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FLOOD INUNDATION AND DAM BREAK ANALYSIS FOR DISASTER RISK MITIGATION (A CASE STUDY OF WAY APU DAM)

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ABSTRACT: This paper presents a numerical modeling to simulate flood inundation and dam break analysis of Way Apu dam for an emergency action plan (EAP), by considering EAP guidelines for ICOLD (International Committee on Large Dam). The Way Apu dam, located in Way Apu River, Maluku, Indonesia is a multi-purpose dam constructed mainly for irrigation, hydropower, water supply, and flood control. Therefore, the dam's outflow discharge needs to be analyzed, due to the large amount of rainfall in eastern Indonesia. Thus, there is a need to analyze flood inundation mapping and dam break simulation in a bid to identify the flood mitigation risk zone and early warning system, within the downstream area of Way Apu dam. In this study, the flood inundation mapping and dam break simulation were analyzed using HEC-RAS 5.0.7. The analysis results of flood routing generate the outflow peak discharge reduction over spillway were 7.36 % (Ten years return period discharge, Q_{10}) and just 2.14% (Probable maximum flood discharge, Q_{PMF}), indicating the simulation results of Hec-Ras 5.0.7 model for conditions with or without dam break did not show significant difference in dam's downstream area. According to these results, 6 sub-districts are affected by the flood (Grandeng, Waeleman, Wanakarta, Waenetat, Debowae, Mako) with a maximum flood height range between 1-2.5 m (Q_{10}) and 2.9-4.2 m (Q_{PMF}). The simulation results of arrival time also showed the estimation of evacuation time for Q_{PMF} ranges from 6 - 12 hours.

Keywords: Way Apu dam, Flood inundation, Dam break, and Hec-Ras 5.0.7.

1. INTRODUCTION

Indonesia's future projections of water availability aim to solve the problem of water crisis and food security. Therefore, the nation built 222 large dams and plans to build 31 new large dams before 2023, in order to achieve these conditions. The Way Apu dam in Buru island, Maluku Province, is one of the dams to be completed in 2022. Thus, the dam's outflow discharge must be analyzed, due to a large amount of rainfall in eastern Indonesia. Analyzing the flood inundation mapping and dam break simulation is therefore necessary for emergency action plans and flood mapping implementation. The Emergency Action Plan (EAP) refers to the ICOLD Regulation (International Committee on Large Dam), and serves to minimize the risk of property damage as well as casualties within the downstream area, in case of dam failure. EAP focuses majorly on disaster management, based on Flood Inundation Mapping (FIM) as well as identifying the flood risk zones for formulating flood management [1].

Meanwhile, dam break analysis mainly characterizes and identifies potential dam failure, due to the post effects of floods from a dam breach [2]. Several studies related to dam break simulation have been conducted in Indonesia. [1] performed dam break analysis and created flood inundation map of Krisak dam (Wonogiri, Central Java), while [3] conducted a numerical model for dam break over a movable bed, using finite volume method. In addition, [4] conducted an experimental model of dam break flow around several blockage configurations, while [5][6] conducted flood inundation numerical modeling due to break in Way Sekampung dam (Lampung) and Cipanas dam (West Java), using Hec-Ras model. [7] conducted the assessment of flood propagation due to several dams break in Banten Province to estimate the inundated area due to a dam break. This study therefore aims to analyze flood inundation mapping and break in Way Apu dam, using HEC-RAS 5.0.7 to identify the risk zone and early warning system of flood mitigation, within the dam's downstream area.

Several research regarding dam break analysis using Hec-Ras, have also been conducted by [8][9]. This model is suitable for overtopping as well as piping failure breaches in earthen dams and concrete dams. The resulting downstream flood wave is routed with unsteady flow equations [10]. Thus, there is a need to analyze flood inundation mapping and dam break simulation, in order to identify the risk zone and early warning system of flood mitigation, in the Way Apu dam's downstream area, using Hec-Ras 5.0.7.

2. RESEARCH SIGNIFICANCE

In this paper, we investigate the application of Hec-Ras 5.0.7 in the dam break analysis of the Way Apu dam. The numerical scheme available in Hec-Ras 5.0.7 can be used as an early warning system of disaster mitigation in this area. The results of this model are necessary for emergency action plans and flood mapping implementation. Finally, the model also can be used as a reference for dam-break modeling in Indonesia.

3. METHODOLOGY

The Way Apu Dam is located in Way Apu River, Buru Island, Maluku Province of Indonesia (Figure 1).

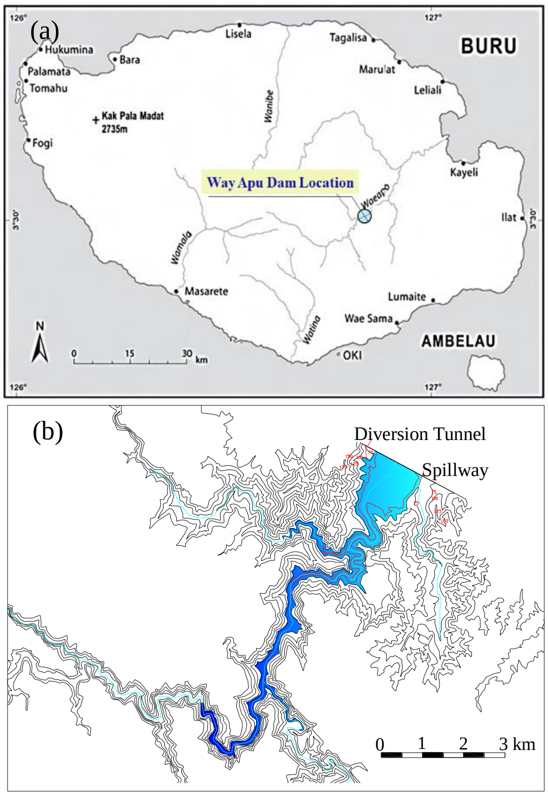


Fig. 1: (a) Location and (b) Storage area of Way Apu dam

Furthermore, the dam is an earth-fill type, with a 37-meter height and an estimated effective storage of 27 million m^3 (Figure 1b). The spillway crest is a free flow ogee type, with an elevation of El. +134 sl, and a length of 60 meters [11].

3.1 Hydrology Data

In this study, the rainfall-runoff transformation was analyzed with the ITS-2 Synthetic Unit Hydrograph (SUH) model, developed by considering fractal characteristics of a watershed, as the synthetic unit hydrograph model variable [12]. This model shows the best performance in Central Sulawesi Province, with geographical proximity to the study area [13].

In addition, ITS-2 SUH formulates a single curve equation derived from the gamma distribution equation, part of a two-parameter continuous probability distribution (2PGDF).

The ITS-2 SUH main parameters' equation form includes T_p (Time of Peak), T_b (Time Base), and Q_p (Peak Discharge). Also, the T_p and T_b equations are multiplied by a coefficient to be used in calibrating the model. Meanwhile, the coefficient is set as 1, in cases where calibration was not performed, due to absence of observational data.

$$Tp = C1(0.102L - 0.162D - 0.524\,Rl + 1.24) \quad (1)$$

$$Tb = C2(0.136A - 43.0\,S + 11.5) \quad (2)$$

$$Qp = \frac{R0}{3.6\,Tp}\,x\,\frac{A}{A\,SUH} \quad (3)$$

$$q(t) = \left\{\left(\frac{T}{Tp}\right)\exp\left(1 - \frac{T}{Tp}\right)\right\}^{C3} \quad (4)$$

Where, T_p, Q_p, T_b, define as peak time (hour), peak flow (m^3/s), and base time (hour), C1 represents the time of peak coefficient, C2 denotes the time base coefficient and C3 signifies the coefficient of hydrograph form factor, developed as a continuation of the ITS-1 SUH equation, L is mainstream length (m), A is the area of the watershed (km^2), S is the slope of the mainstream, R is unit rainfall (mm), A_{SUH} is an area under hydrograph curve, T is time (hour), D is drainage density (km/km^2) and R_l is the ratio of river length (dimensionless)[12]. In this study, the rainfall-runoff transformation was analyzed for several return period discharges (Q_{10}, Q_{100}, Q_{1000}, Q_{PMF}).

3.2 Flood Inundation Analysis

The flood inundation was analyzed from the flood routing calculation in the reservoir, calculated using the modified pul's method equation. According to its equation, the difference between the inflow (I) and outflow (Q) is equal to the rate of storage change (equation 5).

$$I - Q = \frac{dS}{dt} \quad (5)$$

$$\frac{(I1+I2)}{2}.\Delta t - \frac{(Q1+Q2)}{2}.\Delta t = S2 - S1$$

$$\frac{(I1+I2)}{2}.\Delta t - [S1 - \frac{Q1.\Delta t}{2}] = [S2 - \frac{Q2.\Delta t}{2}]$$

Where, I, Q denote inflow and outflow rate (m^3/s), S represents storage (m^3), t represents time (second).

Subsequently, the result calculations of flood routing were used as data input for the Hec-Ras 5.0.7 model, to analyse flood distribution in the Way Apu dam's downstream area. The simulation results are also a possible reference for flood mitigation and early warning system in this area. Hec-Ras develops the continuity and momentum equations (equation 6 and 7) as basic equations for hydraulic simulations [10][14].

Continuity Equation

$$\frac{\partial A}{\partial t} - \frac{\partial Q}{\partial x} - ql = 0 \quad (6)$$

Momentum Equation

$$\frac{\partial A}{\partial t} - \frac{\partial QV}{\partial x} + gA\,[\frac{\partial z}{\partial x} + Sf] = 0 \quad (7)$$

Where, Q represents discharge (m^3/s), x signifies the distance (m), t represents time (second), A denotes the cross-sectional flow area (m^2), S_f signifies the energy line slope, q_l represents lateral inflow (m^3/s), and V represents the flow velocity (m/s).

3.3 Dam Break Analysis

Previous studies on determining breach parameters concluded earth fill dam breaches due to overtopping amounted to 35%, while piping amounted to 38%, foundation failure amounted to 21%, and the rest were induced by other factors. Thus, the estimation of breach location, size, and development time are crucial for an accurate estimation of the outflow hydrographs as well as the downstream inundation. Several researchers suggested a simplified trapezoidal dam breach model for simulating dam breach hydrodynamics [10].

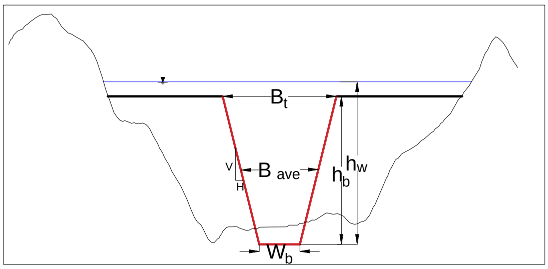


Fig. 2: Dam breach parameters in Hec-Ras.

The breach dimensions (Figure 2) were described as average breach width, breach side slope, and breach time formation, and the breach formation time must be estimated.

In 2008, Dr. Froehlich determined the breach parameters (equation 8 and 9), based on the investigation of 74 earthen, zoned earthen with a core wall (clay), and rockfill data sets to develop as set of equations, for predicting average breach width (B_{ave}) and breach formation time (t_f), as an update from previous research [15].

$$B\,ave = 0.27.Ko.Vw^{0.32}.hb^{0.04} \quad (8)$$

$$tf = 63.2\sqrt{\frac{Vw}{ghb^2}} \quad (9)$$

Where, K_o represents constant (1.3 for overtopping, 1.0 for piping), V_w denotes reservoir volume at the time of failure (cubic meters), h_b signifies the height of final breach (meters), g represents gravitational acceleration (9.81 meters per second squared)

4. RESULT AND DISCUSSION

The results of return period flood design hydrographs using ITS-2 SUH obtained a PMF (Probable Maximum Flood) condition peak discharge (Q_p) of 3786.4 m^3/s. Subsequently, the results of return period flood design hydrographs from Q_{10}, Q_{100}, Q_{1000}, and Q_{PMF} (Figure 3) were used as the input of unsteady flow model in Hec-Ras 5.0.7 for two conditions, with and without a dam break.

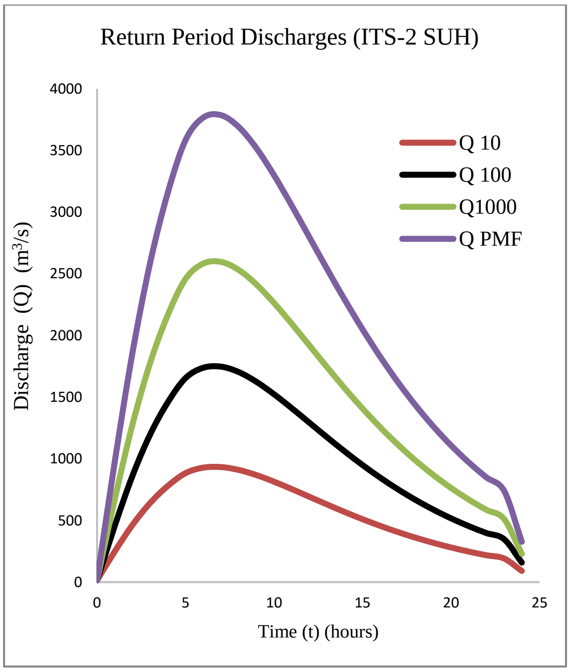


Fig. 3: Hydrograph discharge of several return periods.

According to Figure 4, the calculation of reservoir flood routing using the modified pul's method equation obtained an insignificant reduction of outflow discharge. Table 1 shows the reduction percentage of inflow-outflow peak discharge.

Figure 4 shows the flood routing inflow-outflow hydrograph of Q_{10}, Q_{100}, Q_{1000}, and Q_{PMF}. The peak discharge outflow flowing over spillway led to a 7.36% and 2.15% reduction in Q_{10} and Q_{PMF} condition, respectively. This is due to the extreme rainfall in eastern Indonesia and the reservoir storage's insignificant effect to reduce peak discharge, as a flood control.

Table 1: Percentage inflow-outflow peak discharge (Q_p) reduction.

Return Period Discharge	Peak Discharge (Q_p) (m^3)		Q_p Reduction (%)
	Inflow	Outflow	
Q_{10}	933.0	864.3	7.36
Q_{100}	1747.2	1661.3	4.92
Q_{1000}	2596.6	2510.4	3.32
Q_{PMF}	3786.3	3704.9	2.15

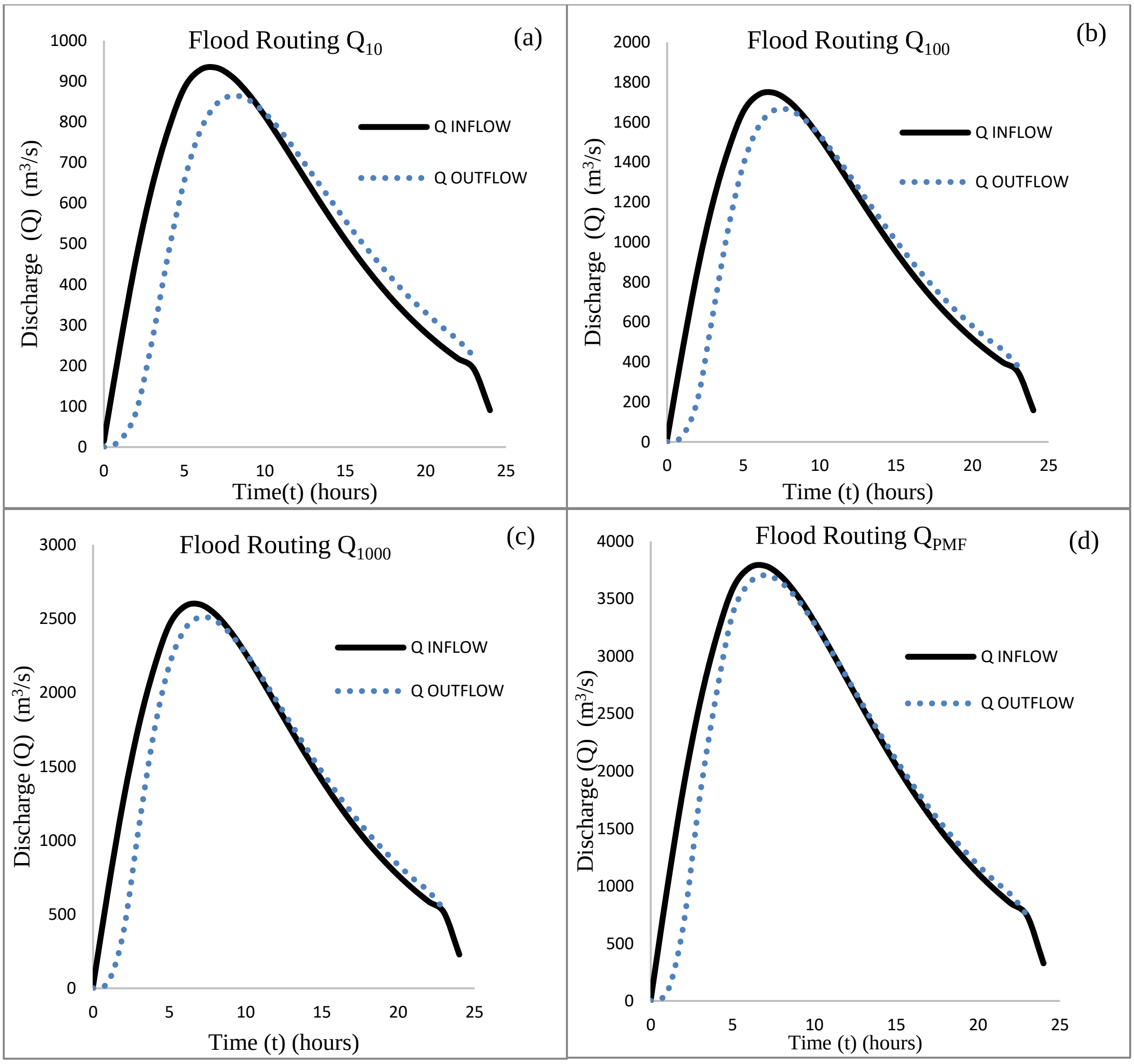


Fig. 4: Flood routing hydrograph in several return periods (a) Q_{10} (b) Q_{100} (c) Q_{1000} (d) Q_{PMF}.

4.1 Flood Inundation Map (No Dam Break)

Flood inundation modeling in the dam's downstream is based on the outflow hydrograph value passing through the spillway (Figure 4) as the input of flow hydrograph unsteady flow model in Hec-Ras 5.0.7. Figure 5 shows the inundation map results in several return periods.

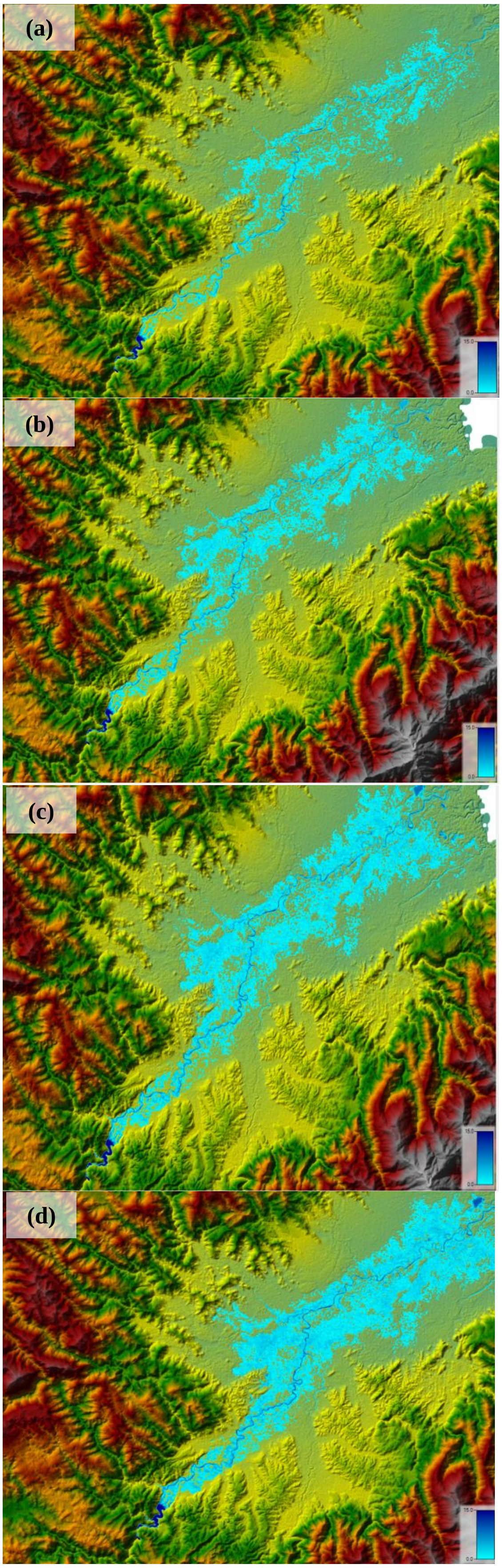


Fig. 5: Inundation map from flood modeling using Hec-Ras 5.0.7 (a) Q_{10} (b) Q_{100} (c) Q_{1000} (d) Q_{PMF}.

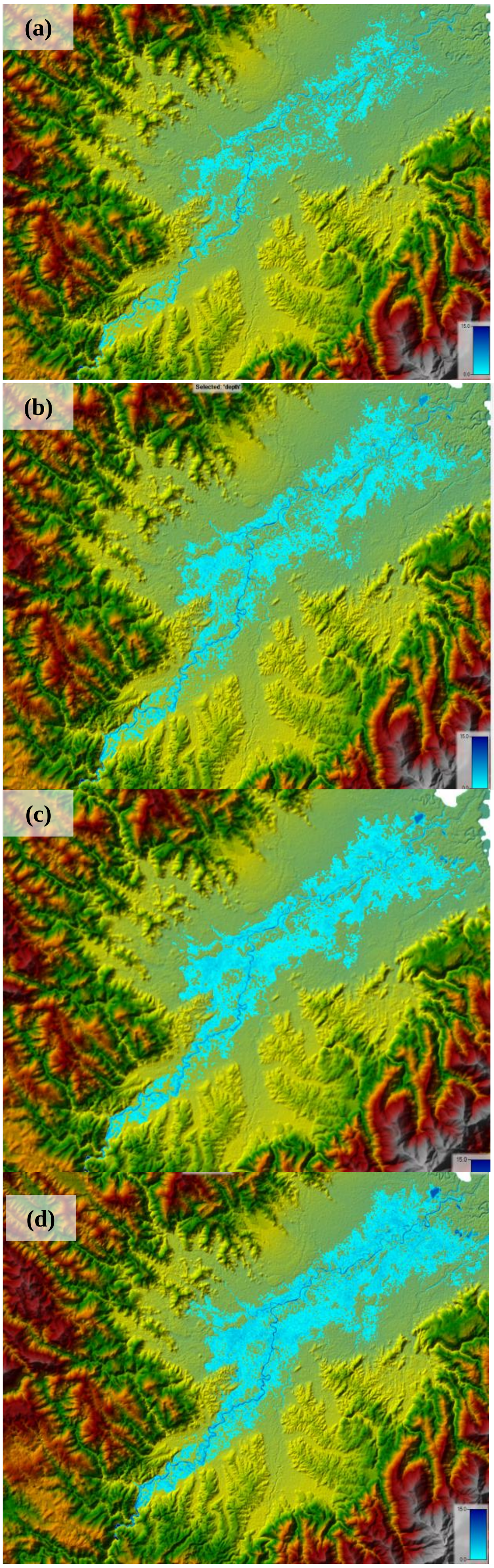


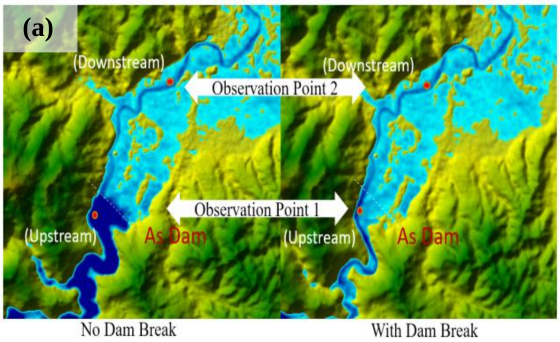
Fig. 6: Inundation map due to dam break using Hec-Ras 5.0.7 (a) Q_{10} (b) Q_{100} (c) Q_{1000} (d) Q_{PMF}.

4.2 Dam Break Simulation Result

The inundation map due to dam break was generated using four scenarios, Q_{10}, Q_{100}, Q_{1000}, Q_{PMF}. Based on the dam breach parameters obtained using Froelich [15] equation, the average breach width (B_{ave}) is 118 meter, height of final breach is 37 meter, overtoping constant (K) is 1.3, and breach formation time (t_f) is 0.96 hour. These values were then used as input for dam breach dimensions in Hec Ras 5.0.7. Figure 6 shows the inundation map obtained from the Hec-Ras 5.0.7 simulation result.

A comparison of the result without and with dam break (Figure 5 and 6) show the significant result of water depth in the dam's upstream area. Meanwhile, in the downstream area no significant difference was obtained with the same result of flood routing in Figure 4. Figure 7 shows the detail of stage hydrograph in the upstream and downstream area observation points.

In addition, Figure 7 also shows the comparison of stage hydrograph for two scenarios (Q_{1000} and Q_{PMF}) in the observation point, as the result of dam breach simulations.



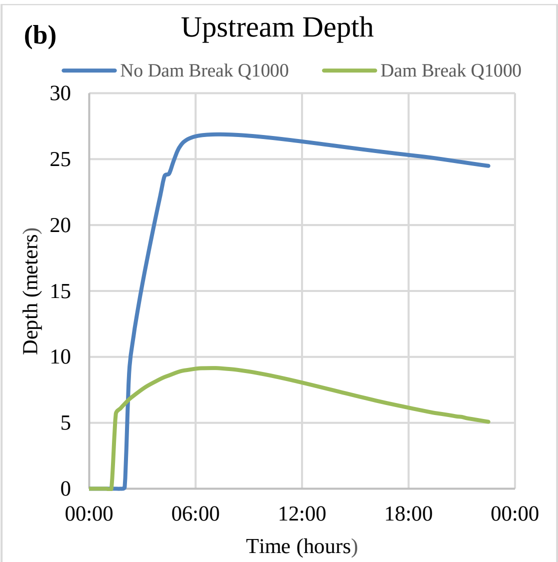


Fig. 7(a) Water depth observation point, (b) Q1000 stage hydrograph in upstream

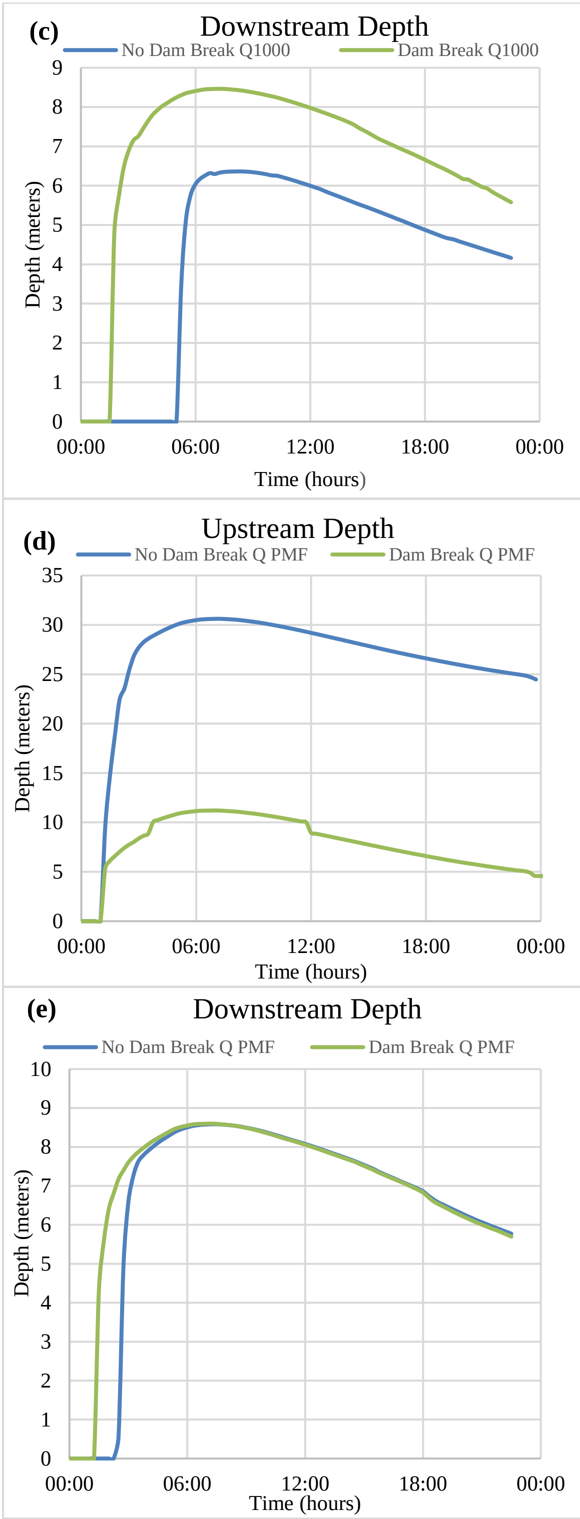


Fig. 7(c) Q_{1000} stage hydrograph in downsteram, (d) Q_{PMF} stage hydrograph in upstream, (e) Q_{PMF} stage hydrograph in the downstream

The water depth simulation results of Hec-Ras 5.0.7 due to dam break led to significantly decrease in the upstream area of about 15.25 meter (Q_{1000}) and 18.5 meter, due to dam break.

Conversely, in the dam's downstream area, the water depth in the way Apu river led to a significant increase in Q_{1000} simulation of about 2m, compared to the simulation without dam break condition (Figure 7c). However, in Q_{PMF}, the flood inundation does not have a significant difference (Figure 7e).

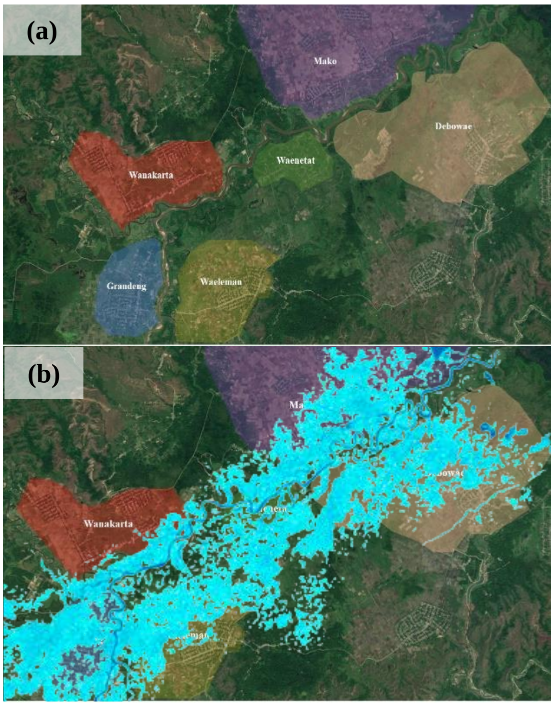


Fig. 8: (a) Sub-district affected zones of dam break (b) Flood inundation spread map of each district.

According to the inundation map (Figure 8), 6 sub-districts are affected zones from flooding due to dam break (Figure 8). The affected districts, Grandeng, Waeleman, and Waenenat, were the three completely inundated in the entire area. Meanwhile, Mako, Wanakarta, and Debowae sub-districts were only affected in a few parts of the area (Figure 8b, c). Tables 2 and 3 show the maximum inundation height and travel time in each affected zone.

Table 2 Maximum depth of inundation

Sub-District	Maximum Depth (m)			
	Q_{10}	Q_{100}	Q_{1000}	Q_{PMF}
Grandeng	1.88	2.86	3.4	3.91
Waeleman	2.57	3.24	3.73	4.21
Wanakarta	1.23	1.99	2.44	2.92
Waenetat	1.4	2.13	2.52	3.13
Debowae	1.05	2.18	2.75	3.29
Mako	1.51	2.33	2.87	3.41

The Q_{10} simulation maximum water depth varies between 1.05 - 2.57 m, while the Q_{PMF} counterpart varies between 2.92-4.21 m. In addition, the most affected zone is Waelaman sub-district, with the highest inundation height (4.21 m) for Q_{PMF} in residential areas.

Table 3 Time arrival of flood due to dam break.

Sub-District	Distance from Dam (km)	Time Arrival (hour)			
		Q_{10}	Q_{100}	Q_{1000}	Q_{PMF}
Grandeng	11.15	10.3	8.2	7.11	6.1
Waeleman	14.92	9	7.1	6.31	6
Wanakarta	18.34	10.4	8.3	7.4	7
Waenetat	18.34	13.4	11.1	9.5	9
Debowae	26.23	19.0	15.2	13.3	12.1
Mako	26.05	17	14.3	13.13	11.5

Table 3 shows the arrival time of flood. This was used to estimate an evacuation time for Q_{PMF} ranges of 6 hours, for Waeleman, the closest Sub-district (14.9 km), and 12 hours, Debowae, the farthest.

5. CONCLUSION

Based on the analysis result of flood routing, the outflow peak discharge reduction over spillway obtained were 7.36 % (Q_{10}) and 2.14% (Q_{PMF}), indicating the simulation results of Hec-Ras 5.0.7 model for conditions with and without dam break did not show significant difference in the dam's downstream area. According to the results of Dam Break modeling, 6 sub-districts are affected by the flood (Grandeng, Waeleman, Wanakarta, Waenetat, Debowae, Mako) with varying flood heights of 1-2 m (Q_{10}) and 2-3 m (Q_{PMF}). In addition, the simulation results of arrival time show the estimated evacuation time for Q_{PMF} ranges from 6-12 hours.

6. ACKNOWLEDGMENTS

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