frac{(\tau_{x-}^{s} \tau_x^b)}{\rho} + \frac{1}{\rho}\left[\frac{\partial}{\partial x}(h\tau_{xx}^{e}) + \frac{\partial}{\partial y}(h\tau_{xy}^{e})\right]$$

Where:

$$Q = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix} \; ; F = \begin{bmatrix} h \\ hu^2 + 0.5gh^2 \\ huv \end{bmatrix} \; ;$$

$$G = \begin{bmatrix} h \\ huv \\ hv^2 + 0.5gh^2 \end{bmatrix} \; ; \quad S = \begin{bmatrix} 0 \\ ghS_{0x} - ghS_{fx} \\ ghS_{0y} - ghS_{fy} \end{bmatrix}$$

The conservation equation is:

$$\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = \frac{\partial F_v}{\partial x} + \frac{\partial G_v}{\partial y} + H \qquad [5]$$

Where:

$$Q = \begin{bmatrix} h \\ p \\ q \end{bmatrix}; \quad F = \begin{bmatrix} p \\ hu^2 + 0.5gh^2 \\ huv \end{bmatrix} \; ;$$

$$G = \begin{bmatrix} q \\ huv \\ hv^2 + 0.5gh^2 \end{bmatrix} \quad ; \quad F_v = \begin{bmatrix} 0 \\ \frac{h\tau_{xx}^e}{\rho} \\ \frac{h\tau_{xy}^e}{\rho} \end{bmatrix} \quad G_v = \begin{bmatrix} 0 \\ \frac{h\tau_{xy}^e}{\rho} \\ \frac{h\tau_{yy}^e}{\rho} \end{bmatrix}$$

$$H = \begin{bmatrix} S^p - gh\frac{\partial Z_b}{\partial x} + \Omega q + \frac{(\tau_x^s - \tau_x^b)}{\rho} - \frac{h}{\rho}\frac{\partial P_a}{\partial x} \\ S^q - gh\frac{\partial Z_b}{\partial y} + \Omega q + \frac{(\tau_y^s - \tau_y^b)}{\rho} - \frac{h}{\rho}\frac{\partial P_a}{\partial y} \end{bmatrix}$$

C. Hydraulic Structure Parameter

Hydraulic structure parameter for the modeling of dam failure was flooded design and inflow hydrograph for calculating reservoir routing. Synder method was used to find the flood design for 25 years, 100 years, and 1000 years, PMF and inflow hydrograph could be calculated. Based on the hydrologic analysis, the peak discharge is Probability Maximum Flood (PMF) for using data by using data for calculated reservoir routing (shown in Fig.4).

The equation for calculating reservoir routing is in equation 6.

$$\left(\frac{I_1 + I_2}{2}\right)\Delta t + \left(\frac{O_1 + O_2}{2}\right)\Delta t = S_2 \qquad [6]$$

Where:

S_1 = Storage capacity t_1
S_2 = Storage capacity t_2
I_1 = spillway inflow t_1
I_2 = spillway inflow t_2
O_1 = spillway outflow t_1
O_2 = spillway outflow t_2

Reservoir routing Eq.7 can be developed as follows:

$$\left(\frac{I_1 + I_2}{2}\right) + \left(\frac{S_1}{\Delta_t} - \frac{O_1}{2}\right) = \left(\frac{S_2}{\Delta_t} + \frac{O_2}{2}\right) \qquad [7]$$

$$\left(\frac{S_1}{\Delta_t} - \frac{O_1}{2}\right) = \psi \qquad [8]$$

$$\left(\frac{S_2}{\Delta_t} - \frac{O_2}{2}\right) = \varphi \qquad [9]$$

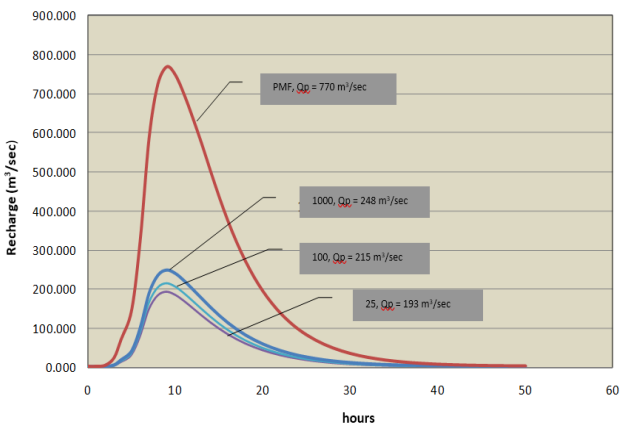


Figure 4. Reservoir flood routing with synder method

Where:

ψ = inflow (m^3/sec)

φ = outflow (m^3/sec)

D. Dam Area

Malahayu Dam is located in Malahayu Village (108°49'10" EL and 7° 01'45" SL), Brebes, Central Java, Indonesia (shown in Fig.5). Malahayu Dam is one of the oldest infrastructures in Indonesia. This dam is mainly used for irrigation and flood control. Currently, the dam is managed by the Central River Region of Cimanuk-Cisanggarung.

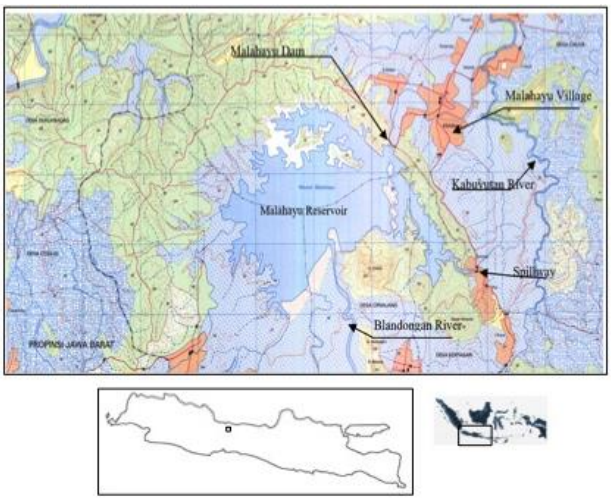
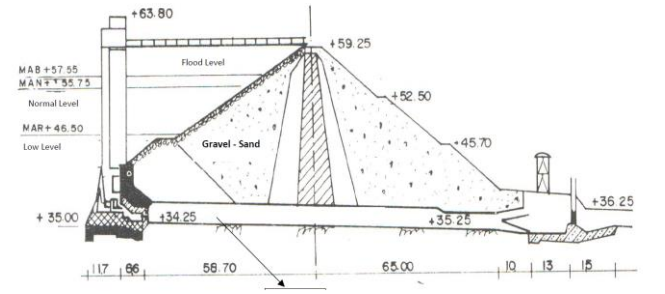


Figure 5. Malahayu dam location

The Malahayu Dam was constructed in 1934-1937. The Malahayu dam is a type of homogenous earth dam, built for irrigation purposes. The downstream side consists of residential areas and the inhabitants are mostly farmers. The height of Malahayu dam is 31.35 m, the length is 176 m, and the effective storage is 35.080 million m^3. The elevation of crest dam is El.+59.25 sl. Type of spillway is over-flow ogee and the capacity is 33.72 m^2/sec (Fig.6).



(a)

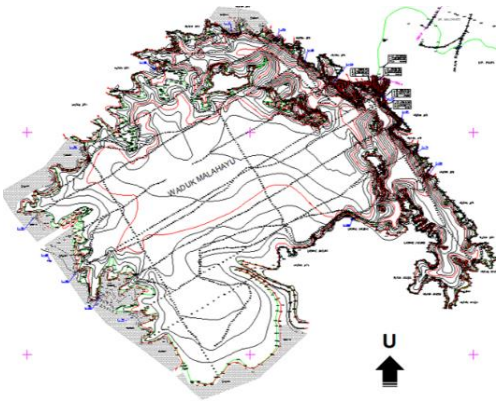
(b)

(c)

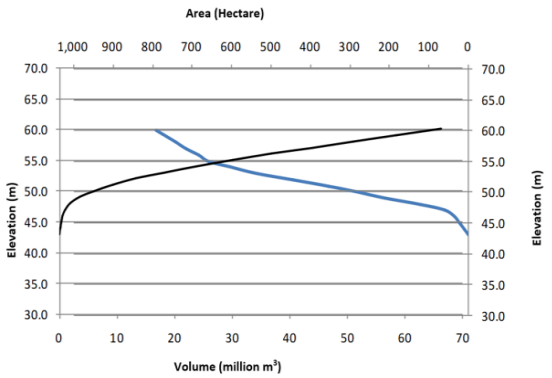
Figure 6. Malahayu dam (a) cross section ; (b) intake; (c) outlet. Sourse:[9]

E. Storage Capacity and Hydraulic Capacity

Bathymetry and tachymetry surveys assist in calculating the storage capacity. Thus, based on the topographic map, the storage capacity could be calculated (Fig. 7).



(a)



(b)

Figure 7. Capacity storage (a) topographic map; (b) capacity curve

The type modeling of failure dam is overtopping and piping. Overtopping is based on the calculation of flood routing spillway at Probability Maximum Flood (PMF) condition and this is a region vulnerable to earthquakes. Piping is the maximum storages capacity and Probability Maximum Flood.

IV. RESULT AND DISCUSSION

The most interesting findings were to predict flooding due to Malahayu dam failure to make emergency guidelines in reducing the loss of life from dam failure, in which at the time of modeling there were two approaches that needed to be conducted, which were:

1. Modeling assumptions of dam failure
2. Inundation probability map
3. The conditions of inundation
4. The estimation of impact on the number of victims and infrastructure

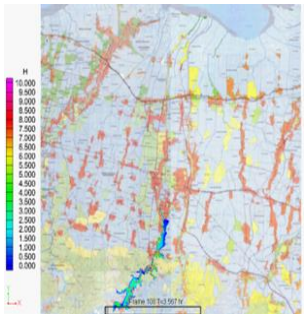
The result from the three aforementioned items will be used as the guidelines for the planning of disaster mitigation or more commonly known as EAP. This document aims to minimize the impacts of dam failure that could affect the property or even the community. Figure 8 shows the dam modelling failure using the piping failure scenario. It could be seen that the movement of the stream was from the upstream to the downstream side of the dam. In such condition, the time needed from the occurrence of dam failure (T = 0) to inundate the affected area was 16.17 hours.

Hydrograph illustration of the proposed dam in the event of dam failure is shown in Fig. 9. In this graph, specifically P 3, it could be seen that to reach the depths of 7 meters, it needs around 1.6 hours and to reach the heights above 1.5 m it needs 42 minutes. The peak discharge maximum (Q) value for the piping scenario of approximately 1463 m^3/sec, a time to peak of 1812 sec or 0.5 hours and a total duration of a significant outflow of about 137904 sec or 38 hours.

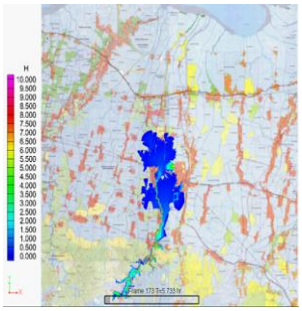
Figure 10 shows the dam failure model using the overtopping scenario. The peak discharge maximum (Q) value for the overtopping scenario of approximately 2089 m^3/sec, a time to peak of 3018 sec or 8.3 hours and a total duration of a significant outflow of about 137904 sec or 36 hours. It illustrates the movement of the stream from upstream to downstream that has more time compared to the piping scenario.

The comparation of two condition of dam failure, it was found that the flood discharge due to overtopping failure was higher than piping failure, but time arrival for piping failure is faster than overtopping.

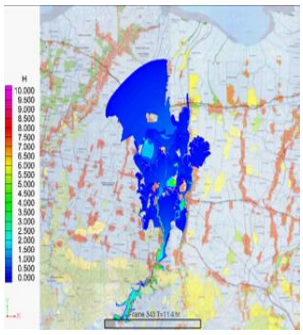
Therefore, Overtopping failure was selected for inundation map for the EAP (Fig.12). It was observed that several villages such as Malahayu, Maibah, Nangerang, Nambo were located within 7.8 km from the Malahayu dam, categorized as a high-risk area, with time arrival of flood ranges from 0.4 to 1.4 hours after the dam break (Table 1). Table 1 shows the affected area and the depth of inundation. Based on the Hazard Classification of Public Work and Housing Guidelines [25], Malahayu Dam is classified to be a very hazardous infrastructure because the population at risk is more than 1000 inhabitants.



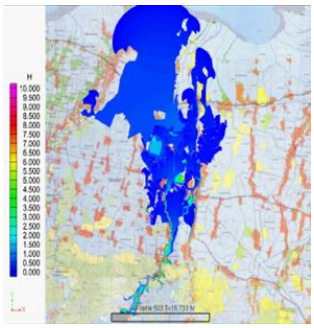
b. 3.5 hours



c. 5.7 hours



c. 11.44 hours



d. 16.17 hours

Figure 8. Flooded area due to piping failure

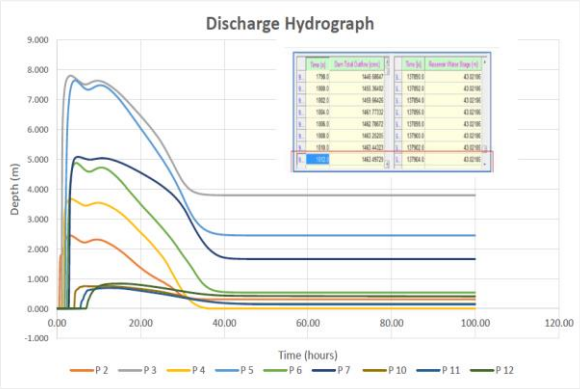
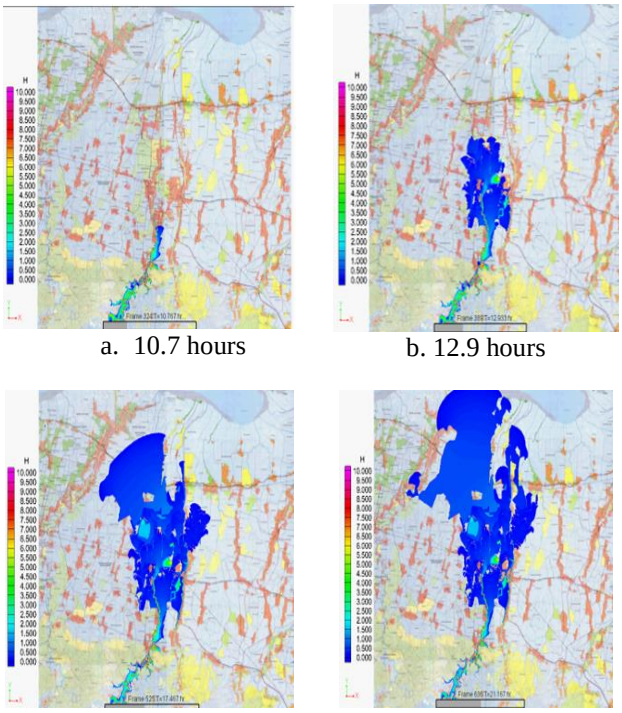


Figure 9. **Hydrograph due to piping failure**



a. 10.7 hours b. 12.9 hours

b. 17.4 hours d. 21.1 hours

Figure 10. Flooded area due to overtopping failure

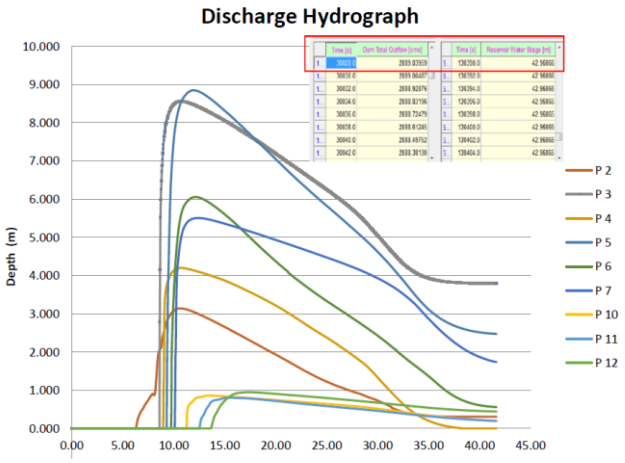
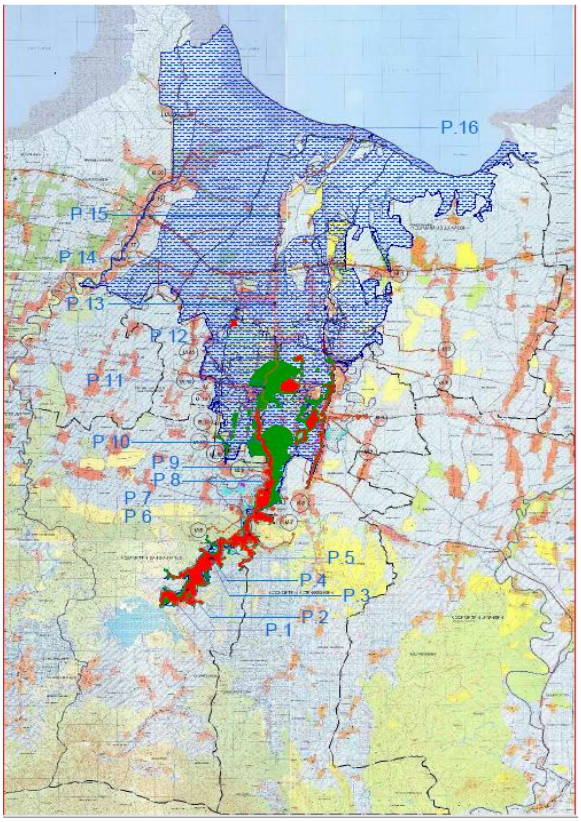


Figure 11. Hydrograph due to overtopping failure

Table 1. Inundation Area due to overtopping

Village	Inundation			
	Distance from dam (km)	Class	Depth (m)	Arrival Time (h)
Malahayu	1,4	H	0,9	0,4
Maibah	2,7	H	3,3	0,7
Nangerang	5,8	H	8,8	1,1
Nangerang	5,9	H	4,3	1,2
Nambo	7,8	H	9,2	1,4
Buara	10,2	H	6,4	1,9
Banjarharjo	12,3	H	5,6	2,3
Baros	15,4	H	2,0	2,7
Sindangjaya	17,7	H	2,6	3,0
Pende	18,8	M	0,8	3,3
Jagapura	22,3	M	0,8	4,0
Limbangan	25,2	M	0,9	5,3
Tegongan	26,9	L	0,02	6,5

Note:
H: High M: moderate L: Low



Depth: Red: > 2m, Green: 0.5m – 2m, Blue: < 0.5m

Figure 12. Inundation map

This result can be used by potential risk and local emergency preparedness agency in formulating emergency plan activities including evacuation procedures.

Emergency plan activities are divided into five phases, which are planning, mitigation, preparedness, response, and recovery. All phases depend on data from stakeholders. It is critical to have the right data to respond to and take appropriate actions specialty in actual event. Emergency personal in charge often requires detailed information to protect human life, property, and environment. Most of data requirements are spatial and located on a map. By utilizing a GIS, all stakeholders can share information through a database consisting of computer-generated maps at one location. Without this capability, emergency workers must contact many department managers, assess their unique maps, and their unique data. During most emergency situations there is not enough time to gather these resources. Thus, emergency in charge must estimate and make decisions without adequate information. This condition costs time, money, and in some cases, lives.

V. CONCLUSION

This paper presents an approach to predict inundation hazards areas at downstream sides due to dam failure by combining Navier Stokes in ZhongXing HY-21 and ArcGIS into a hydraulic model. The dam failure model is overtopping. This model was selected for inundation map which is can be used by local emergency preparedness agency and the community at risk in formulating emergency management activities including evacuation. The overtopping failure was selected for the model with peak discharge maximum (Q_{max}) is 2089 m^3/sec. The fastest arrival time is 0.4 hours (24 minutes). Several villages catagorized as a high-risk area. GIS possesses the potential to reduce time and employ resources required for developing the analysis, mapping the results, and measuring flood depth including developing an emergency system because all stakeholders can share information through a database consisting of computer-generated maps at one location.

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