The Prediction of Debris Flow Based on Eruption and Rainfall Event for River Infrastructure Mitigation: Study Case Opak River, Sleman Regency

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Abstract. Mount Merapi is a volcano active in Indonesia. The eruption that occurred in 2010 was a major eruption with a return period of 100 years. Dominant debris to the Opak – Gendol Watershed; the biggest debris flood occurred in 2010 – 2011. One of the disaster mitigations on the Opak River is the Sabo Dam infrastructure. Currently, in the upper reaches of the Opak River, there are 5 Sabo Dams. In 2022, 2 additional Sabo Dams were built, namely OP RRC4 and OP RRC3a. This study will be used modelling 2D HEC-RAS Non-Newtonian before the construction of 2 Sabo Dams and after the construction of 2 Sabo Dams with river geometry measured in 2020 and flood discharge as measured from rainfall triggering debris flow on 03 January 2011, from this rainfall a 6-hour rain distribution was carried out using the PSA coefficient to be input in the HEC-HMS, the hydrological parameters used on 03 January 2011, were used to calculate the Q100 flood discharge. The results of modelling at the observation point using the Q100 showed that the elevation of the debris flow after the presence of the new Sabo Dam series could be reduced by up to 47.21 %, Sabo Dam effectively reduces the rate of debris flow to reduce the potential debris flood.

1 Introduction

Mount Merapi is one of the most active volcanoes in Indonesia. Mount Merapi is located on the island of Java; the eruption period of Mount Merapi is once every 4 (four) years. The eruption that occurred in 2010 was a major eruption with a return period of once every 100 years. The eruption in 2010 released sediment in the form of sand and stone material of approximately 140 million m3; this material, along with the falling rain, was

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distributed in 15 (fifteen) rivers that disgorge on Mount Merapi. Pyroclastic flows from the eruption of Mount Merapi in 2010 were dominant in the Opak – Gendol River Basin.

High-intensity rains can result in debris flow flooding, which results in huge losses. Debris flow is a two-phase mixed flow, solid phase and liquid phase. The solid phase is in the form of sediment grains the size of sand to rocks measuring more than one meter [1], debris flows as sediment flows and air mixing, which resembles a continuous flow shape and is influenced by gravity [2]. Debris flows move very quickly and usually occur in areas with steep slopes where collapse occurs, and the rainfall intensity in the area is high [3].

The largest debris/lava flows occurred in 2010 – 2011; one of the debris flooding events in the Opak River was on 03 January 2011. Mitigation of debris flood disasters includes the construction of the Sabo Dam to control sediment/debris so that it can minimize the potential for debris flooding.

In this study, modelling will be carried out using 2D HEC-RAS Non-Newtonian 2D HEC-RAS (HEC-RAS 6.3.1) to determine the effectiveness of the Sabo Dam on lowering the water level/debris flow and velocity downstream of 2 new Sabo Dams in 2022 using a 100-year return period debris flood discharge (Q100) with parameters which are used from the calculation of the debris flood discharge in the debris flood event on 03 January 2011 in the Opak River.

HEC-RAS is a program developed by the United States Army Corp of Engineers (USACE), In HEC-RAS 6.0 can integrate non-Newtonian effects into any unsteady flow simulation, the initial approach to the debris and mudflow flow simulation is to add the debris and mudflow loss slope (S_{MD}) into the momentum equation by replacing the influence of the Non-Newtonian flow as friction Slope (S_f) can be interpreted as a mathematical approach to include changes in flow, this approach describes how the material/debris changes shape due to shear stress [4]. In Non-Newtonian Fluids, there are rheological models based on their classification [4], namely Bingham (Hyperconcentrated), turbulent-Quadratic-Herschel-Bulkey (Mud and Debris Flow), Voelmy (Snow Avalanche) and Mohr-Coulomb (Clastic).

Before Hecras version 6, it is common practice to utilize standard Newtonian fluid-based hydraulic and sediment transport equations for hyperconcentrated flow modelling. On the other hand, debris or mud flows are usually completely non-Newtonian and hence basic hydraulic, and sediment transport equations are not applicable [5].

Besides HEC-RAS, there are several software for modelling 2D debris flows, including SIMLAR, Kanako and DFLOWZ. Modelling lava floods with SIMLAR 2.1 can describe the distribution of lava floods horizontally and vertically (height of lava floods), SIMLAR can also model the velocity of lava floods [7]. Kanako 2D, developed For alluvial fans, it uses a 2-D numerical simulation model to reproduce changes in flow depth and sedimentation to simulate the passing area of debris flow [8]. DFLOWZ is software with output that can be used as an initial prediction of potential areas Affected by debris flows; this program is also able to analyze the direction of debris flow and the extent of areas that have the potential to be inundated by debris flow deposits [3].

In this study, the Non-Newtonian HEC-RAS (HEC-RAS 6.3.1) was chosen because HEC-RAS is very familiar to be used for hydraulic modelling and is practical to use; in HEC-RAS Non-Newtonian distribution of debris flow can be known including the water level elevation, depth and velocity, as well as the user, can adjust the Yield Strength and Mixture Dynamic Viscocity parameters according to the conditions in the field.

2 Material and methods

2.1 Study area

Opak River Basin is located in the Special Region of Yogyakarta (DIY). The area of Opak watershed is 1.376,34 km2 with a river length of ± 171.75 Km [7]. The study location is in Cangkringan District, Sleman Regency, Yogyakarta Special Region. The results of the delineation analysis of the Watershed showed that the catchment area of the study location in the Opak River is 9.405 Km2 and the length of the Opak River (Main River at the Study Location) is 10.198 Km. Results of Watershed Delineation in Study Locations in Fig. 1.

The existing conditions at the study site before the presence of Sabo Dam OP RRC4 and Sabo Dam OP RRC3a contained 5 Sabo Dams in existing conditions, namely Sabo Dam OPC Kaliadem, OP D1, OP D2, OP D3 and OP Pagerjurang. In 2022 there will be the addition of 2 Sabo Dams, namely Sabo Dam OP RRC4 and OP RRC3a.

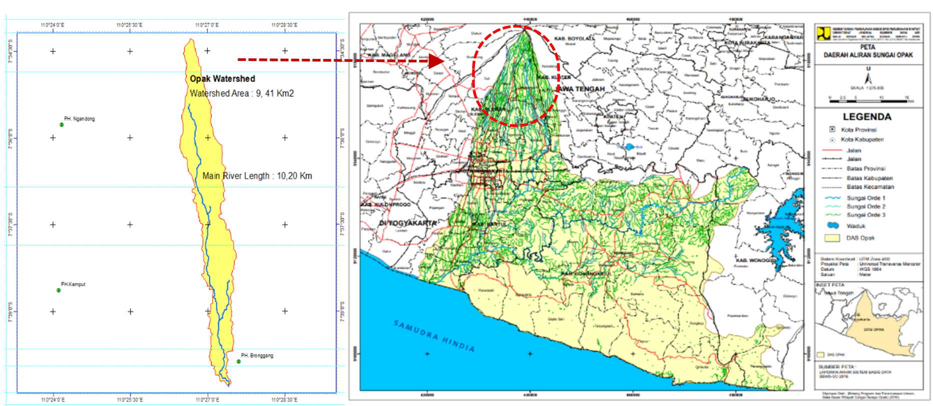

Fig. 1. Results of watershed delineation in study locations

2.2 Conceptual approach

Mount Merapi is an active volcano in Indonesia; when an eruption occurs, Mount Merapi releases material and is distributed in 15 rivers that originate at Mount Merapi, one of which is the Opak River. When it rains, the material is carried along with the flow, which causes debris flows and has the potential to cause flooding. Debris floods cause economic and social losses, one of which is damage to residents' agricultural land, settlements, collapsed bridges, etc.

The way to predict debris flow is by referring to the day the debris flood occurred, from the rainfall that triggers the debris flow, then calculating the flood discharge, verifying it with events in the field and calculating the return period flood; in this study, the 100 year return period is calculated. One of the debris flood disaster mitigations is the

Sabo Dam Infrastructure Development. Sabo Dam acts as a sediment controller and can minimize the potential for debris flows to occur. This research also studies the effect of the Sabo Dam for the debris flow in the Opak River (**Fig. 2**).

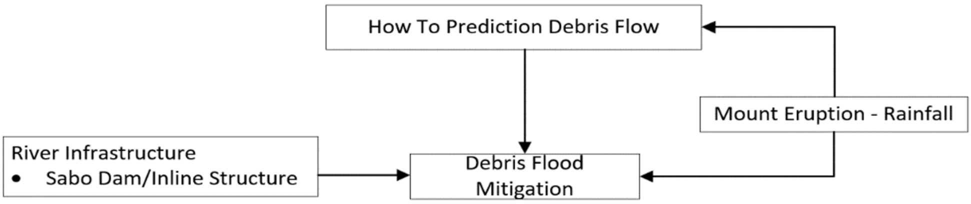

Fig. 2. Conceptual diagram

2.3 Research flow diagram

This study uses discharge data from modelling using the SCS Curve Number loss method and the Snyder Unit Hydrograph transform method at HEC-HMS [9], the Snyder synthetic unit hydrograph method. F.F. Snyder came from the United States in 1938, utilizing DAS parameters to obtain synthetic unit hydrographs [10]. The results of calculating the discharge data will then be multiplied by the Cd value based on the formula from Takahashi [2]; after that, debris flood discharge will be obtained and simulated using Non-Newtonian HEC-RAS [4]. The simulation results will later obtain the depth and velocity of debris flow prior to the presence of Sabo Dam OP RRC3a and Sabo Dam OP RRC4 at the observation point. Methodology Flowchart in Fig. 3.

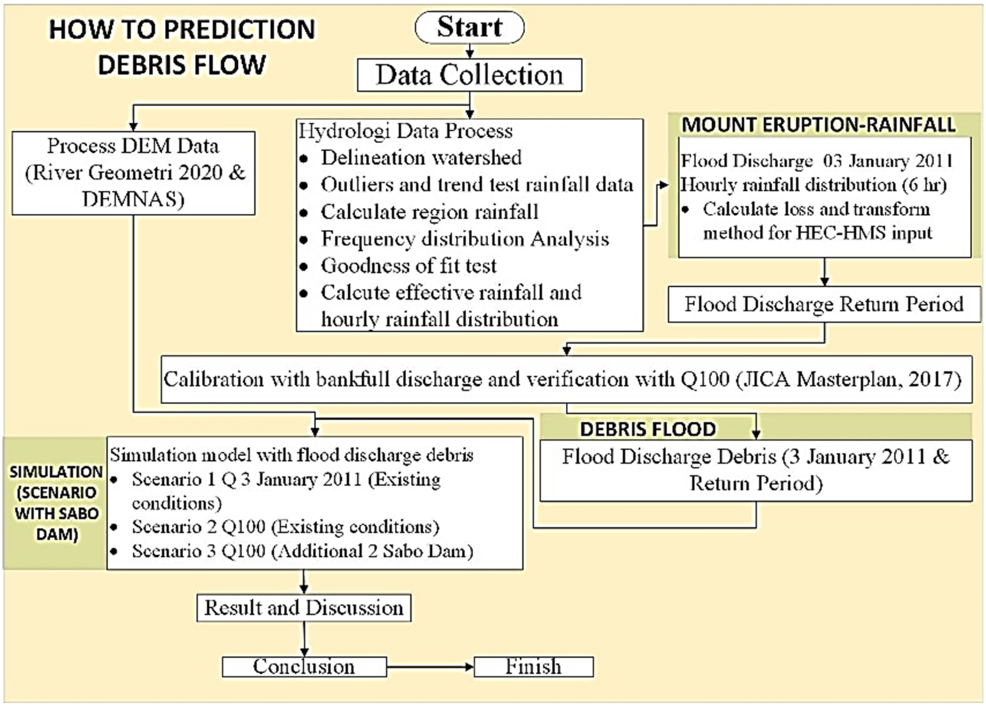

Fig. 3. Methodology flowchart

2.4 Debris flows

Debris flow undergoes various changes, starting from solid, viscous when it starts flowing, grains disperse, liquid and thickens, and grains reassemble and solidify when it stops flowing. In such a complex and multi-phase system, there is a constant exchange of momentum between the grains [11]. A wide range of natural flows present non-Newtonian properties, including mudflows, Debris flows, lahars, and snow avalanches [4]. In Newtonian fluids, the relationship between shear rate and shear stress is linear and passes through the origin. Non-Newtonian fluids have a shear rate vs shear stress relationship, which can be nonlinear and/or does not pass even though the origin [4]. Mathematical models for simulating non-Newtonian flows can be classified into single-phase and two-phase models. The single-phase model describes the properties of the mixture and solves the mixture conservation equations in [4], according to Hergarten and Robl [12]. The two-phase model considers the liquid and solid phases of the mixture and solves the conservation equations for the mixture for each phase according to Bozhinsky and Nazarov [13] in [4].

2.5 Non-newtonian flow equations

2.5.1 Continuity Equation

The form of the unsteady flow differential equation from the conservation of mass (continuity) equation in the condition of water mixed with solids is as follows:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (hV) = q \tag{1}$$

Where η is the flow surface elevation, t is time, h is water depth, V is velocity vector, and q is lateral discharge according to unit length, to account for external and internal fluxes.

2.5.2 Momentum Equation

The equation for the conservation of the momentum of the average depth can be written by Hergarten and Robl [12] in [4]:

$$\frac{\partial V}{\partial t} + (V \cdot \nabla)V = -g\cos^2\varphi \nabla\eta + \frac{1}{h}\nabla \cdot (\nu_t h \nabla V) - \frac{\tau}{\rho_m R}\frac{\cos\psi}{\cos\varphi}\frac{V}{|V|} \tag{2}$$

Where g is the gravitational acceleration, ν_t is the viscosity of the turbulent flow, τ is the total basal stress, ρ_m is the density of the water-solid mixture, R is the hydraulic radius, |V| is the magnitude of the velocity vector, φ is the water surface slope, and ψ is the inclination angle of the current velocity direction.

The critical term in this analysis is τ, the fluid stress. in the non-Newtonian model using the following equation [14] :

$$\tau = \tau_r + \tau_{MD} \tag{3}$$

Where τ_r is the basal stress and τ_{MD} comes from the stress-strain (rheology) model selected for the material [14]. The basal stress incorporates bed roughness, making it a function of the friction slope S_f:

$$\tau_r = \gamma R S_f \quad (4)$$

Where γ is the unit weight of the fluid, R is the hydraulic radius, and S_f is friction slope from manning equation:

$$S_f = \left(\frac{nV}{kR^{2/3}}\right)^2 \quad (5)$$

Where V is the velocity and k is a unit conversion factor.

2.6 Rheology (stress-strain relationship) of non-Newtonian fluids

Rheology is the study of how materials deform under stress (**Fig. 4**). Rheological models are often expresses as simple relationships between stress and strain [4].

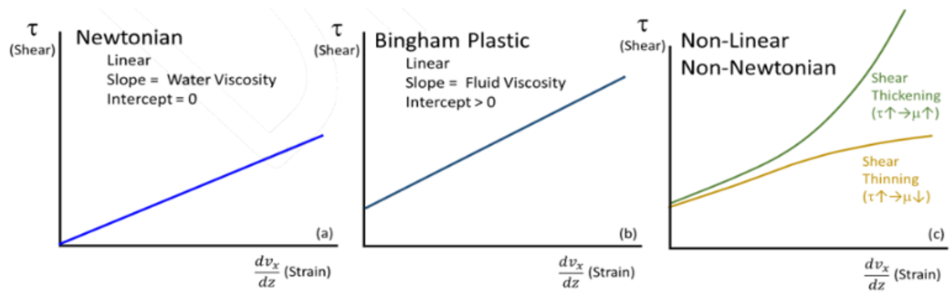

Fig. 4. Rheological model, (a) clear water and (b,c) mud and debris flows [4]

In this study, the Bingham rheological model is used to represent non-Newtonian fluids (Debris flows). The Bingham model (Bingham 1922) in [4] is one of the simplest rheological models. The Bingham stress formula is as follows:

$$\tau_{MD} = \tau_y + \tau_v \quad (6)$$

$$\tau_v = \mu_m \dot{\gamma} \quad (7)$$

Where τ_y is the yield stress, τ_v is the viscosity stress, μ_m is the dynamic viscosity of the mixture, and $\dot{\gamma}$ is the shear rate.

2.7 Verification, debris flows discharge calculation, and prediction

2.7.1 Verification

The flood discharge on January 3 2011, and the return period flood discharge from the calculation results were verified with a bankfull discharge in the field; the bankful discharge was compared to the 2-year return period (Q2) discharge with a maximum difference error percentage of 5%, in addition, verification of the calculation results was also carried out debit for the 100 year return period (Q100) with the 2017 JICA Masterplan Review study [17].

2.7.2 Calculation

Based on the guidelines in the Sabo Work Manual, the 100-year flood probability (Q100) of the design discharge is used to determine the flood discharge including sediment [15]. Flood flow including sediment is determined according to the following formula:

$$Q_S = Q_w \cdot (1 + Cd) \tag{8}$$

Where Qs is Flood discharge with sediment (m3/sec), Qw is Design flood discharge (m3/sec), and Cd is Sediment concentration ratio.

The value of Cd can use the formula developed by Takahashi [2] as follows:

$$Cd = \frac{\rho_w . Tan\ \theta}{(\rho_m - \rho_w).(Tan\ \emptyset - Tan\ \theta)} \tag{9}$$

If the calculated value (Cd) is greater than 0.9 C*, Cd should be considered as 0.9 C*, and if it is less than 0.3, then it is considered as 0.3.

Where Cd is the sediment concentration in the river (%), C* is the concentration of sediment deposited (about 0.6), ρ_w is the density of water (tons/m3), ρ_m is the density of sediment (tons/m3), ϕ is the internal shear angle (°), and θ is the average slope of the riverbed.

2.7.3 Prediction

Prediction of debris events is made by looking for the water level at the time of the debris incident with the debris flood discharge on January 3 2011, because the river topography/geometric data used is 2020 data (data after the eruption of Mount Merapi in 2010) it is assumed that the water level is up to the debris flow overtopping the canal. Modelling uses Non-Newtonian HEC-RAS with the parameters in **Table 9**. Based on information from the news and local residents, on January 3 2011, there was a debris flood reaching ± 1 - 2 m around the location of the Jalan Pakem - Kalasan Bridge and the Cangkringan District Police and according to information from residents too at the study site after the 2010 eruption of Mount Merapi experienced a change in a width reaching 10 – 20 m.

3 Result and discussion

3.1 Land cover

The results of the land cover analysis based on the land cover map from BIG (Geospatial Information Agency Indonesia) found that the Opak watershed in the study location has grassland/bare land cover, plantations, settlements and activities, paddy fields, shrubs and dry fields/fields. The majority is covered by plantations covering an area of 3.6 km2 with a percentage of 38.31%. From the analysis of the Harmonized World Soil Database

(HWSD) map, it is found that the Dominant Loamy Sand Land belongs to the Hydrologic Soil Group (HSG) type A; from these results, the Curve Number (CN) Composite [16] can be calculated.

Based on the analysis results, it was found that the CN Composite was 59, the CN Composite was CN in normal/dry conditions, and the CN in wet conditions (CNw) [17] was obtained at 77. Considering the flooding that occurs during the rainy month, the CN Wet (CNw) is taken at 77. The Impervious value for the Opak watershed at the study site is assumed to be 75% for all land cover, referring to research conducted by Syarifuddin M. et al. in 2017 in Mount Merapi [18].

3.2 Eruption event with rainfall (03 January 2011)

Based on observations on rain data from Bronggang Station obtained from BBWS Serayu Opak, daily rainfall (R24) during the debris flood incident was 78 mm. Daily rainfall data was then corrected with ARF to 77 mm and distributed into hourly rainfall data using the PSA 007 method recommended in the Technical Guide for Calculation of Flood Discharge at Dams by Ministry Public Works and Housing. In this study, the distribution used is the distribution for 6 (six) hours. Distribution of rain on 03 January 2011 in **Table 1**.

Table 1. Distribution of rain on 03 January 2011

Time (hr)	1	2	3	4	5	6
Coeff.PSA 007 (6 hr)	0.05	0.10	0.60	0.16	0.06	0.03
Rainfall (mm)	4	8	46	12	5	2
Percentage (%)	5	10	60	16	6	3
Total R24	77	mm				

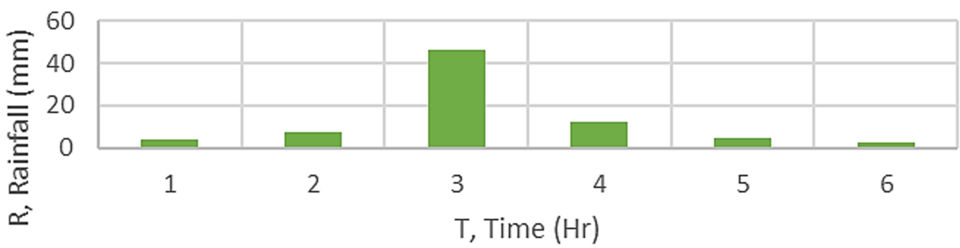

Fig. 5. Graph of rain distribution on 03 January 2011

Hourly rain data were then analysed using the SCS CN loss method and the Snyder's Synthetic Unit Hydrograph transform on the HEC-HMS to obtain a flood discharge. The parameters used in the HEC-HMS are in **Table 2**.

Table 2. Loss and transform parameters in Hec-Hms

Cp	Ct	L (Km)	Lc (Km)	Time Lag (Hour)	Standar Lag (Hour)	CN	Initial Abstraction	Impervious (%)
0.9	1.20	12.89	6.65	3.42	2.05	77	15.17	75

The peak flood discharge on January 3 using HMS – Snyder was obtained at 48.4 m3/s; the results of this calculation were then compared with other Synthetic Unit Hydrograph methods; the results of the comparison are in **Table 3**.

Table 3. Results comparison of unit hydrograph

Time	Flood Discharge (m^3/det)						
	Nakayasu (Alpha=2.0)	ITB-1a	ITB-2a	ITB-1b	ITB-2b	SCS HMS	Snyder HMS
03-01-11	46.93	34.62	45.52	35.83	46.95	41.30	**48.40**

Comparison results with other Synthetic Unit Hydrograph methods are more or less close without including maximum potential retention (S). The results of the calculation of flood discharge using all methods are then averaged and added by 20 % on average, and the result is 50.23 m3/s; a value close to this value is the flood discharge using the HMS Snyder method of 48.40 m3/s, and the selected flood discharge using the Snyder method, the parameters used in the calculation using the Snyder flood discharge are used to calculate the planned return period discharge.

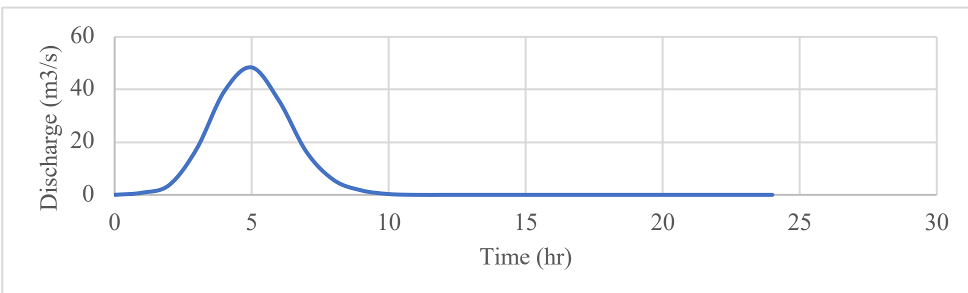

Fig. 6. Flood hydrograph on 03 January 2011

3.3 Flood discharge verification

Analysis of Annual Maximum Daily rainfall into regional rainfall in the DAS at the study location uses the Polygon Thiessen method. Then an analysis of the rainfall for the return period was carried out; the distribution function chosen was the Log Pearson III distribution. The return period planned rainfall is then multiplied by the ARF, along with the return period planned rainfall calculation results in
Table 4.

Table 4. Results rainfall frequency analysis

No	Return Period (Years)	Rainfall Plans x ARF (mm)
1	2	129.51
2	5	153.64
3	10	169.74
4	25	190.30
5	50	205.83

 https://doi.org/10.1051/e3sconf/202450002015

No	Return Period (Years)	Rainfall Plans x ARF (mm)
6	100	221.58

Table 5. Return period and 03 January 2011 peak discharge

No	Return Period (Years) & 03 January 2011	Flood Discharge Snyder Hec-HMS (m^3/s)	Flood Discharge Debris flow (m^3/s)
(1)	(2)	(3)	(3) x (1 + Cd)
1	03-Jan-2011	48.4	62.92
2	2	85.7	111.41
3	5	103.3	134.29
4	10	115.2	149.76
5	25	130.3	169.39
6	50	141.8	184.34
7	100	153.5	199.55

The results of the flood hydrograph are multiplied by the discharge coefficient, which is affected by sediment based on the results of the calculation of Cd (sediment concentration); the results of the calculation of Cd are obtained at 0.06 because the results are <0.3 then Cd is considered 0.3 [2], then the flood discharge with sediment Qs = Qw. (1 + 0.3). Recapitulation of the planned peak discharge, 3 January 2011 peak discharge and flood discharge with sediment/debris is shown in **Table 5**.

The Q2 peak flood discharge of 85.7 m3/s was calibrated by comparing the results of Synthetic Unit Hydrograph hydrological analysis for a 2-year return period (Q2) with a bankfull flood discharge. This calibration was carried out at two measurement locations using cross-section data for 2020. The following is a comparison between the 2-year return period flood discharge and bankfull discharge:

Table 6. Comparison of Q2 snyder's synthetic unit hydrograph with bankfull discharge

Location	Q2 (m^3/s)	$Q_{bankfull}$ (m^3/s)	Deviation	Error (%)
Cross Section 1	85.70	86.14	0.44	0.51
Cross Section 2	85.70	90.15	4.45	4.93

Based on the **Table 6**, it is found that the Q2 discharge value resulting from Snyder's Synthetic Unit Hydrograph Q2 calculation is close to the bankfull discharge value. The Q100 flood discharge was also verified by calculating the 2017 JICA Masterplan Review with a Q100 of 171.34 m^3/s [19] in [20]. The results of the calibration and verification are close enough, so the values calculated by Snyder's Synthetic Unit Hydrograph can be used.

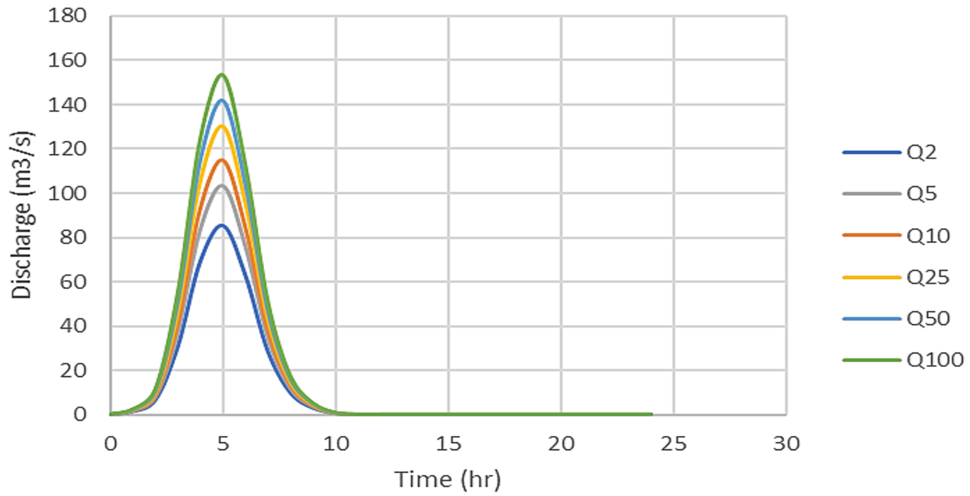

Fig. 7. Flood hydrograph return period

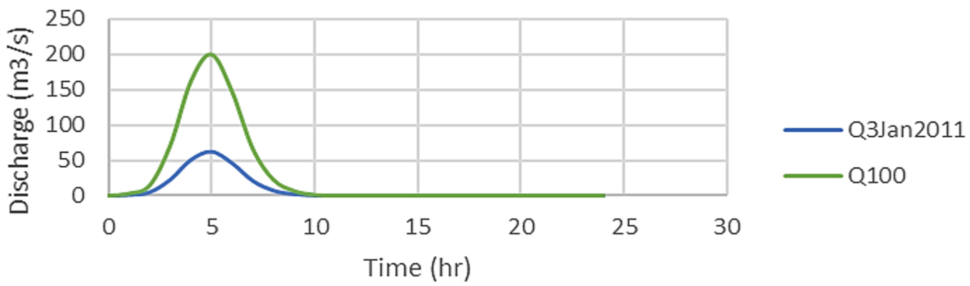

Fig. 8. Flood hydrograph debris flows 3 January 2011 & 100 years

3.4 Simulation scenarios for mitigation

Modelling in HEC-RAS uses ± 10 Km 2020 River geometry data and National Digital Elevation Model for Coastal Application (DEMNAS) data. **Table 7** shows the modelling scenario in HEC-RAS.

Table 7. Scenario modelling on HEC-RAS

Scenario	Upstream	Downstream
1	Flow Hydrograph Debris Flows 3 January 2011 (Existing conditions)	Normal depth (slope 0.06)
2	Flow Hydrograph Debris Flows Q100 (Existing conditions)	Normal depth (slope 0.06)
3	Flow Hydrograph Debris Flows Q100 (After the existence of 2 Sabo Dam)	Normal depth (slope 0.06)

Based on the value of Cd = 0.3, the rheological model used is the Bingham model [2]; for the value of yield stress and dynamic viscosity of the mixture using User Yield 150 Pa and User Defined Viscocity 1.48 Pa-s, this value is used based on the condition modelling approach during debris floods January 03, 2011, in this condition, there are 4 existing Sabo dams from upstream.

Table 8. Input parameter simulation in HEC-RAS

Parameters	**Method**	**Value**
Concentration Volumetric (Cd)	Takahashi	0.3
Rheology Model	Bingham	-
Yield Strength	User Yield	150 Pa
Mixture Dynamic Viscosity	User Defined Viscosity	1.48 Pa-s

There are two observation points in Scenarios 1, 2 and 3, namely, point 1 downstream of the Jalan Pakem-Kalasan bridge and Point 2 upstream of the Jalan Pakem-Kalasan bridge. The results of scenario 1 modelling (Date 03 January 2011) obtained run off conditions at Point 1 and Point 2, the water depth reached 5.28 m with a speed of 5.88 m/s at Point 1, and the water depth reached 3.67 m with a speed of 4.71 m/s at Point 2.

The model simulation results show that the elevation of debris flow after the presence of the new Sabo Dam can be reduced by up to 47.21 % based on the observation points taken at point 1 and point 2. At Observation Point 1, the water level before the Sabo Dam was 6.18 m with a velocity of 9.30 m/s, and at point 2 before, the Sabo Dam was 4.66 m with a velocity of 7.38 m/s. Simulation results after the Sabo Dam water level at observation point 1 was 4.38 m with a velocity of 9.61 m/s, and at observation point 2 was 2.46 m with a velocity of 7.66 m/s. Based on the simulation results, the conditions after the existence of the Sabo Dam Series were able to reduce the elevation of debris flow water level. Simulation Result at Point 1 and Point 2 for Scenarios 1, 2 and 3 in **Fig. 9**.

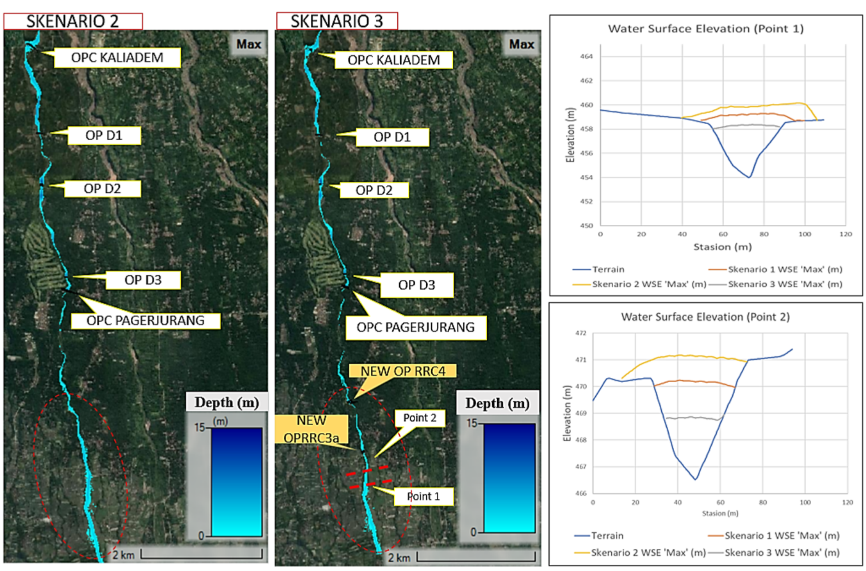

Fig. 9. Distribution of debris flows (Scenario 2 & 3) and Water Surface Elevation (WSE) Simulation Result at Point 1 and Point 2 (Secenario 1, 2 and 3)

The bridge on Jalan Pakem-Kalasan has an elevation of 471.52 – 471.842 m, the simulation results at Point 2 (upstream of the bridge) from all scenarios the water level does not exceed 471.52 m, in this condition the bridge is safe.

4 Conclusion

Based on the concentration of sediment Cd = 0.3, modelling using the Bingham rheological model with yield strength and user yield parameters of 150 Pa and Mixture Dynamic Viscocity parameters with user Defined Viscocity of 1.48 Pa-s is considered to represent field conditions. Overall, the existing conditions of the Opak River before and after the existence of Sabo Dam OP RRC4 and Sabo Dam OP RRC3a at the study site with river geometry data for 2020 are still unable to accommodate flood discharge with sediment concentrations at several downstream points after the last existing Sabo Dam on the 3 January 2011 debris flood incident and flood 100-year return period (Q100).

Based on modelling results at the observation point using the Q100, it was found that the elevation of the debris flow after the new Sabo Dam Series could be reduced by up to 47.21 %. The 2 series of new sabo dams can also protect the bridge on Jalan Pakem-Kalasan, preventing potential bridge collapse due to debris flows. The addition of the Sabo Dam OP RRC4 and OP RRC3a in the Opak River is effective in reducing the water level so that it is feasible as a disaster mitigation effort that can reduce the potential for debris floods in the future.

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