Simulation of debris flows in the watershed of the Putih River, Indonesia using SIMLAR 2.1

J Ikhsan¹, R Ardiansyah² and D Legono³

¹ Civil Engineering Department, Universitas Muhammadiyah Yogyakarta 55183, Indonesia
² Student of Civil Engineering Department, Universitas Muhammadiyah Yogyakarta 55183, Indonesia
³ Civil Engineering and Environmental Department, Gadjah Mada University, Yogyakarta 55281, Indonesia

*Corresponding author: jazaul.ikhsan@umy.ac.id

Abstract. In 2010, the eruption of Mount Merapi produced a huge volcanic material for debris flows. One area affected by the debris flows is the watershed of Putih River. To predict the impact caused by debris flows can be done by using software such as the Simulation Lahar (SIMLAR) 2.1. In this paper, debris flow modelling will be carried out using SIMLAR 2.1 in conditions without sabo dams and using sabo dams. This simulation aims to determine the effectiveness of the sabo dams in reducing the impact of debris flows. The data used are rainfall data, DEM and sediment data in Putih River. The results show that the sabo dam building can slow down the velocity of debris flow. In addition, sabo dams also function as a barrier to riverbed erosion in the Putih River watershed. Based on the results above, it can be concluded that SIMLAR 2.1 can predict the impact of debris flows in the Putih River watershed.

Keywords: putih river, SIMLAR 2.1, debris

1. Introduction
Debris flow is a widespread phenomenon in both volcanic and non-volcanic mountainous places around the world. These floods have resulted in considerable morphological changes along riverbeds and mountain slopes, as well as extensive property damage and deaths [1-4]. As a result, research into preventative measures is critical to avoid the downstream hazard. Preventive measures necessitate the examination of hydraulic, hydrological, sediment size distribution, topographical, and other aspects and the consideration of alternative scenarios. Indonesia lies during three volcanic arcs: the Mediterranean Mountains, the Australian Path, and the Pacific Path. Indonesia is a volcano-prone territory because of these circumstances [5]. There are 129 volcanoes in Indonesia, with 83 of them actively active. The majority of the land around active volcanoes is used for agricultural purposes. Because the area around the volcano is extremely vulnerable and the populace is not well-prepared, the danger of being impacted by eruptions or debris flows increases [6].

Debris flow is a volcanic hazard that can occur outside of an eruption when volcanic material is mixed with rain. When significant volumes of material are pushed downstream by rivers that originate in volcanoes and reach settlements and infrastructure, debris flow becomes harmful [7]. The Merapi
Volcano eruption in 2010 was the largest in the last 100 years, releasing large amounts of sediments that turned into debris flows during the wet season. Between October 2010 and February 2011, debris flows occurred 280 times [8]. The southwest slope of Mount Merapi, particularly the Putih River's riverbanks, has been hit the hardest by debris flows. The debris flow caused 2,082 people to be displaced, 67 houses loosed, 262 houses to be badly damaged, 32 houses to be moderately damaged, and 47 houses to be slightly damaged [7].

Constructing dams, limiting land usage, and evacuating residents are common remedies taken to reduce the risk of debris flows. One method for occupant evacuation is to use non-structural mitigation by building a telemetry system for forecasting and early warning [9]. The hazard zone coverage and the course of debris flows are two frequent uncertainties while planning any countermeasures. For engineering designs and evaluation of their efficiency, a numerical model appropriate for dynamic simulation for field cases is a very helpful tool [10]. In this research, the debris flow simulation was carried out using the SIMLAR application version 2.1. to predict the affected area and effectiveness of sabo dams in the Putih River watershed, Magelang Regency.

2. Research Methods

2.1. Location
The research was conducted in the Putih River watershed, located in Magelang Regency, Central Java, with the UTM WGS 1984 49S zone. The area of the Putih River watershed is 23.791 km², with the length of the Putih River is 23.5 km. The research location is shown in Figure 1.

2.2. Material
This research used materials or materials from secondary data obtained from the Sabo Dam Research and Development Institute (Balai Sabo), Yogyakarta. The data obtained are Putih River sediment data, 2015-2019 rainfall data at Pucanganom Station (Figure 1), and data regarding the location and dimension of the sabo dams.

2.2.1. Rainfall data
Rainfall data were obtained from the Sabo Dam Research and Development Center in Yogyakarta. Rain data used is the last five years, namely rainfall data of period 2015-2019. The data comes from the rainfall station located in Pucanganom, Srumbung, Magelang Regency.
2.2.2. DEM data
The recommended topographic map is DEM data with a maximum spatial resolution of 15 m. In this study, and the resolution used is eight m². The DEMNAS topographic map can be downloaded from the website: tides.big.go.id. DEMNAS has a spatial resolution of 8 m² or 0.27 seconds in *.tif format. In SIMLAR software, topographic maps must be in *.Asc format, therefore DEMNAS maps must first be converted to *.Asc format via ArcGIS software.

2.2.3. Sediment data
Sediment data uses samples from the upstream of Putih River, which is the sediment production zone. The parameters needed are the potential volume of sediment and the distribution of sediment grain gradations. Enter sedimentation data as follows, estimated sediment source: 9,300,000 m³, sediment deposit density: 1800 kg/m³, the density of mud water: 1.79 g/cm³, sediment density: 1.80 g/cm³, and grain gradation.

2.2.4. Dimension and Location Sabo Dams
This simulation uses 13 sabo dams (Table 1) as input materials, locations sequentially from upstream to downstream, including sabo dam PU-D1 Mranggen, PU-C11-12 Gremeng, PU-C9 Cabe Lor, PU-RD 1, PU-RD2, PU-RD3, PU-RD4, PU-RD5 Mranggen, PU-C8A Srbumbung, PU-RD6 Srbumbung, PU-RD7 Srbumbung, PU-C8 Ngaglik, PU-C2 Gempol. The dimensions of the sabo dams are entered by increasing elevation points in ArcGIS according to the height according to the available data.

| No. | Sabo Facility Name | Coordinate x  | y  |
|-----|-------------------|---------------|----|
| 1   | PU-D1 (Mranggen)  | 429754        | 9161972 |
| 2   | PU-C11/12 (Gremeng)| 429266       | 9161743 |
| 3   | PU-C9 (Cabe Lor)  | 428358        | 9161423 |
| 4   | PU-RD1            | 428006        | 9161322 |
| 5   | PU-RD2            | 427777        | 9161229 |
| 6   | PU-RD3            | 427423        | 9161029 |
| 7   | PU-RD4            | 427176        | 9160893 |
| 8   | PU-RD5            | 426965        | 9160714 |
| 9   | PU-C8A (Srbumbung)| 426015        | 9160459 |
| 10  | PU-RD6            | 425563        | 9160171 |
| 11  | PU-RD7            | 425164        | 9159893 |
| 12  | PU-C8 (Ngaglik)   | 424623        | 9159621 |
| 13  | PU-C2 (Gempol)    | 422738        | 9159404 |

2.2.5. Boundary data
For running the SIMLAR, it needs the series data of discharge in the upstream area. In the downstream area, the boundary condition is not needed.
2.3. SIMLAR V2.1
Simulation Lahar (SIMLAR) is one of the debris flow simulation applications. The SIMLAR was developed using the finite difference method. For finite difference calculation, the leap-frog method is used. Specifically, the forward difference is used for the time term, the central difference for the pressure term, and the directional difference for the inertia term choosing either the forward or backward difference depending on the flow direction. The application is still suitable for volcanic mudflow. The application consists of three sub-chapters of the programs; namely, the first is a flood hydrograph calculation program. The second is a hydrograph calculation program due to the collapse of a natural weir. The third is a 2D debris-flow simulation program. To estimate the debris flow direction, SIMLAR uses the debris flow modelling method with a numerical model in which sludge water is also considered a fluid unit. The debris flow simulation is based on a partial differential equation that regulates the debris flow as follows:

- Mass conservation equation of water
  \[
  \frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0
  \]

- The momentum and force conservation equation (x direction)
  \[
  \frac{\partial M}{\partial t} + \beta \frac{\partial (uM)}{\partial x} + \beta \frac{\partial (vN)}{\partial y} = -gh \frac{\partial H}{\partial x} - \tau_{bx} \rho_T
  \]

- The momentum and force conservation equation (y direction)
  \[
  \frac{\partial M}{\partial t} + \beta \frac{\partial (uM)}{\partial x} + \beta \frac{\partial (vN)}{\partial y} = -gh \frac{\partial H}{\partial y} - \tau_{by} \rho_T
  \]

where:
- \( h \) = Flow height
- \( t \) = Time (s)
- \( M \) = Debris flow rate per unit width x direction (m\(^2\)/s)
- \( N \) = Debris flow rate per unit width y direction (m\(^2\)/s)
- \( \beta \) = Momentum correction
- \( H \) = Flow depth (m)
- \( g \) = Gravity
- \( \tau_{bx} \) = The component of the riverbed shear stress in the x direction
- \( \tau_{by} \) = The component of the riverbed shear stress in the y direction
- \( \rho_T \) = Mass flow density
- \( u \) = Average velocity in the x direction
- \( v \) = Average velocity in the y direction

- The equation for the conservation of sediment in the river
  \[
  c_s \frac{\partial Z_b}{\partial t} + \left( \frac{\partial q_{Bx}}{\partial x} + \frac{\partial q_{By}}{\partial y} \right) = 0
  \]

where:
- \( c_s \) = Concentration of riverbed sediments
- \( q_{Bx} \) = Sediment discharge in the x direction
- \( q_{By} \) = Sediment discharge in the y direction
- \( q_{Bx} + q_{By} \) = The amount of base sediment (bedload)

3. Result and Discussion
Two cases of debris flow were carried in Putih River, Magelang Regency, the Central Java, Indonesia are used to test the performance of the numerical model. The first scenario was run without sabo dams, and the second scenario was run with sabo dams. The simulation results are the debris flow propagation from time to time and the areas affected by debris flow along the river. The results for the distribution of debris flow for two scenarios are shown in Figure 2.
In the simulation without the sabo dam at the 30th minute, the volume of debris produced was 161.9 m$^3$, with a flood discharge of 0.09 m$^3$/s and a flow velocity of 0.136 m/s. In 270 minutes, the volume of debris was 61,751.0 m$^3$, the flood discharge was 3.98 m$^3$/s, and the flow velocity was 0.62 m/s. Then in the 780th minute, the volume of debris produced was 13,840.7 m$^3$, with a flood discharge of 0.20 m$^3$/s and a flow velocity of 0.192 m/s. In the simulation with the sabo dam at the 30th minute, the volume of debris produced was 161.9 m$^3$, with a flood discharge of 0.092 m$^3$/second and a flow velocity of 0.125 m/s. Then for 270 minutes, the debris volume was 55,858.6 m$^3$, the flood discharge was 3.98 m$^3$/s, and the flow velocity was 0.570 m/s. Then the 780th minute, the volume of debris produced was 9,113.1 m$^3$, the flood discharge was 0.20 m$^3$/second, and the flow velocity was 0.176 m/s.

Based on the result, it can be concluded that there are changes to the parameter of sediment volume and velocity when the simulation with sabo dams and without sabo dams. These parameters tend to decrease when simulating using the sabo dam, as shown in Figure 3 and Figure 4. This condition is very reasonable; when the simulation uses the sabo dam, there will be a reduction in the value of the river slope parameter. A decrease in the river's slope will cause the flow velocity's value to decrease, as shown in Figure 3. With a reduction in flow velocity, the volume of sediment transport will also fall for each time interval, as shown in Figure 4. In addition, the presence of the sabo dam will also provide a reservoir for the transported sediment to settle upstream of the sabo dam. This condition also affects why the volume of sediment transport decreases when the simulation uses sabo dams. Another impact is velocity reduction. The arrival time of debris flow at a point will be slower when simulating using a sabo dam than a simulation not using a sabo dam, as shown in Figure 2.

**Figure 2.** The affected area due to debris flow in the scenario without sabo dams and with sabo dams
Based on the results as shown in Figure 2, Figure 3, and Figure 4, this indicates that SIMLAR 2.1 can provide predictions regarding areas that will be affected by debris flows. However, some shortcomings need further study, including the following. Some places should not be affected by the debris flows, but the simulation results affect the area. This condition is caused by the digital elevation map (DEM), which cannot perfectly describe the actual conditions [11]. In this simulation, using DEM from the DEMNAS map with a resolution of 8 x 8 m. Topographic data affects the accuracy of the simulation results. For this reason, DEM data with a maximum spatial resolution of 30 m is required. The accuracy of the simulation results will be better when the simulation uses DEM data with a spatial resolution of 5-10 m [12]. In addition, the flow velocity obtained is still very low compared to the debris flow velocity from the results of previous studies. Sulistyani et al. [13] received measurement data in the Putih River of 3.5 m/s for a rain intensity of 48.55 mm. The rainfall data used in this study is 56.8mm/3 hours, so the flow velocity should be estimated at 1.369 m/s. The deviation of flow velocity in this study compared to the research results by Sulistyani et al. was 62.5% smaller than the results of observations. The modelling results of debris flows have a smaller velocity than the results of observations caused by several factors, namely the discharge data and DEM maps that are not the same. The modelled flood discharge has a smaller value. This condition is due to data limitations from observations in the field in
terms of measuring flood discharge. Then, the changing topographic needs resulted in the topographic data not being able to approach the conditions in the area so that the observed lahar velocity and modelling results had deviations. In addition, many main factors affect the velocity of debris flow, including grain size, slope angle, sediment concentration, etc. [14-21]. So, it is necessary to do further research on the effect of these parameters on the results of flow velocity in SIMLAR.

4. Conclusion
By creating a map of each hydrograph distribution that has been predetermined, the SIMLAR 2.1 application program can model debris flows. River cross-section and sabo dam construction influence the length and velocity of debris flows. Nevertheless, further research needs to investigate the accuracy of the simulation results, such as affected area due to debris flow and velocity simulation result of debris flow are still not satisfactory.

Acknowledgements
The authors would like to thank the Ministry of Education and Culture of the Republic of Indonesia, which has funded this research activity through the 2021 Decentralization Scheme PDUPT Grant. The author would also like to thank all those who helped carry out this research to be carried out smoothly.

References
[1] Takahashi T 1991 Debris flow IAHR Monograph Series Rotterdam, Balkema
[2] Hunt B 1994 Newtonian fluid mechanics treatment of debris flows and avalanches Journal of Hydraulic Engineering, ASCE 120 No 12 pp 1350-1363
[3] Huang X, and Garcia M H 1997 A perturbation solution for Bingham-plastic mudflows, Journal of Hydraulic Engineering ASCE 123 No 11 pp 986-994.
[4] Shrestha B B, Nakagawa H, Kawaike K, and Baba Y 2008 Numerical simulation on debris-flow deposition and erosion processes upstream of a check dam with experimental verification Annuals of Disaster Prevention Research Institute, Kyoto University No 51 B pp 614-624
[5] Prasdya P A 2016 Evaluation of sabo dam capacity in mitigation efforts Thesis, the University of Muhammadiyah Yogyakarta (in Indonesian)
[6] Giyarsih S R 2013 Impact of debris flow on social aspects: case study of debris flow after the Merapi eruption in 2010 in Cangkringan district, Gadjah Mada University Press (in Indonesian)
[7] Wimbardana R and Sagala S A H 2013 Community preparedness for the hazards of the debris flow of Mount Merapi Bumi Lestari Journal Vol 13 No 2 pp 394-406 (in Indonesian)
[8] Surono, Jousset P, Pallister J, Boichu M, Baniorno M F, Budisantoso A and Lavigne F 2012 The 2010 explosive eruption of Java's Merapi volcano-A”100-year event Journal of Volcanology and Geothermal Research 241-242 pp. 121-135
[9] Achmad A C 2015 Evaluation on the implementation of early warning system for debris flow in Merapi area (case study at boyong river) Journal of the Civil Engineering Forum Vol 1 No 3 pp 77-84
[10] Liu K F and Huang M C 2009 Numerical simulation of debris flows, Proceedings of the ASME 28th International Conference on Ocean, Offshore and Arctic Engineering, Hawai, USA, pp. 1-8
[11] Ikhsan J, Hardjosuwarno S and Rahardjo A P 2012 Developing numerical model of debris flow 2D as a tool in early warning system Proceedings of the MSD 2012, Hoddaka, Japan
[12] Hidayat R, Musthofa A and Bahri P 2017 Influence of rainfall intensity to lahar flood velocity and height based on similar 2.1 modelling Teknik Hidraulik Journal Vol 8 No 1 pp 125-134 (in Indonesian)
[13] Sulistiyani, Nandaka IGM, Atin L S, Sulistio A, Nurudin and Rozin M 2015 Application of the Cross Correlation Method for Calculation of Lava Flow Velocity in Putih River, Boyong River and Senowo River Yogyakarta BPPTKG (in Indonesian).
[14] Cao C, Song S, Chen J, Zheng L and Kong Y 2017 An approach to predict debris flow average velocity *Water* **2017** *9* 205