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Potential debris flow of the Tuva River in Sigi Regency, Central Sulawesi Province

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Abstract. Flash floods/debris floods that occur in the Tuva River of Sigi Regency are streams of water mixed with various materials such as wood, rocks, mud, and others that have a very fast flow speed. Flash floods submerged the residential area of the community with a water presence of 3 m which had claimed the lives of 2 people. Flash floods occur after catastrophic earthquakes and soil liquefaction. Where the topographic conditions around the Tuva River are very steep and the characteristics of the river widens upstream and narrows downstream, there is the potential for avalanches of liquefaction of mountain ridge land that enters the river which forms a natural weir in the Tuva River. The modeling conducted in this research utilized a Digital Elevation Model (DEM) map with a resolution of 5-10 meters using Hec-RAS software. The modeling focused on the dam break of a natural dam, resulting in a debris flow volume of 104.663 m3/s. With the non-Newtonian flow model, the study determined a flooded area of 58.978 hectares or 0.589 square kilometers with a maximum flow velocity of 2645.33 m/s. This has the potential to erode the riverbed and supply sediment transport to the Miu River.

Keywords: *debris; Hec-Ras; non-newtonian flow.*

1 Introduction

One of the rare phenomena that rarely occurred in Indonesia but has been happening frequently in recent years in one of the provinces of Indonesia, namely Central Sulawesi Province, is called flash floods/debris flow. Flash floods are the rapid flow of water mixed with various materials such as wood, rocks, mud, and others, with a very high flow velocity. The velocity of debris flow depends on the type of material it carries. Materials with coarse grain gradation (wood, rocks) have velocities ranging from 3 to 10 m/s, while materials with fine gradation (sand, mud, and soil) have velocities ranging from 2 to 20 m/s. From the hypothesis, it can be concluded that the smaller the materials carried by the debris flow, the faster the flow will be [1].

The earthquake that occurred on September 28, 2018, at 18:02 WITA (Eastern Indonesia Time) centered in Donggala Regency, with a depth of approximately 10 km and a magnitude of 7.4 on the Richter scale [2]. The earthquake was felt in various regions such as Donggala Regency, Sigi Regency, Palu City, and other cities/regencies on the island of Sulawesi. A flash flood occurred on Thursday, December 12, 2019, which affected Bola Papu Village, Kalawi District, Sigi Regency, submerging dozens of houses and damaging the Mangila Bridge. It was reported that the incident claimed the lives of two people [3]. On Sunday, April 26, 2020, heavy rainfall occurred during the night upstream of Tuva River, resulting in a flash flood. Then, on Monday, October 11, 2021, another flash flood submerged dozens of houses in Dusun 2, Tuva Village, Gumbasa District, Sigi Regency [2].

Previous research has employed methods to determine hydrological calculations for debris flow. It has been observed that the rainfall during debris flow events may be lower than the maximum annual rainfall. Additionally, even minimum daily rainfall in various basins can trigger debris flows, as stated by Cui et al. In reference [4], a case of debris flow in the Mesilau River is documented. The event had a cumulative rainfall of 66.3 mm and a maximum rainfall intensity of 14.2 mm/hour. The event lasted for 7 days and occurred on Friday, June 5, 2015, as reported by Rosli et al. [5]. According to Syarifuddin et al. [6] and Lavigne et al. [7], rainfall ranging from 40 to 42 mm occurring over 2 hours poses a risk of triggering debris flow. In reference [8], the characteristics stated by Sukatja C Bambang et al. indicate that the tributaries in Sigi Regency, which have very steep slopes, have the potential for recurring natural disasters such as flash floods/debris flows. Additionally, these rivers also have a widening width upstream but narrow downstream.

Debris flow is the flow of water mixed with soil and rocks, caused by the gravitational force of the Earth. It is characterized as being part flood and part rockslide (Iverson, 1997). The occurrence of debris flow is primarily attributed to high surface water flow resulting from heavy rainfall, leading to erosion of soil and rocks on steep slopes. To classify a flow as debris flow, it must consist of at least 50% sand or larger materials in its composition [9]. Debris flow is a mixture of fine and coarse materials along with water that moves towards the lowest elevation due to the influence of slope, as described by Takahashi in [10]. The geometric characteristics, river morphology, bed load type, and streamflow discharge can be considered as key indicators to determine debris flow behavior [11]. In terms of composition, debris flows often consist of large rocks, as stated in the HEC-RAS guidebook [12].

The topographical features that can lead to flash floods generally occur in Indonesia in areas such as Mount Merapi, old mountain ranges, and steep hills with slopes ranging from 26° to 45°. These areas also have a significant difference in elevation between the river source and the river mouth. The greater the elevation difference between the upstream and downstream of the river, the more significant the increase in flood volume. Flash floods are caused by the increased erosion or scouring along the river channel, and sudden or rapid increases in surface water volume due to high-intensity rainfall events. High-intensity rainfall is typically defined as a total rainfall of 150 mm or a rainfall rate of 35 mm per hour. Continuous heavy rainfall with an intensity of 0.50 mm per hour or more for a duration of over 3 hours can also contribute to flash floods [8]. These factors combined can lead to a significant rise in water levels and the occurrence of flash floods.

Widjaja and Gautama (2019), as mentioned in [13], conducted research in Poi Village, Sulawesi, focusing on debris studies using the Bingham model in the FLO-2D program. The findings indicated that the affected area by the debris flow was approximately 400 hectares, with a maximum thickness of 7.2 meters and a maximum velocity of 11 meters per second. The recommended measures for managing debris flow included physical interventions such as the use of sabo dams and non-physical measures such as relocating residents to safer areas. In addition, the HEC-RAS Non-Newtonian model can be utilized to determine the distribution of debris flood flow. This software modeling helps in mapping the distribution of debris flow and the patterns of erosion and sedimentation caused by debris floods. The analysis provides an initial prediction of the effects of the earthquake on September 28, 2019, which led to soil liquefaction in the mountains of the Tuva watershed. The resulting avalanches formed natural dams that had the potential to trigger debris flow. This modeling tool enables users to predict the direction of debris flow, allowing for alternative disaster management analysis. By analyzing the influential parameters that cause flash floods and debris floods, this software helps to generate initial solutions for handling debris floods.

To obtain more detailed information on the flow rate of debris flood and sediment flow rate of debris flood, you can use the non-Newtonian options in the Hec-Ras software. This non-Newtonian flow has several forms, which can be observed based on the concentration of solid particles and the mixture concentration greater than that of regular fluid. The gradation of solid particle sizes becomes a specific parameter that helps determine their classification. When the concentration of solid particles changes to coarse, the fluid passes through five classifications [14].that is:

Table 1 Fluid Classification.

Classification	Type	Condition
Hyperconcentration	Bingham	Cv > 30 %
Mud flow and debris	Turbulent_Quadartic Herchel-Bulkkley	Cv > 60 %
Avalanche	Voellmy	
Plastics	Mohr_Coulomb	Ns > 0.1

For this modeling, the Turbulent Quadratic Herschel-Bulkley model is used based on the conditions in the Tuva River, where there is a mud and debris flood with a Cv (concentration volume) greater than 60%.

2 Research Methods

2.1 Location Research

The research site is located in the Tuva River, administratively situated in Tuva Village, Gumbasa Sub-district, Sigi District, Central Sulawesi Province. Astronomically, it is located between 01° 19' 30" South Latitude and 119° 57' 96" East Longitude. This can be seen in Figure 1, depicting the Tuva River Basin after delineation using Hec-HMS software, which has a watershed area of 5.405 km2 and a river length of 5.578 km. for Hec-RAS modeling, In this research, the length of the river modeled is 2.145 km.

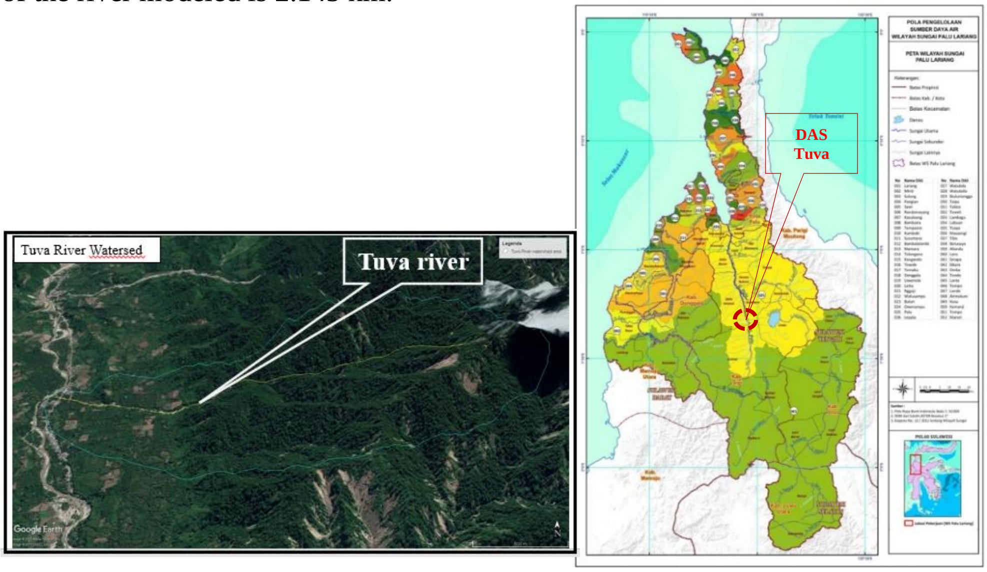

Figure 1 Tuva River research site.

2.2 Methods

2.2.1 Conceptual

The earthquake that occurred in Central Sulawesi Province (Palu) resulted in ground movements in the mountain ridges of Sigi Regency. When it rains, the soil will descend to the riverbed and settle inside the river, indirectly forming a natural dam. If there is a high intensity of rainfall lasting more than 3 hours, the natural dam will experience erosion, leading to the collapse of the natural dam (DAM BREAK). This event will cause a flow of debris in the Tuva River.

The predicted debris flow occurs at a designed flood discharge with a return period of 100 years. The flow is characterized by fast-moving water-carrying debris such as wood, rocks, soil, and mud (Non-Newtonian flow). To obtain analysis results that approximate the depth of flow and velocity of the debris flow, the Hec-Ras Non-Newtonian software can be used. This research aims to determine the difference in depth and velocity between Newtonian and Non-Newtonian flows during debris flow events and to assess the extent of inundated areas for Newtonian and Non-Newtonian flows.

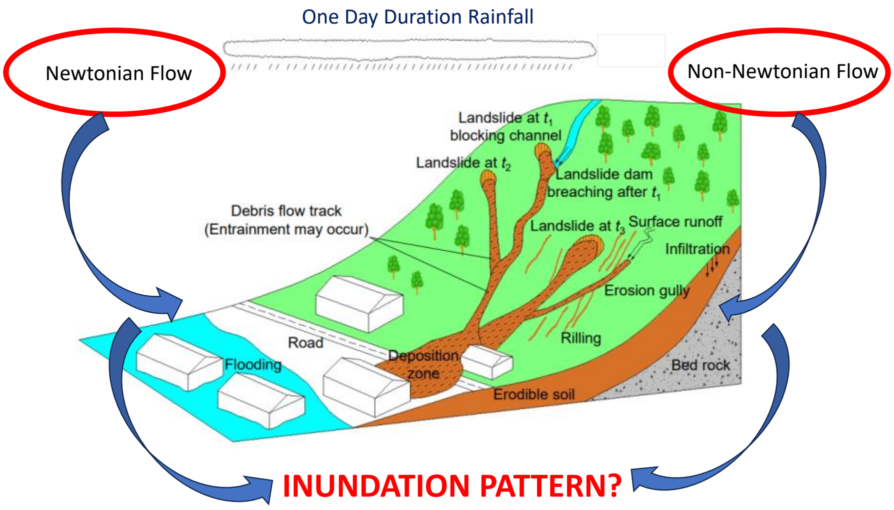

Figure 2 Conceptual diagram.

2.2.2 Research flowchart

This research utilizes a Digital Elevation Model (DEM) map called DEMNAS, downloaded from https://tanahair.indonesia.go.id/demnas/#/ with a black-and-white display [13]. Then watershed delineation (DAS) was performed using HEC-HMS, he SCS Curve Number loss method, Snyder Unit Hydrograph transformation method, and Snyder synthetic unit hydrograph method are used in this study. The SCS Curve Number loss method is a hydrological method that originated in the United States in 1938 and is utilized in HEC-HMS to obtain synthetic unit hydrographs based on watershed parameters [14]. By using the Takahashi formula, the discharge data is multiplied by the Cd value [10]. The analysis results are used to create HEC-RAS Dam Break, HEC-RAS Newtonian, and Non-Newtonian modeling [15]. To obtain the simulation results for the depth of debris flow and the velocity of debris flow. Research flowchart in figure 3.

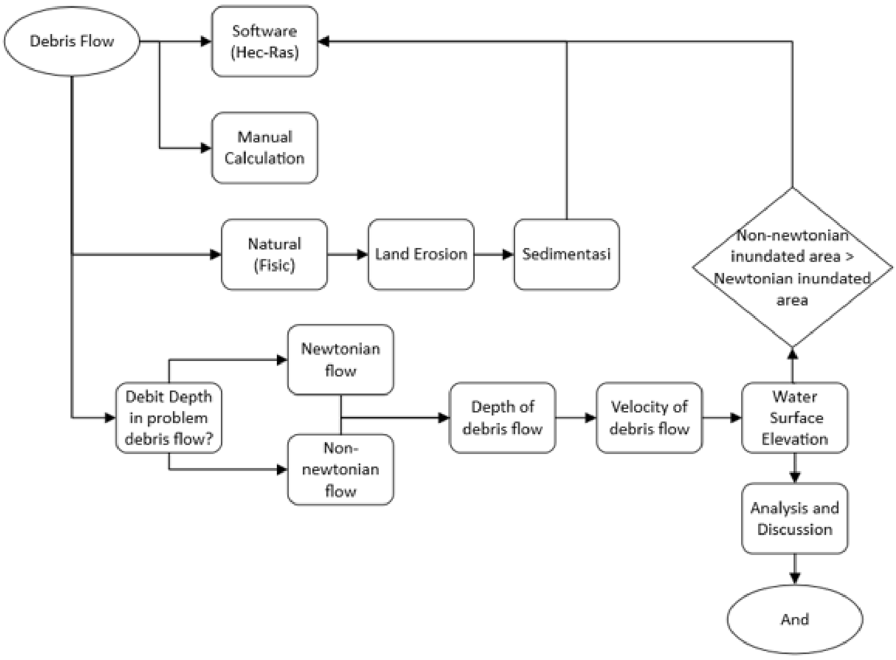

Figure 3 Research flowchart.

2.3 Simulation Dam Break

Post-earthquake, soil liquefaction occurs, leading to landslides from the riverbanks into the river, forming natural dams. The debris event that follows is assumed to be similar to a dam break. For the dam break modeling, a Digital Elevation Model (DEM) map downloaded from the page Your country website will be utilized. The modeling will involve storage areas, perimeter areas, and SA/2D connection, as shown in Figure 4 below.

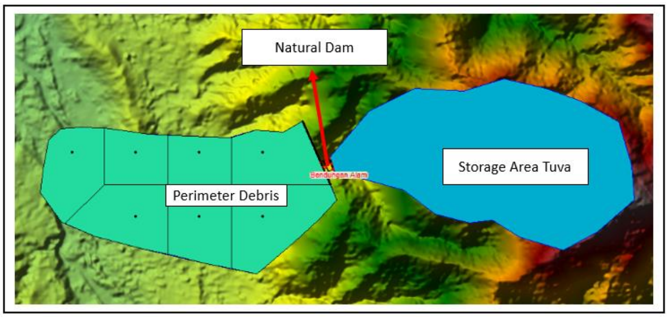

Figure 4 Dam break modeling.

The predicted natural dam shape has a spillway height with an elevation of 480 m with a natural dam collapse scenario the base scouring position is on the river axle at a distance of 5 m with the final height of the natural dam of 1 m which is at an elevation of 385 m with a right-left scouring position ending in a slope position of 0.5 for the dam collapse event in the setting on September 13, 2019, at 00:00.

2.4 Debris flow

The process of debris flow transformation begins with solid particles that transition into a viscous state as they flow. The flow can be described as both liquid and viscous, with particle dispersion occurring during the flow. When the flow comes to a stop, the particles reassemble and solidify [16]. There are several types of non-Newtonian flow characteristics, such as mudflows, debris flows, lahars, and snow avalanches [18]. In non-Newtonian fluids, the shear rate versus shear stress relationship can be nonlinear and may not pass through the origin [18]. According to Hegrgarten and Robl [19], the conservation equations for mixtures and the properties of non-Newtonian flow can be described using a single-phase mathematical model [10]. However, to distinguish between liquid and solid in non-Newtonian flow and to solve the conservation problems of each phase, a two-phase model [10] in [20] can be utilized.

2.5 Debris flow discharge

In 2010, JICA released a guidebook titled "Manual Sabo Works" which discusses the influence of sediment on the magnitude of flood discharge (referenced in [18]). Qw (design flood discharge), which is calculated based on the 100-year return period flood discharge considering the sediment influence, represented by sediment concentration (Cd).

$$Q_s = Q_w\ (1 + C_{d)} \quad (1)$$

$$C_d = \frac{\rho_w . Tan\theta}{(\sigma - \rho_w).(Tan\emptyset - Tan\theta)}$$

$$C_d = \frac{1000\ .\ Tan\ 36{,}67°}{(2770 - 1000).(Tan\ 35° - Tan\ 36{,}67°)} = 0{,}06$$

Where Qs represents the sediment influence on the planned flood discharge, Qw represents the flood discharge calculated using the HSS Snyde equation, Cd represents the sediment concentration, ρ_w represents the water mass density with a value of 1000 kg/m³, σ represents the sediment mass density with a value of 2770 kg/m³, ∅ represents the sediment's shear angle of 35°, θ represents the average river bed slope. Given the Cd value (sediment concentration) of 0.064, which is below 0.3, the Cd value is considered to be 0.3. The results of the calculation for the planned flood discharge considering the sediment influence/debris flood discharge are shown in the table below.

2.6 Non-Newtonian flow equations

Continuity Equation

The conservation of mass can be expressed using the following equation:

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

Change in elevation of the flow surface t is time, η is depth, hV is velocity vektor, and q is ateral flow rate per unit length, to account for external and internal fluxes.

Momentum Equation

The momentum of the average depth can be written by Hergarten and Robl [20] in [20]:

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

With the following definitions g as gravity with a value of 9.81, ν_t is the turbulent flow viscosity, τ is the total basal stress, ρ_m is the bulk density of the water-solid mixture, R is the hydraulic radius, | V| is the magnitude of the velocity vector, φ is the slope of the water surface, and ψ is the angle of inclination with respect to the direction of the flow velocity.

For the fluid stress equation in a non-Newtonian model, the following formula can be used [20]:

$$\tau = \tau_r + \tau_{MD} \quad (2)$$

where the selection of material for the stress-strain model (rheology) is based on the basal stress and derived from τ_r τ_MD[[20]. The combination of basal stress with channel bed roughness makes it a function of friction slope Sf.

$$\tau_r = \gamma R S_f \tag{3}$$

where the unit of fluid weight is τ_r hydraulic radius is γR, and friction slope from the Manning's equation S_f.

$$S_f = \left(\frac{nV}{kR^{2/3}}\right)^2 \tag{4}$$

where the flow velocity is V and the unit conversion factor is k.

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

According to S. Gibson and A. Sánchez in the HEC-RAS manual book [18], the study that investigates shape changes under pressure is called Rheology. Rheology is the branch of science that deals with the flow and deformation of materials under stress. In [21], a rheological model is described as a simple relationship between stress and strain, as depicted in Figure 4.

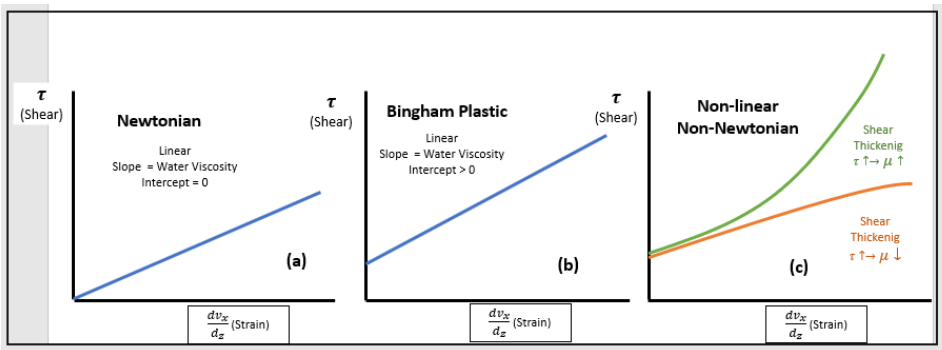

Figure 5 Rheology model, (a) clear water and (b,c) mud and debris flow [20].

This research utilizes the Bingham rheological model, assumed as a non-Newtonian fluid (debris flows). The Bingham stress model can be written as follows:

$$\tau_{MD} = \tau_y + \tau_v \tag{5}$$

$$\tau_v = \mu_m \dot{\gamma} \tag{6}$$

Where yield is .τ_y the yield stress is τ_v, the viscosity is μ, the shear rate is γ˙

3 Results and discussion

3.1 Changes in the Tuva basin

The visual observation method can be employed to comprehend debris flow issues, as mentioned by Alfianto, A., Iswardoyo, J., & Sukatja, C. B., in [22]. Changes in the River Basin Area (DAS) before and after an earthquake can be observed in Figure 5, where part a demonstrates a condition where the river is still abundantly covered with lush vegetation, indicating that the DAS is still in good condition. However, in Figure 5 part b, the Tuva River can be seen to have experienced numerous landslides and sedimentation within the river. Based on these two conditions, it can be analyzed that the Tuva River has undergone significant morphological changes from before the earthquake occurred to after the earthquake.

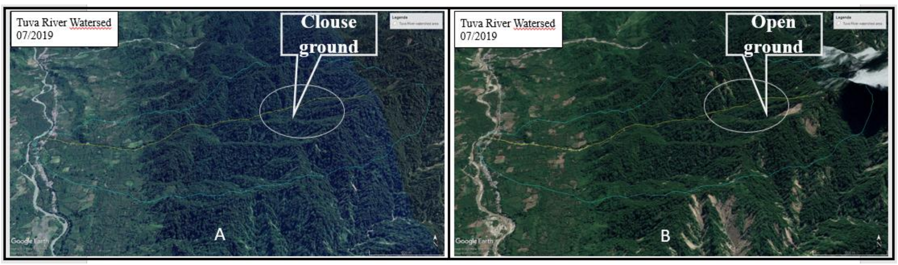

Figure 5 The condition of the Tuva River before the earthquake (a), Tuva River condition after earthquake and debris flood (b).

3.2 Hidrology Tuva

Figure 6 shows the results of the analysis using the HEC-HMS software, which indicates that the catchment area of the Tuva River is 5,405 km2. The planned flood discharges for various return periods, including 2 years, 5 years, 10 years, 25 years, 50 years, and 100 years, were considered in the analysis.

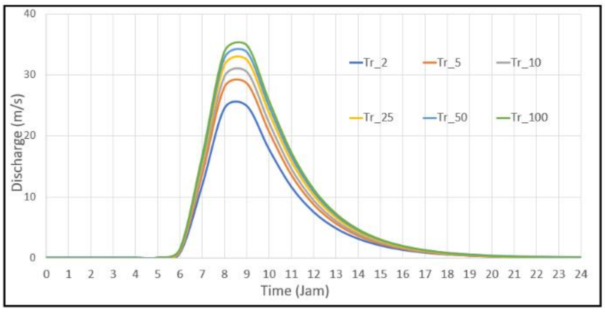

Figure 6 Hidrograf Tuva

Table 2 Periode return and debris flow discharge.

No	Return Period (Years)	Design Flood Discharge (m/s)	Debris Flood Discharge (m/s)
1	2	24.97954	32.4734
2	5	28.62433	37.21162
3	10	30.51818	39.67364
4	25	32.51465	42.26905
5	50	33.78728	43.92346
6	100	34.91812	45.39355

The results of the planned flood hydrograph analysis multiplied by the sediment-affected discharge coefficient are obtained. The calculation of Cd (sediment concentration) yields a value of 0.06, which is less than 0.3. Since the result is smaller than 0.3, the Cd value is set to 0.3. Therefore, the calculation for Qs (sediment discharge) is obtained as Qs=Qw.(1+0.3). The summarized results can be found in Table 2. This modeling is conducted for the debris flood using the debris flood discharge for a return period of 100 years.

3.3 Results of dam break modeling

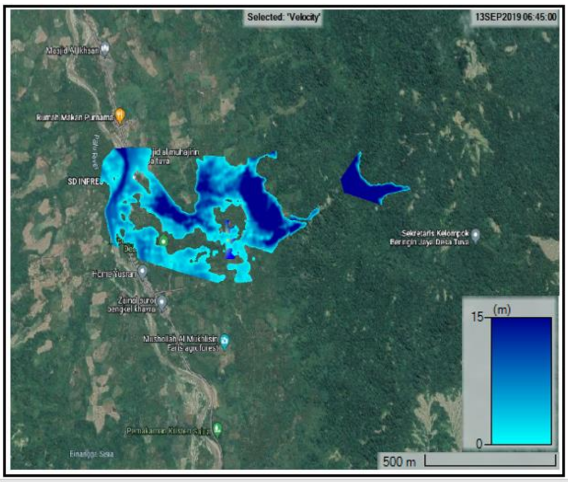

Figure 7 Dam break modeling results.

Based on the debris flood simulation results in Figure 7 above, it can be observed that the distribution of debris flood flow is most pronounced in residential areas or around the estuary where the Tuva River meets the Miu River. The Tuva River serves as a significant sediment transport pathway to the Miu River, resulting in a reduction in the capacity of the Miu River and potential changes to the morphological balance of the Miu River. The debris flow volume at a water surface elevation of 499 m amounts to 104.663 m3/s.

3.4 Comparison between Newtonian and Non-Newtonian flows

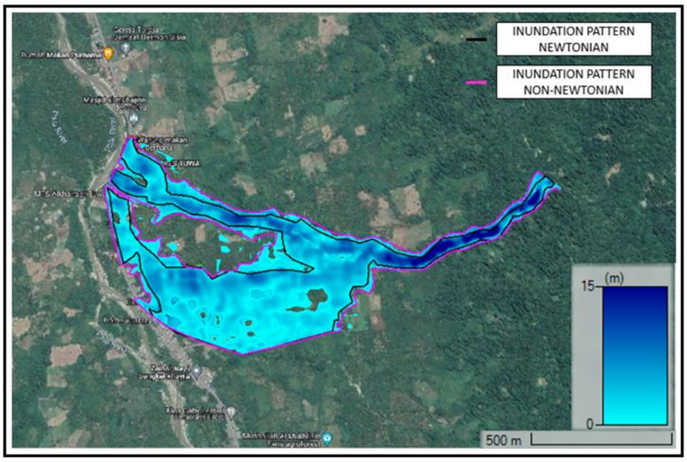

Figure 8 Depth of Newtonian and Non-Newtonian flow modeling results.

Based on the modeling results shown in Figure 8 (Depth), the area of inundation for the Newtonian flow is 44.872 hectares or 0.448 km², while the area of inundation for the Non-Newtonian flow is 58.978 hectares or 0.589 km². These results indicate that the area of inundation for the Non-Newtonian flow is larger compared to the Newtonian flow or regular flooding.

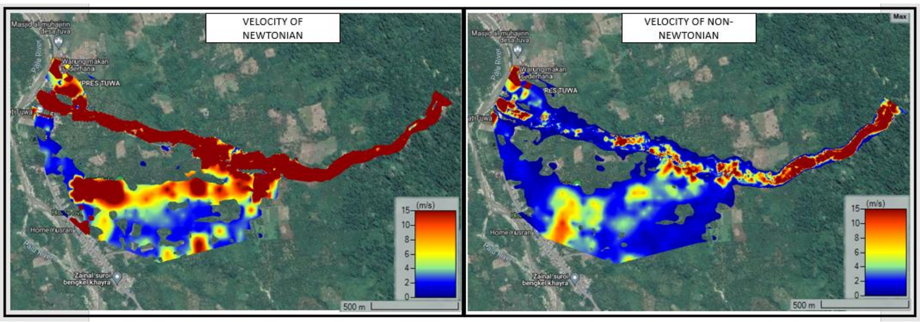

Figure 9 Velocity of Newtonian and Non-Newtonian flow modeling results.

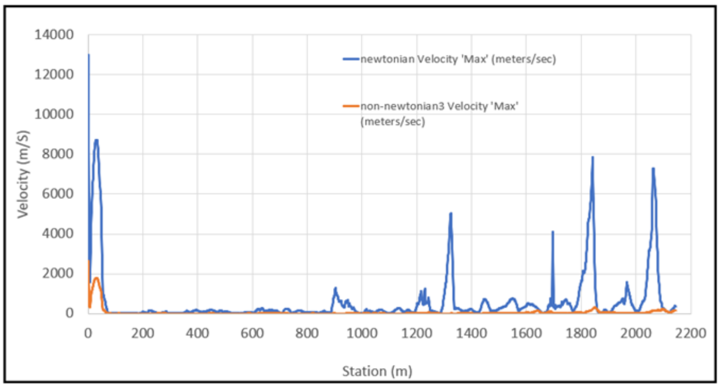

Figure 10 Graph of Newtonian and non-Newtonian velocities

Based on Figure 10, modeling Newtonian flow and non-Newtonian flow using the software, the Newtonian flow results in a very high velocity of 12,987.67 m/s. However, in the non-Newtonian flow modeling, where there was a significant sediment concentration, the flow velocity slowed down to 2645.33 m/s. Based on the obtained results, the velocity of the Newtonian flow appears to be unrealistic, while the velocity of the non-Newtonian flow is still within an acceptable range.

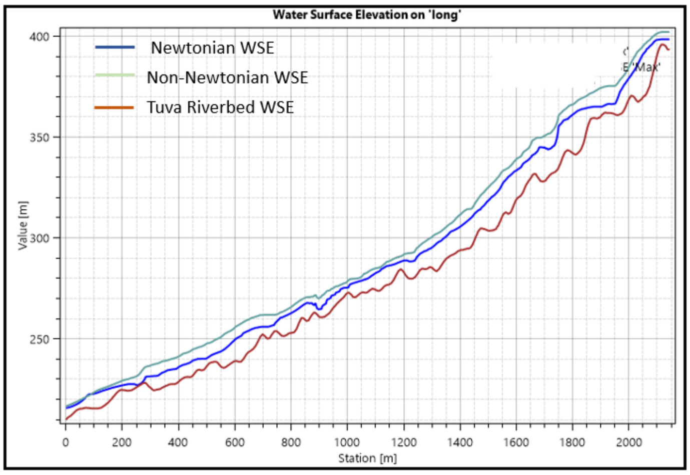

Figure 11 Water Surface Elevation (WSE) Newtonian and Non-Newtonian

From the modeling results using the Q100 debris flood discharge in Figure 11, it is observed that using the Hec-RAS software, the water surface elevation (WSE) increases when the flood water elevation is influenced by sediment concentration. However, the velocity decreases or slows down as it moves towards flatter areas, causing sediment deposition and formation.

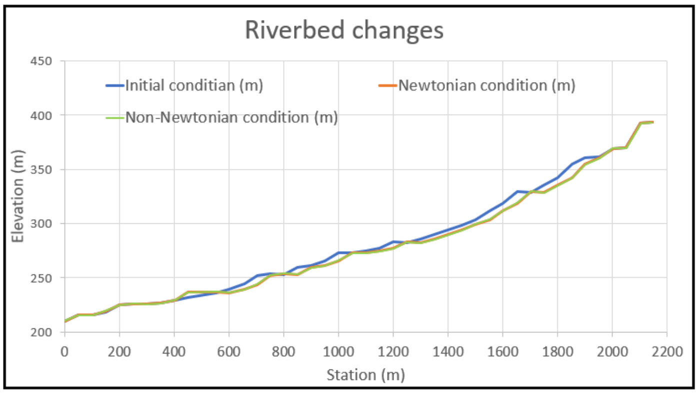

Figure 12 Riverbed changes

In Figure 12 above, the analysis results indicate that there are changes in the riverbed of the Tuva River after the debris flood. In the upstream and middle sections of the Tuva River, there is a predominant decrease in the riverbed (degradation), while in the downstream section, there is an increase in the riverbed (aggradation). This implies that the Tuva River serves as a sediment transport supplier to the Miu River. It is important to address this issue promptly to prevent a reduction in the bank full capacity of the Miu River.

4 Conclusion

After conducting hydraulic analysis in this study using Hec-ras software, it can be concluded that the Tuva River has a very high risk of debris flooding with the potential for debris flooding as follows:

1. The debris flow that occurred in the Tuva River, Sigi Regency, occurred after a natural disaster of an earthquake and soil liquefaction, where landslides from the mountain ridge formed a natural dam. The Tuva River, located in a highland area, has a very steep slope. When heavy rainfall hits the village, it has the potential to cause flash floods. Based on the results of dam-break modeling, the estimated volume is 104.663 m3/s.
2. From the non-Newtonian flow modeling results, it was found that the Tuva River has the potential for debris flow with a flooded area of 58.978 hectares or 0.578 square kilometers, with a maximum flow velocity of 2645.33 meters per second. This debris flow has the potential to erode the riverbed and supply sediment to the Miu River.
3. In the upstream and middle sections of the Tuva River, there is a decrease in the riverbed elevation (degradation), while in the downstream section of the Tuva River, there is an increase in the riverbed elevation (aggradation).

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References

[1] Hermawan. Banjir bandang di Indonesia. Badan Geologi. Pusat lingkungan geologi bandung. 2007.
[2] BMKG. Ulasan Guncangan Tanah Akibat Gempa Bumi Utara Donggala Sulteng,28 September 2018, Bidang Seismologi Teknik-BMKG.https://cdn.bmkg.go.id/Web/UlasanGempaDONGGALA_28092018_rev13102018.pdf (diunduh 20 Maret 2023).
[3] BPBD. Dinas Kesehatan Kab. Sigi. Banjir bandang di sigi 12-12-2019. https://pusatkrisis.kemkes.go.id/Banjir-Bandang-di-SIGI-SULAWESI-TENGAH-12-12-2019-37
[4] Cui, P. Chen, X., Waqng, Y., Hu, K., & Li, Y., Jiangjia Ravine debris flows in south-western China, Springer: in Debris-flow hazards and related phenomena, pp. 565-594, 2005.
[5] Rosli, M.I., Che Ros, F., Razak, K.A., Ambran, S., Kamaruddin, S.A., Nor Anuar, A., Marto, A., Tobita, T., Ono, Y., Modelling debris flow runout: a case study on the Mesilau Watershed, Kundasang, Sabah. Water, 13 (19), p. 2667, 2021.
[6] Syarifuddin, M., Oishi, S., Legono, D., Hapsari, R.I. and Iguchi, M., Integrating X-MP radar data to estimate rainfall-induced debris flow in the Merapi volcanic area, Advances in water res., 110, pp. 249-262, 2017.
[7] Lavigne, F. & Thouret, J. C., Sediment transportation and deposition by rain-triggered lahars at Merapi Volcano, Central Java, Indonesia, Geomorphology, 49 (2), pp. 45-69, 2003.
[8] Sukatja C Bambang. dkk. Mitigasi penanggulangan bencana banjir debris pasca gempa palu 2018, Jurnal Teknik Hidraulik, vol.12,no.1,Juni 2021
[9] King, H. M., 2011, What is a Debris Flow ?, https://geology.com/articles/debris-flow/, diakses tgl 01 Mei 2023.
[10] Takahashi, T., Debris flow, mechanics, prediction and countermeasures, ed.1, Taylor & Francis/Balkema, 2007.

[11] Gregoretti, C. & Fontana, G. D., The triggering of debris flow due to channel-bed failure in some alpine headwater basins of the dolomites: analyses of critical runoff, Hydrological Processes: An International Journal, 22(13), pp. 2248-2263, Oct. 2007.

[12] HEC., HEC-RAS 2D user's manual v6.1, Available online:https://www.hec.usace.army.mil/confluence/rasdocs/r2dum/latest (accessed on 03 Maret 2023).

[13] Badan Informasi Geospesial. Digital Elevation Model Nasional dengan resolusi 5-10 m, tahun 2021. Diakses dari https://tanahair.indonesia.go.id/demnas/#/demnas.

[14] Zahroni Aulia., Kajian Efektifitas Pengendalian Sedimen Sungai Yeh Sah Pasca Erupsi Gunung Agung pada 2017-2019 di Provinsi Bali, Thesis Magister Program of Water Resources Management, ITB, Bandung.2022.

[15] Zahroni, A., Harlan, D. Soentoro, E., Nugroho, E.O., Aprillian, Z., *Analysis Curve Number Value to Estimate Debris Flow in the Mount Agung Volcanic Area, Bali, Indonesia*., 3rd IGSC Conference, ITB, 21 Dec 2022.

[16] J. Cahyono, "Teori Aliran Puing," [Online]. Tersedia: http://jcpoweryogyakarta.blogspot.com/, . [Diakses 2023].

[17] B. Scharffenberg, M. Bartles, T. Brauer, M. Fleming, dan G. Karlovits, "Sistem Pemodelan Hidrologi HEC-HMS, Panduan Pengguna.," Pusat Teknik Hidrologi. Institut Korps Insinyur Angkatan Darat AS untuk Pusat Teknik Hidrologi Sumber Daya Air, Davis, CA, hlm. 640, 2018, [Online].

[18] S. Gibson dan A. Sánchez, "Manual aliran HEC-RAS, Lumpur dan Puing," Institut Korps Insinyur Angkatan Darat AS untuk Pusat Teknik Hidrologi Sumber Daya Air, Davis, CA, hlm. 58, 2020.

[19] S. Hergarten dan J. Robl, "Pemodelan gerakan massa cepat menggunakan persamaan air dangkal dalam koordinat Cartesian," Nat. Bahaya Bumi Syst. Sci., vol. 15, no. 3, hlm. 671–685, 2015, doi: 10.5194 / nhess-15-671-2015.

[20] Bozhinskiy dan A. N. Nazarov, "Model dua fase aliran puing," dalam 2nd Int. Conf. on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment., 2000, hlm. 263–269.

[21] S. Gibson *dkk.* , "Evaluasi Skala Prototipe Algoritma Non-Newtonian di HEC-RAS: Lumpur dan Aliran Puing Studi Kasus Santa Barbara dan Brumadinho," *Geosciences (Swiss)*, vol. 12, no. 3, 2022, doi: 10.3390/geosciences12030134.

[22] Hadiranti., Sueharno,A.W.H., Prasetyo, A., Nugroho, E.O., Putranto, A.E., The Prediction Of Debris Flow Based On Eruption and Rainfall Event For River Infrastructure Mitigation: Study Case Opak River, Sleman Regency., 3rd IGSC Conference, ITB, 21 Dec 2022.

[23] Alfianto, A., Iswardoyo, J., & Sukatja, C. B., Efektivitas dan Kelengkapan Bangunan Sabo di Sungai Togurara Daerah Gunungapi Gamalama, Jurnal Teknik Hidraulik, 10(2),90 –103. 2019.