Estimation of debris flow using Curve Number analysis for The Mount Agung Volcanic event, Bali, Indonesia

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Abstract. After the 2017 eruption, rainfall-induced debris flow was generated within several rivers in where upstream area at Mount Agung. On 27 November 2017, a debris flow occurred in the Yeh Sah River after a rainfall intensity of 32 mm/day was monitored at the Rendang Observation Station. Estimation of rainfall-runoff-induced debris flow at this event is difficult and uncertain because this event occurred at 01.00 – 06.00 local time. This study focused on analyzing curve number value to estimate debris flow based on the 27 November 2017 event at Yeh Sah River Basin. Daily rainfall on 27 November 2017 was distributed to 6 hours using the PSA coefficient and then applied to generate runoff potential using the modified NRCS-CN for the hydrologic loss method and the SCS Unit Hydrograph for the transform method, applied in HEC-HMS 4.10. Hydrological model results are verified with the debris flow modeling using 2-D non-Newtonian features in HEC-RAS 6.3.1 with geometry based on topography 2016 and 2020. The results of the hydraulic model are validated with debris plain boundaries obtained from Google Earth imagery in 2018 and field observations in 2022. The result showed that the estimation of the debris flow event on 27 November 2017 using curve number values which consider five days of rainfall depth and land use/land cover slope of Yeh Sah River Basin was more comparable to the real condition.

1 Introduction

Mount Agung (8.34° S, 115.51° E) in Bali, Indonesia is one of the most dangerous and active volcanoes in the world. The 2017 Eruption was the greates since 1963, threatening approximately 200,000 people who live within the hazard zone and more than 140,00 people evacuate, causing airport closures in Denpasar, Lombok, Banyuwangi and Jember, Syahbana et al. in [1].

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Mount Agung's previous eruption in 1963, one of the ten largest volcanic eruptions of the 20th Century with a Volcanic Explosivity Index (VEI) of 5, killed more than 1000 people due to 19 – 26 km high plumes and 10.5 to 14 km in length pyroclastic flows (hot and cold lava), Kusumadinata in [2].

Several studies have been carried out to define hydrological thresholds for debris flows. Rainfall-induced debris flow could be smaller than the annual maximum rainfall. The minimum daily rainfall-induced debris flow varies between different basins, Cui, et al. in [3]. The debris flow in Mesilau River was induced by 66.3 mm cumulative rainfall recorded for seven days, with the highest intensity being 14.2 mm/h which triggered the 5 June 2015 event, Rosli, et al. in [4]. Syarifuddin, et al. in [5] and Lavigne, et al. in [6] stated that debris flow risk of 40-42 mm of rainfall in 2 hours is still hazardous following accumulate rainfall amount in 2 h was 40 mm on Mount Merapi. The rainfall data for the debris flow that occurred at Yeh Sah river on 27 November 2017, was 32 mm/day (from the Rendang Sta.). Rainfall on 27 November 2017 is smaller than research by Lavigne and Syarifuddin but larger than research by Wu, et al. in [7] which states the minimum daily rainfall necessary to trigger debris flows at Jianjia Ravine is 20 mm/day. Verification of rainfall data at several observation stations around the Yeh Sah river basin and the Geophysics Station in Denpasar was carried out to ensure that the rainfall that occurred on 26-27 November 2017 can be used.

Debris flow is a mixed flow of fine-coarse material and water that moves under the influence of the slope of the river, Takahashi in [8]. The main parameters in the triggering of debris flow are the geometrical and morphological characteristics of the site (slope and river cross-profiles), material availability and its size, and lastly, runoff discharge, Gregoretti and Fontana in [9]. The material composition of the debris flow is dominated by coarse material, as described by Hecras in [10] and shown in the following Figure.

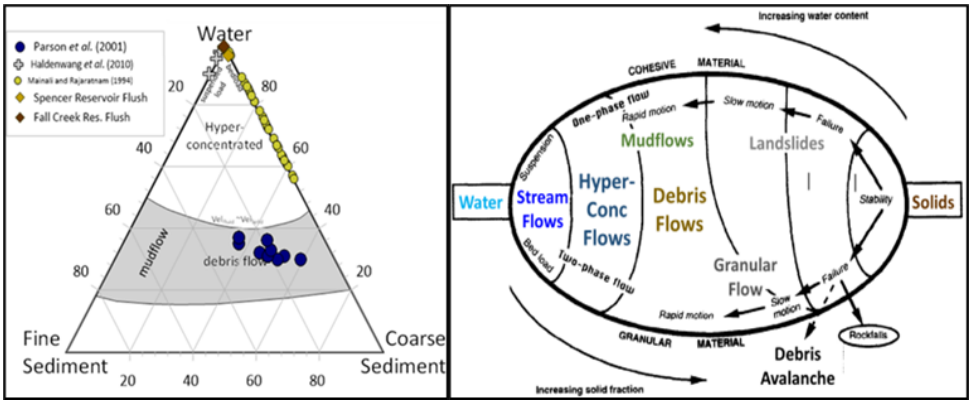


Fig. 1. Taxonomy of mud and debris flow, HEC-RAS in [8].

This study focuses on CN value for the hydrologic loss method to generate runoff potential. The SCS-CN loss model provides better results for the hydrologic response of the catchment in generated rainfall-runoff debris flow, Berti, et al. in [11]. The runoff estimate using the NRCS-CN method provides three antecedent soil moisture condition (AMC) that depends on five days of rainfall depth. The AMC-I is a five-day rainfall depth of less than 35 mm, The AMC-II is 35 to 52.5 mm and the AMC-III is over 52.5 mm, Chow, et al. in [12]. Several hydrological models use the CN value for AMC-II (traditional/normal condition) and were assigned based on the traditional NRCS-CN method which does not consider slope such as Syarifuddin, et al. in [5] and Berti, et al. in [11] where the s slope of land use is the important parameter in determining runoff and affect runoff estimation significantly, Huang, et al. in [13] and Garg, et al. in [14].

The problem behind this research is that the use of the traditional NRCS-CN method (AMC-II) is not following the debris flow event on 27 November 2017. The purpose of this study was to analyze the CN value by considering the AMC and the effect of slopes on the 27 November 2017 debris flow event.

2 Study area

The study area was the Yeh Sah river basin and Yeh Sah River, which are located on the southwestern flank of Mount Agung. The Yeh Sah River suffered the effects of the 2017 eruption with the most significant debris flow, Syahbana, et al. in [1] and Andaru, et al. in [15]. Administratively, Yeh Sah River Basin belongs to Rendang District, Karangasem Regency, Bali, Indonesia.

2.1 Topography

Elevation in Yeh Sah River Basin varies from 450 m to 3000 m (Mount Agung Area). The Basin slope in the Yeh Sah river basin was generated from the Slope Degree Map of Bali Province obtained from BIG in [16]. Data Elevation Model (DEM) obtained from BIG in [17]. Geometries Data of Yeh Sah River obtained from BWS Bali-Penida were topographic surveys in 2016 [18] and 2020 [19].

2.2 Land use and land cover

Land use and land cover in the Yeh Sah river basin were generated from the Land Use and Land Cover Map (shape file format) of Bali Province, obtained from BIG in [20]. The harmonized World Soil Database (HWSD) map of the hydrological soil group (HSG) obtained from FAO Soils Portal in [21] is used to determine the correct hydrologic soil group for the Yeh Sah river basin.

3 Material and methods

3.1 Conceptual Method

The conceptual method in this study is how to analyze CN value in hydrological modeling so that the estimation of the debris flow was more comparable to the real condition.

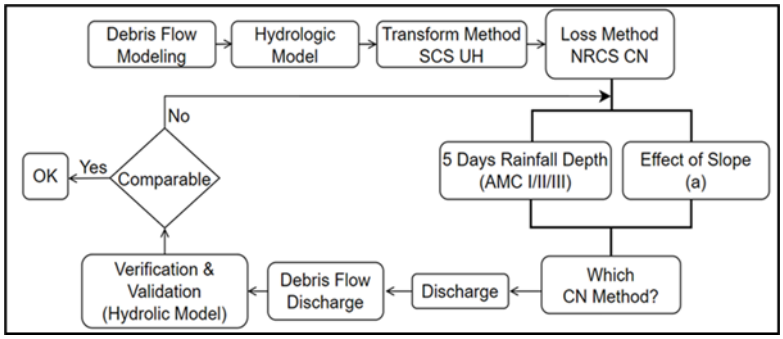


Fig. 2. Conceptual diagram.

3.2 Rainfall

Rainfall data (Tabel 1) is daily rainfall (R24) obtained from the BWS Bali-Penida. Rainfall measurements were carried out starting at 07.00 so that the debris flood event in the early hours of 27 November 2017 was the rainfall data for 26 November 2017. The daily rainfall data is used as area rainfall using the Thiessen polygon method.

Table 1. Data availability of observation station around Yeh Sah river basin.

No	Station	Rainfall depth (mm/day)					
		22-Nov	23-Nov	24-Nov	25-Nov	26-Nov	27-Nov
1	Rendang	22	15	28	4	32	13
2	Pegotan	0	9	4	4	31	0
3	Klungkung	0	58	18	0	0	5
4	Selisihan	1	0	46	40	0	0
5	Telengan	1	3	0	5	12	0
6	Tampaksiring	11	2	30	5	15	0
7	Geofisika Denpasar	24.5	4.1	84.8	20	0.4	3

The area rainfall data is then multiplied by the area reduction factor, BSN in [22]. The area reduction factor is shown in the Table 2.

Table 2. Area reduction factor and areal rainfall.

Area (km²)	ARF
1 - 10	0.99
10 - 30	0.97
30 - 30000	1.152 - 0.1233 Log A

The distribution of hourly rainfall uses the PSA 007 method which is recommended in the Technical Guidelines for the calculation of flood discharge at dams issued by Balai Teknik Bendungan in [23]. In this study, the selected distribution was for 6 hours, according to the area of the watershed is relatively small and it is very rare for the rain to occur with a duration of more than 6 hours (Table 3).

Table 3. The distribution of daily rainfall.

Time step (hour)	R/Rtotal	Time step (hour)	R/Rtotal
1	0.05	4	0.16
2	0.1	5	0.06
3	0.6	6	0.03

3.3 NRCS-CN calculation methods

The study adopted the NRCS-CN method to estimate. The NRCS-CN method is based on two fundamental hypotheses and water balance, SCS in [24]:

$$P = Ia + F + Q \quad (1)$$

$$\frac{Q}{P-Ia} = \frac{F}{S} \quad (2)$$

$$Ia = \lambda . S \quad (3)$$

where P is the precipitation (mm), Ia is the initial abstraction (mm), F is the cumulative infiltration (excluding Ia), Q is the direct runoff (mm), S is the potential maximum retention

(mm) and λ is the ratio of initial abstraction. Combining Eq. (1), Eq. (2) and Eq. (3), can be expressed:

$$Q = \frac{(P-Ia)^2}{P+S-Ia} \quad (4)$$

Equation (4) is valid for P > Ia, differently, Q = 0. The parameter S is defined as:

$$S = \frac{25400}{CN} - 254 \quad (5)$$

where CN is the curve number of runoff for hydrologic soil cover, which is a function of land cover, and the type of soil, and varies with one of three AMC. The AMC depends on the rainfall depth of the five-day antecedent that depends on season/weather which is further categorized as AMC-I, AMC-II and AMC-III. The values of CN range from 0 to 100. Huang, *et al*. in [13] proposed a simplified approach and an equation for slope-modified CN for AMC-II ($CN_{2\alpha}$):

$$CN_{2\alpha} = CN_2 \frac{322.79+15.63(\alpha)}{\alpha+323.52} \quad (6)$$

Sobhani in [25] proposed an approach for AMC-I and III (CN_1 and CN_3):

$$CN_1 = CN_2 \frac{2.334-0.01334}{CN_2} \quad (7)$$

$$CN_3 = CN_2 \frac{0.4036+0.005964}{CN_2} \quad (8)$$

Sharpley and Williams in [26], proposed some slope adjustments to CN2:

$$CN_{2\alpha} = \frac{1}{3}(CN_3 - CN_2)(1 - 2e^{-13.86\alpha}) + CN_2 \quad (9)$$

Shobani in [25] proposed some slope adjusments to CN_2, as follows:

$$CN_{2as} = CN_{2a} \frac{2.334-0.01334}{CN_{2a}} \quad (10)$$

Hawkins [27] proposed some slope adjustments to CN3, as follows:

$$CN_{3\alpha} = \frac{CN_{2a}}{0.427+0.00573\, CN_{2a}} \quad (11)$$

where CN_1 is CN for AMC-I, CN_2 is CN for AMC-II, CN_3 is CN for AMC-III, $CN_{2\alpha}$ is slope-adjusted CN_2, $CN_{3\alpha}$ is slope-adjusted CN_3 and α (m/m) is the slope.

All approaches (AMC I, AMC II and AMC II) for traditional, with and without slope adjustment, are used in this study to calculate the effect of slope-corrected on debris flow estimation. In this study, the Sobhani and the Hawkins equation have been used to calculate CN_1 and CN_3. Approaches from Huang, Sharpley, Sobani and Hawkins have been used to calculate slope adjustment (slope-modified CN). This is based on research by Mishra in [28] who suggested the Sobhani approach is best for CN_1 and the Hawkins for CN_3. The AMC is determined based on the daily rainfall data and slope of each land cover/land use was calculated based on the slope map using ArcMap 10.5. The Ia has been estimated using the expression equation (3), assuming λ as 0.2 for sub-basins 2 and 3, 0.1 for Sub-basin 1. Finally, direct runoff in each sub-basin for the 27 November 2017 rain event was calculated by adopting equation (4).

3.4 Hydrologic model

The hydrological analysis uses Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). CN values were entered for each sub-basin using the Soil Conservation Service (SCS) sub-basin loss method Eq. (6) – (11). The imperviousness of the surface for sub-basin 1 was set for 75%, sub-basin 2 and sub-basin 3 using impervious values based on

USDA. The SCS unit hydrograph is used as a transform method to calculate the actual surface runoff for each sub-basin. The lag time was set according to Eqs. (12) – (13). The Muskingum use as a routing method and the base flow was neglected because of field observation of the upstream region of the Yeh Sah river basin showed dry conditions.

$$T_c = \frac{L^{0.8}(S+1)^{0.7}}{1140.Y^{0.5}} \tag{12}$$

$$Lag\ Time = 0.6T_C \tag{13}$$

where Tc is the time of concentration (hour), L is the length of the main river (ft), S is the potential max. retention (mm) and Y is the average basin slope (%).

3.5 Debris flow discharge

The According to the manual of Sabo Works issued by JICA in [30], the debris flow discharge shall be decided by considering the ratio of sediment concentration *Cd.*

$$Q_S = Q\ .\ (1 + Cd) \tag{14}$$

$$Cd = \frac{\rho_w.Tan\ \theta}{(\sigma-\rho_w).(Tan\ \phi - Tan\ \theta)} \tag{15}$$

$$Cd = \frac{1100\ .Tan\ 12.9°}{(2780-1100).(Tan\ 25° - Tan\ 12.9°)} = 0.6 \tag{16}$$

whereas Qs is debris flow discharge including sediment (m³/s), Q is peak debris flow discharge (m³/s), Cd is the ratio of sediment concentration (%), ρ_w is water mass density (kg/m³), σ is sediment mass density (kg/m³), ϕ is the internal friction of material (°) and θ is average main river slope (°).

3.6 Hydraulic model

In this study, the hydraulic analysis uses HEC-RAS 6.3.1. Based on a non-Newtonian algorithm library called DebrisLib, HEC-RAS applies single-phase, rheological approaches to non-Newtonian simulations, Gibson, *et al.* in [30] and Floyd, *et al*. in [31]. This study uses full SWE (shallow water equation) and the non-Newtonian approach is Harchel-Bukley. The equation of momentum and conservation, HEC-RAS in [10] is as follows:

$$\frac{\partial V}{\partial t} + (V.\nabla)V = -g cos^2\varphi \nabla\eta + \frac{1}{h}\nabla.(\upsilon_t h \nabla V) - \frac{\tau}{\rho_m R}\frac{cos\psi}{cos\varphi}\frac{V}{|V|} \tag{17}$$

where g is the acceleration of gravitational, υ_t is a turbulent eddy viscosity, φ is correction factor of sthe lope, ρ_m is the water-solid mixture density, R is the hydraulic radius, $|V|$ is the magnitude of the velocity vector, φ is the slope of water surface, and ψ is the inclination angle of the current velocity direction. The critical term for this analysis is τ, the fluid stress. In the non-Newtonian model:

$$\tau = \tau_r + \tau_{MD} \tag{18}$$

where τ_r is the basal stress and τ_{MD} based on the stress-strain rheology (the model selected for the material). The function of the friction slope (S_f):

$$\tau_r = \gamma R S_f \tag{19}$$

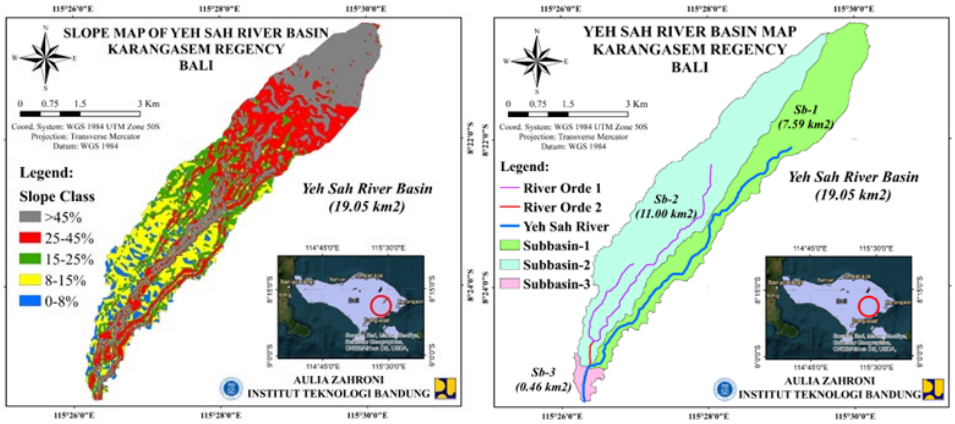
where γ is the fluid unit weight, R is the radius of hydraulic, and S_f is the friction slope based on Manning's equation:

$$S_f = \left(\frac{nV}{kR^{\frac{2}{3}}}\right)^2 \tag{20}$$

where V is the velocity and k is the conversion factor unit. In clearwater analysis, this stress term collapses to τ_r. HEC-RAS includes several and more complicated non-linear approaches to non-newtonian closures, Gibson, *et al.* in [32] and Floyd, *et al.* in [33]. All procedures were done following the standards of HEC-RAS 6.3 for mud and debris flow.

4 Results and discussions

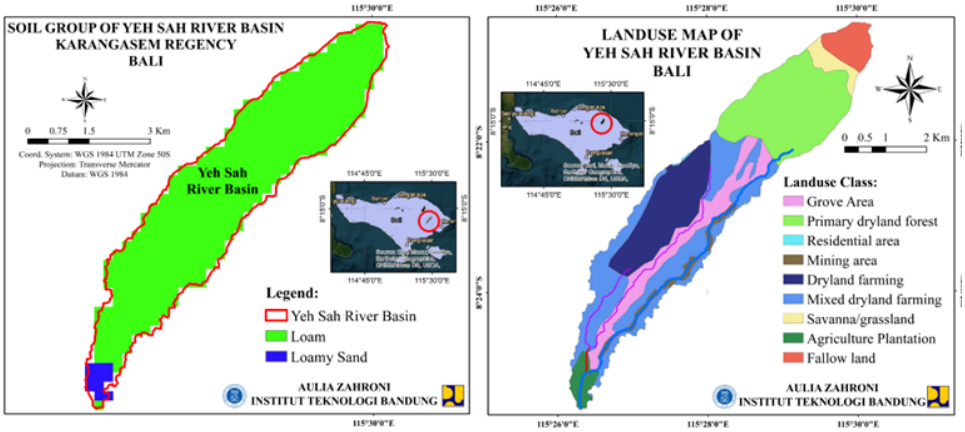
The Yeh Sah river basin has an area of 19.05 km^2 and the length of the main river is 9.51 km. The Yeh Sah river basin is then divided into 3 sub-basins (Figure 3a).



(a) **(b)**

Fig. 3. (a) Yeh Sah river basin **(b)** slope percent map of Yeh Sah river basin.

The Basin slope class of > 45% is 26.56%, 25-45% is 30.45%, 15-25% is 18.01%, 8-15% is 18.90% and 0-8% is 6.09% of the total area (Figure 3b).



(a) **(b)**

Fig. 4. (a) Land use/land cover **(b)** soil group map of Yeh Sah river basin.

The ten major land use classes of Yeh Sah River Basin found were: grove area, primary dryland dense forest, residential area, mining area, agriculture, savanna/grassland, agriculture plantation, fallow land, dry farming mixed plantation and mixed dryland farming (Figure 4a). The percent coverage of each class for over sub-basin is tabulated in Table 4.

Table 4. Slope and area of land use class.

No	Land use class	Sub Basin-1		Sub Basin-2		Sub Basin-3	
		Area (km^2)	Slope (m/m)	Area (km^2)	Slope (m/m)	Area (km^2)	Slope (m/m)
1	Grove area	0.63	0.13	1.89	0.12	0.00	0.00
2	Primary dryland forest	2.84	0.29	2.42	0.27	0.00	0.00
3	Residential area	0.00	0.06	0.02	0.13	0.00	0.00
4	Mining area	0.61	0.11	0.00	0.00	0.00	0.00
5	Agriculture	2.15	0.11	0.00	0.00	0.00	0.00
6	Savanna/grassland	0.37	0.39	0.17	0.45	0.00	0.00
7	Agriculture Plantation	0.04	0.13	0.15	0.13	0.41	0.11
8	Fallow land	0.94	0.27	0.05	0.46	0.00	0.00
9	Dryland farming	0.00	0.00	3.27	0.12	0.00	0.00
10	Mixed dryland farming	0.00	0.00	3.04	0.11	0.06	0.08
	Σ	7.59		11.00		0.46	

The map of soil textural classes is prepared (Figure 4b) and the coverage area of each soil class has been calculated as shown in Table 5.

Table 5. Sub basin area covered by soil types.

No	Soil Group	Loam	Loamy Sand	Total
		Area (km^2)	Area (km^2)	Area (km^2)
1	Sb-1	5.67	1.93	7.59
2	Sb-2	10.76	0.24	11.00
3	Sb-3	0.46	0.00	0.46
	Σ	16.89	2.17	19.05

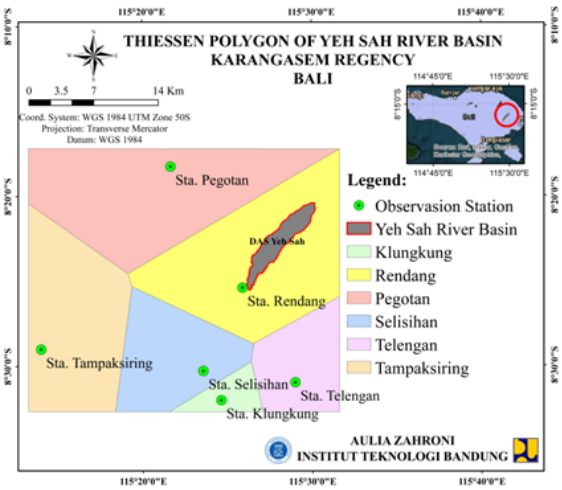


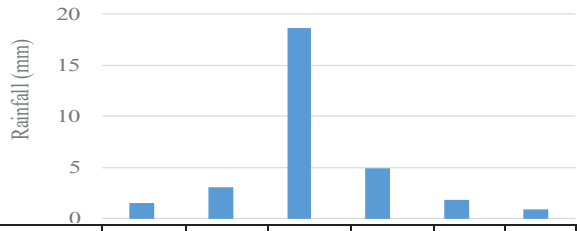
Fig. 5. Polygon Thiessen of Yeh Sah river basin.

The daily rainfall data is used as area rainfall using the Thiessen polygon method. The results of the Thiessen polygon analysis using ArcMap 10.5 found that Rendang Station had 100% influence on the occurrence of rain in the Yeh Sah basin as shown in Figure 5. The area rainfall data is then multiplied by the area reduction factor (ARF). The ARF used for the 19.05 km^2 river basin area is 0.97 shown in Table 6.

Table 6. Area reduction factor and areal rainfall.

Date	Rainfall (mm)	ARF (km²/km²)	Areal Rainfall (mm)
26 Nov 17	32	0.97	31.04

The distribution of hourly rainfall data in Das Yeh is valid due to the limited available rainfall intensity data. The distribution of hourly rain data for 6 hours is shown in figure 6.



Time step (hour)	1	2	3	4	5	6
PSA 007 6 hours coefficient	0.05	0.10	0.60	0.16	0.06	0.03
Rainfall depth (mm)	1.55	3.10	18.62	4.97	1.86	0.93
Persentase (%)	5.00	10.00	60.00	16.00	6.00	3.00
Rainfall R_{24}	31.04	mm				

Fig. 6. The distribution of hourly rainfall.

Based on the depth of rainfall for 5 days in table 1, the CN value used is the CN value at AMC III. The slope of the Yeh Sah River Basin also has a significant effect on the CN value (Table 7).

Table 7. CN Value.

CN Composite	Area (km^2)	CN	CN2α (Huang)	CN1 (Sobani)	CN3 (Sobani)	CN2α (Sharpley)	CN2αs (Sobani)	CN3α (Hawkins)
SB.1	7.59	74.55	75.09	55.91	87.82	78.11	60.64	89.27
SB.2	11.00	76.62	76.99	58.82	88.92	79.48	62.73	89.99
SB.3	0.46	81.00	81.20	64.62	91.35	82.80	67.35	91.85

Initial abstraction is affected by the CN value. The Ia value for each CN method is different. CN in AMC-III with the influence of slope is the minimum value (Table 8).

Table 8. Lag time for each CN method.

CN Types	Lag (min)			Ia (mm)		
	SB.1	SB.2	SB.3	SB.1	SB.2	SB.3
CN	54.48	54.17	10.37	8.67	15.50	11.92
CN2α (Huang)	53.65	53.59	10.31	8.43	15.18	11.76
CN1 (Sobani)	88.91	87.23	16.47	20.03	35.56	27.81
CN3 (Sobani)	35.44	35.85	7.10	3.52	6.33	4.81
CN2α (Sharpley)	35.44	35.85	7.10	3.52	6.33	4.81
CN2αs (Sobani)	49.08	49.69	9.78	7.12	13.11	10.55
CN3α (Hawkins)	33.49	34.34	6.95	3.05	5.65	4.50

Flood discharge modeling can be done after getting the results of the loss model parameters. Modeling the flood discharge in the Yeh Sah watershed using the SCS unit hydrograph (HEC-HMS 4.10) is shown in the Figure 7.

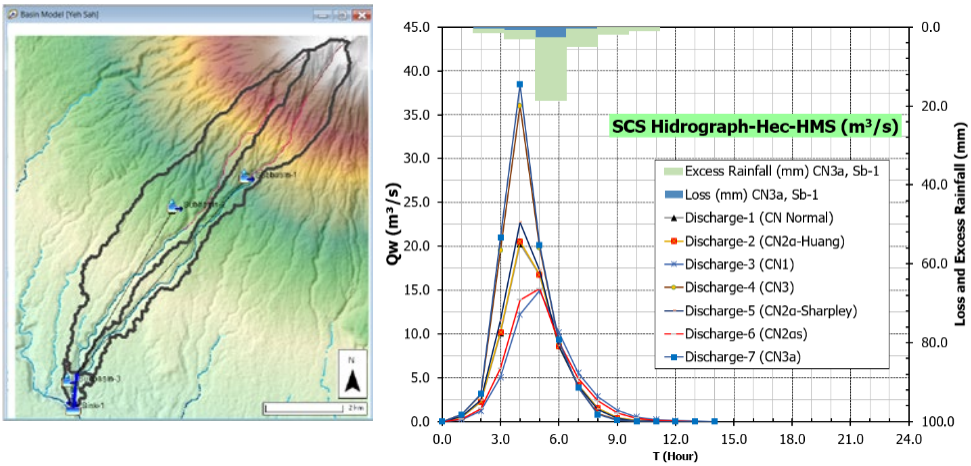
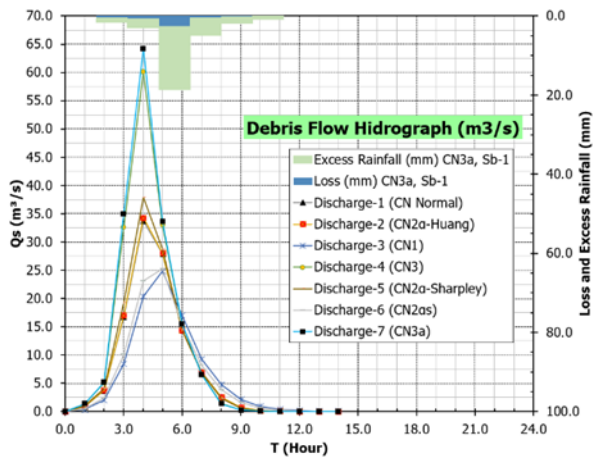


Fig. 7. SCS unit hydrograph (Hec-HMS 4.10).

Using Eq. 14, debris flow discharge has been calculated as tabulated (Table 9).

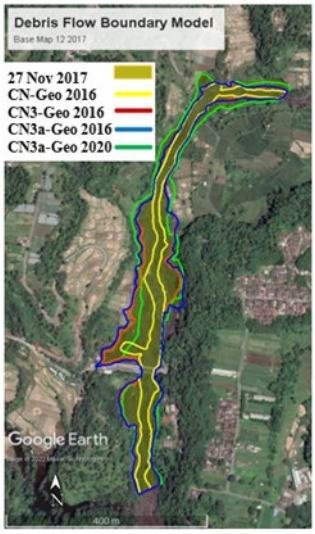
Table 9. The volume of the debris flow dischare is affected by sediment Qw

Discharge	SCS Qw (m^3/s)	Debris Flow Qs (m^3/s)
CN	20.24	33.77
CN2α	20.55	34.29
CN1	14.89	24.84
CN3	36.02	60.10
CN2α (Sharpley)	22.72	37.91
CN2αs	15.14	25.26
CN3α	38.46	64.17



Based on the hydrological modeling results, it was found that the analysis of the CN value gave a significant difference to the debris flow discharge. Debris flows events on 27 November 2017 occurred in AMC III, where the Yeh Sah River Basin is dominant with steep slopes so hydrological modeling in this watershed needs to review AMC conditions and the influence of slope. Verification was carried out on the flood discharge results of CN, CN3 and CN3a with hydraulics modeling using the HEC-RAS 6.3.1 software with geometry from topographic surveys in 2016 and 2020. The modeling results were compared with the debris event boundary on 27 November 2017 obtained from Google Earth 2018 and field observation in August 2022 (Figure 8). The modeling was carried out on the 1.2 km long Yeh Sah River with an inundation area of 7.04 ha.

Fig. 8. Google Earth Imagery and documentation of post-debris event.



The results of the inundation boundary overlay show that there is a significant difference between the debris flow generated from the CN value under normal conditions (CN-Geo 2016, yellow line) compared to 2017 event.

The debris flow discharge generated from the CN value in the AMC-III condition (CN3-Geo 2016, green line) is not the same yet as the debris flow event. The results show that the debris flow discharge generated from AMC and the effect of slope (CN3a-Geo 2016, blue line) is more comparable to the 2017 event.

The flood discharge generated from AMC and the effect of slope (CN3a-Geo 2020, red line) was also modeled on the 2020 geometry to validate the model, and showed better results in some sections. The percentage of model inundation area with debris flow event inundation is shown in the Table 10.

Fig. 9. Debris flow inundation boundary (model and event).

Table 10. Percentage of the model area to 2017 debris flow event.

Item	Area (ha)	Percentage (%)
27-Nov-17 inundation boundary	7.05	100.00
Geometry 2016 - CN	2.69	38.12
Geometry 2016 - CN3	5.75	81.61
Geometry 2016 - CN3a	6.32	89.69
Geometry 2020 - CN3a	6.69	95.02

5 Conclusions

The daily rainfall on 27 November 2017 was 32 mm/day, increasing significantly when the CN was analyzed with the effect of the slope of the land cover and the appropriate AMC. This is evidenced by hydraulic modeling where inundati on was generated in the review area

close to the incident on 27th November 2017. The planning of water structures in the Yeh Sah watershed and other watersheds in the Gunung Agung volcanic area, where field data and historical information on past debris flow activities are limited, the parameters analyzed in this study must be carried out so that the buildings are not over or under-designed. Further research should encourage scientists to examine the validity of proposed approaches in other watersheds by comparing the results of hydrological and hydraulic models with debris flow events. However, using this approach for blind prediction where verification and validation parameters are not available, is exercised with special caution

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References

1. D.K. Syahbana, K. Kasbani, G. Suantika, O. Prambada, A. S. Andreas, U. B. Saing, S. L. Kunrat et al. *The 2017–19 activity at Mount Agung in Bali (Indonesia): Intense unrest, monitoring, crisis response, evacuation, and eruption*, Sci. Rep., **9**, 8848 (2019)
2. P. Cui, X.Chen, Y. Waqng, K. Hu, and Y. Li, *Jiangjia Ravine debris flows in south-western China*, Springer: in Debris-flow hazards and related phenomena, 565 (2005)
3. M.I. Rosli, F. Che Ros, K.A. Razak, S. Ambran, S.A. Kamarudin, A. Nor Anuar, A. Marto, T. Tobita, Y. Ono, *Modelling debris flow runout: a case study on the Mesilau Watershed, Kundasang, Sabah*. Water, **13(19)**, 2667 (2021)
4. M. Syarifuddin, S. Oishi, D. Legono, R.I. Hapsari, and M. Iguchi, *Integrating X-MP radar data to estimate rainfall-induced debris flow in the Merapi volcanic area*, Advances in water res., **110**, 249 (2017)
5. F. Lavigne and J.C. Thouret, *Sediment transportation and deposition by rain-triggered lahars at Merapi Volcano, Central Java, Indonesia,* Geomorphology, **49(2),** 45 (2003)
6. J.S.Wu, L.Q. Tian, Z.C. Kang, S.C. Zhang, and J. Liu, Debris flow and its comprehensive control (Science Press, Beijing, 1993)
7. T. Takahashi, Debris flow, mechanics, prediction and countermeasures *(*ed.1, Taylor & Francis/Balkema, 2007)
8. C. Gregoretti and G.D. Fontana, *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), p. 2248 (2007)
9. HEC., HEC-RAS 2D user's manual v6.1*,* https://www.hec.usace.army.mil/confluence/rasdocs/r2dum/latest (accessed on 22 February 2022)
10. M. Berti, M. Bernard, C. Gregoretti, and A. Simoni, *Physical interpretation of rainfall thresholds for runoff-generated debris flows,* Journal of Geophysical Research: Earth Surface, **125(6),** e2019JF005513 (2020)
11. V.T. Chow, D.R. Maidment, and L.W. Mays, Applied Hydrology (McGraw-Hill Book Company, 1988)
12. H. Huang, J. Gallichand, Z. Wang, and M. Goulet, *A modification to the soil conservation services curve number method for steep slopes in the Loess Plateau of China,* Hydrological Pro., **20**, 579 (2006)

13. V. Garg, B.R. Nikam, P.K. Thakur, and S.P. Aggarwal, *Assessment of the effect of slope on runoff potential of a watershed using NRCS-CN method*, International Journal of Hydrology Science and Technology, **3(2)**, 141 (2013)
14. R. Andaru, J.Y. Rau, D.K. Syahbana, A.S. Prayoga, and H.D. Purnamasari, *The use of UAV remote sensing for observing lava dome emplacement and areas of potential lahar hazards: An example from the 2017–2019 eruption crisis at Mount Agung in Bali*. Journal of Volcanology and Geothermal Research, **415**, 107255 (2021)
15. Badan Informasi Geospasial, Peta Kemiringan Lereng Provinsi Bali, https://www.indonesia-geospasial.com/ (accessed 1 July 2022)
16. Badan Informasi Geospasial, Digital Elevation Model Nasional, https://tanahair.indonesia.go.id/demnas/#/ (accessed 1 July 2022)
17. BWS Bali-Penida, Perencanaan teknis prasarana pengendalian lahar Gunung Agung di Kabupaten Karangasem (2016)
18. BWS Bali-Penida, Laporan pengukuran topografi mutual check (MC-0) Tukad Yeh Sah, Pekerjaan pengendalian banjir Sungai Unda (2020)
19. Badan Informasi Geospasial, Tutupan Lahan 2019, https://www.indonesia-geospasial.com/ (accessed 1 July 2022)
20. Food and Agriculture Organization of United Nation, *FAO Soils Portal-Harmonized World Soil Database v 1.2*, https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed 1 July 2022)
21. Badan Standarisasi Nasional, SNI 2515:2016 – Tata cara perhitungan debit banjir rencana (Jakarta, 2016)
22. Balai Teknik Bendungan, Petunjuk Teknis Perhitungan Debit Banjir Bendungan, (Jakarta, 2017)
23. Soil Conservation Service (SCS), SCS National Engineering Handbook, Hydrology (US Department of Agriculture, 1972)
24. G. Sobhani, A review of selected small watershed design methods for possible adoption to Iranian conditions (MS thesis, Utah State University, Logan, UT, 1975)
25. A.N. Sharpley and J.R. Williams, EPIC – *Erosion/productivity impact calculator: 1. Model documentation*, US Department of Agriculture Technical Bulletin, **1768**, US Government Printing Office, Washington, DC (1990)
26. R.H. Hawkins, Jr. A.T. Hjelmfelt, and A.W. Zevenbergen, *Runoff prob., storm depth and curve numbers, Journal of Irrigation and Dra. Eng.* (ASCE), **111(4)**, 330 (1985)
27. S.K. Mishra, M.K. Jain, P. Suresh Babu, K. Venugopal, and S. Kaliappan, *Comparison of AMC-dependent CN-conversion formulae*, Water Res. Man., **22(10),** 1409 (2008)
28. JICA. Tech. standards and guidelines for planning and design of sabo structures (2010)
29. S. Gibson, I. Floyd, A. Sánchez, and R. Heath, *Comparing single-phase, non-Newtonian approaches with experimental results: Validating flume-scale mud and debris flow in HEC-RAS.* Earth Surface Processes and Landforms, **46(3),** 540 (2021)
30. I.E. Floyd, S. Gibson, R. Heath, M. R. Villanueva, and N. Pradhan, *Development of debris lib. and 1D HEC-RAS and 2D adaptive hydraulics Linkage-Architecture for predicting post-wildfire non-newtonian flows*. Proc. of the Fed. Int. SEDHYD, 24 (2019)
31. S. Gibson, L.Z. Moura, C. Ackerman, N. Ortman, R. Amorim, I. Floyd, M. Eom, C. Creech, and A. Sánchez, *Prototype scale evaluation of non-newtonian algorithms in HEC-RAS: mud and debris flow case studies of Santa Barbara and Brumadinho*, Geosciences, 134 (2022)
32. I.E. Floyd, A. Sanchez, S. Gibson, and G.A. Savant, *Modular, non-newtonian, model, library framework (DebrisLib) for post-wildfire flood risk management*. Hydrology and Earth System Sci. Disc, 1 (2020)