Evaluation of Rainfall-Induces Landslides in Banjarnegara, Central Java, Indonesia Using TRIGRS Model

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Abstract— **Severe landslide followed by debris on 12 December 2014 ruined infrastructures and buried hundreds of peoples in subdistrict Karangkobar, District Banjarnegara, Central Java. A high daily rainfall reached about 200 mm for two days prior to the disaster. This paper presents the prediction and evaluation the landslide area using TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability) version 2.0 model. The model was applied to calculate pore water pressure and the factor of safety (FS) during rainfall infiltration. The model used DEM, geological and geotechnical properties, infiltration variables and rainfall intensity. At the initial condition, before rainfall infiltration, the lowest FS value ranges from 1 to 1.2, where is distributed at the steep slope area near the Jemblung. The simulation results obtained that the steep slope area, where the inclination angle is greater than 30°, are susceptible to failure (FS < 1.2) during the rainfall infiltration. However, in some locations of steep slopes were likely not fail (FS > 1.2). In general, this study concluded that the predicted location of slope failure by TRIGRS agreed with the field observation of the landslide occurrences.**

Keywords— **Factor of Safety; Landslides; Porewater Pressure; Rainfall; Spatial; TRIGRS.**

I. INTRODUCTION

Karangkobar is one of the sub-districts in Banjarnegara. Mountainous hills surround this subdistrict. This condition forces most of the transportation infrastructures are built by cutting the hills and slopes. On 12 December 2014, there was a landslide in more than seven locations [1]. The natural disaster cut off the access to Karangkobar—Banjarnegara, buried hundreds of people and houses. The type landslide is shallow slope failure and followed by debris flow. Rainfall intensity in December 2014 reached 200 mm more for two-day precipitation as shown in Fig. 1. Theoretically, intense rainfall creates temporary water table and increases the soil saturation. Water fills soil pores and decreases soil particle bond. At this state, pore water pressure increased, while the shear strength decreased [2]. When the soil saturated, the soil is in a slurry state and unstable. Therefore, rainfall was considered as a triggering factor in slope instability, beside of high inclination area.

Some coupled infiltration and slope stability model has been developed to model and evaluates landslides. TRIGRS has been widely used to model rainfall infiltration induces shallow landslides [3,4,5]. TRIGRS model was also applied to assess the initial amount of a volume of a landslide for debris flow simulation rather than the real field measurement [6]. Zhuang et al. [7] summarized that TRIGRS generated more satisfactory results at a given precipitation threshold than SINMAP, which is ideal for landslide hazard zoning for land-use planning at the regional scale. Comparison results showed that TRIGRS is more useful for landslide prediction for a certain precipitation threshold, also in the regional scale.

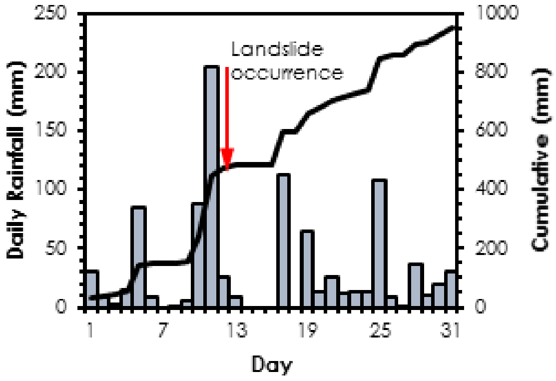

Fig. 1 Precipitation record from the nearest rainfall station in Karangkobar

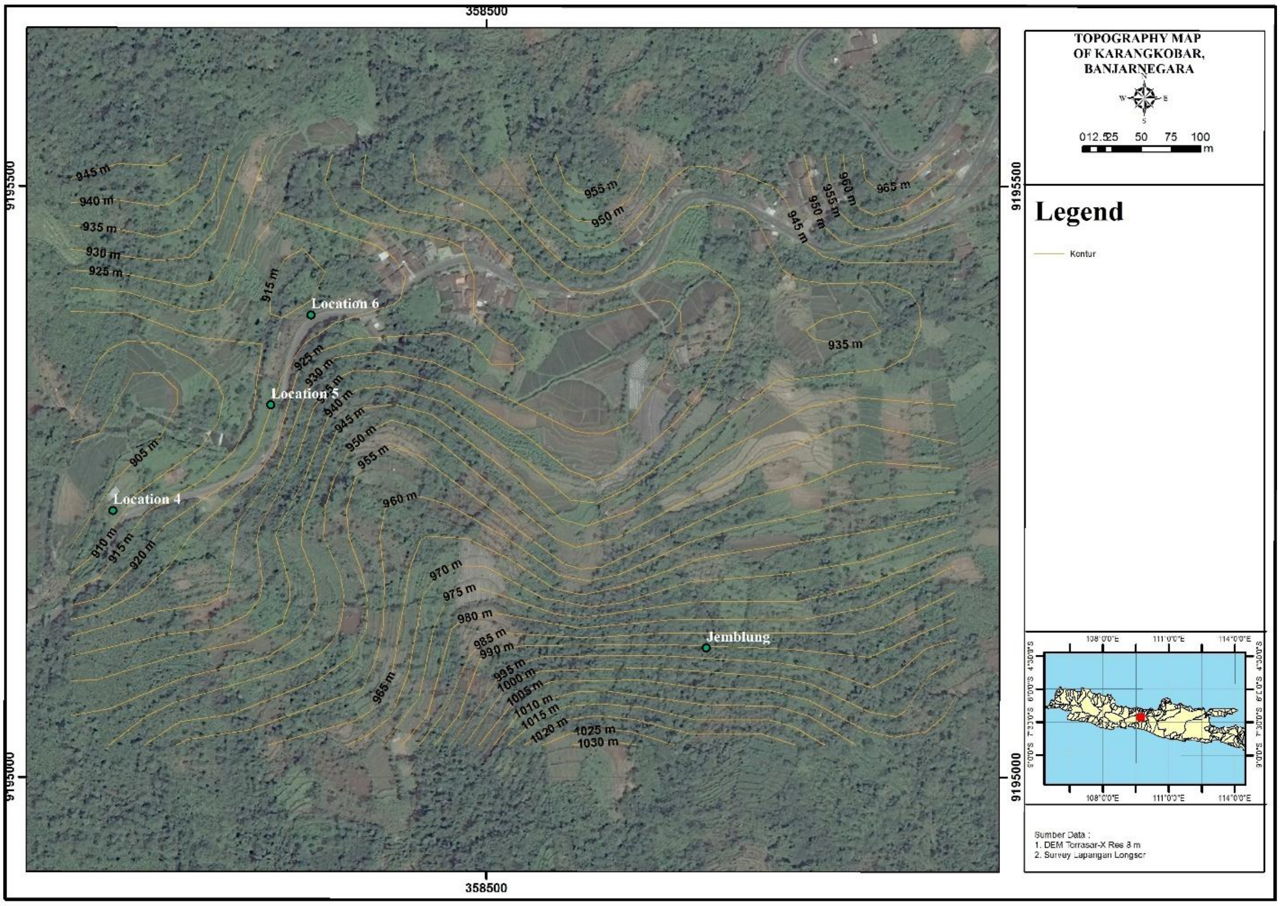

Fig. 2. Topography of the investigated area

$$\psi(Z,t)=(Z-d)\beta+2\sum_{n=1}^{N}\frac{I_{nZ}}{K_S}\left(H(t-t_n)\left(D_1\left(t-t_n\right)\right)^{\frac{1}{2}}ierfc\left(\frac{Z}{2\left(D_1\left(t-t_n\right)\right)^{\frac{1}{2}}}\right)\right)$$

$$-2\sum_{n=1}^{N}\frac{I_{nZ}}{K_S}\left(H(t-t_{n+1})\left(D_1\left(t-t_{n+1}\right)\right)^{\frac{1}{2}}ierfc\left(\frac{Z}{2\left(D_1\left(t-t_{n+1}\right)\right)^{\frac{1}{2}}}\right)\right) \qquad (1)$$

$$\psi(Z,t)=(Z-d)\beta+2\sum_{n=1}^{N}\frac{I_{nZ}}{K_S}H(t-t_n)\left(D_1\left(t-t_n\right)\right)^{\frac{1}{2}}\sum_{m=1}^{\infty}\left(ierfc\left(\frac{(2m-1)d_{LZ}+\left(d_{LZ}-Z\right)}{2\left(D_1\left(t-t_n\right)\right)^{\frac{1}{2}}}\right)+ierfc\left(\frac{(2m-1)d_{LZ}+\left(d_{LZ}-Z\right)}{2\left(D_1\left(t-t_n\right)\right)^{\frac{1}{2}}}\right)\right) \qquad (2)$$

$$-2\sum_{n=1}^{N}\frac{I_{nZ}}{K_S}H(t-t_{n+1})\left(D_1\left(t-t_{n+1}\right)\right)^{\frac{1}{2}}\sum_{m=1}^{\infty}\left(ierfc\left(\frac{(2m-1)d_{LZ}+\left(d_{LZ}-Z\right)}{2\left(D_1\left(t-t_{n+1}\right)\right)^{\frac{1}{2}}}\right)+ierfc\left(\frac{(2m-1)d_{LZ}+\left(d_{LZ}-Z\right)}{2\left(D_1\left(t-t_{n+1}\right)\right)^{\frac{1}{2}}}\right)\right)$$

Since the model in TRIGRS considers a spatial analysis, thus, evaluation of rainfall-induced in Banjarnegara is a necessity to produce landslide hazard map based on the hydro-geotechnical approach using TRIGRS model. This research mainly aims to evaluate the rainfall induces landslide, and to identify the potential landslide area in Karangkobar. This identification is necessary for early warning emergency planning [8].

II. PRINCIPLES OF TRIGRS MODEL

The TRIGRS program is operated by providing an input text file which is open file software. The file comprises many lines, and it is described in the README file bundled with the software. A full description of the previous version of the software and its user manual can be found in [3]. All components are set to be initial condition [4] for all layers. Simulation process uses two layer systems. The bottom layer is saturated soil under water-table. The upper layer lay on the water-table, processed as unsaturated soil. However, the layers are established to be isotropic and causes infiltration analyzed into the transient and steady system. Iverson's solution is applied to solve infiltration model. Transient infiltration affects transient pressure head and changes in the factor of safety in the digital map [3]. Steady state and transient calculated by Equation 1 and 2 respectively. Some variables in each equation are directly derived from experimental data and another calculated by Equation 3 to 7

$$ierfc(\eta) = \frac{1}{\sqrt{\pi}} \exp\left(-\eta^2\right) - \eta erfc(\eta) \qquad (3)$$

$$Z = z / \cos\delta \qquad (4)$$

$$\beta = \cos^2\delta - (I_{ZLT} / K_S) \qquad (5)$$

$$D_1 = D_0 / \cos^2\delta \qquad (6)$$

$$D_0 = K_S / S_S \qquad (7)$$

Which,

d = steady-state depth water table (m);
D_0 = saturated hydraulic diffusivity (m/s)
d_{LZ} = depth of impermeable boundary (m);
I_{ZLT} = steady (initial) surface flux (m/s);
K_S = saturated hydraulic conductivity (m/s);
n^{th} = time interval infiltration
S_S = specific storage;
t = time (s);
δ = slope angle (°);
ψ = ground water pressure head (m);
z = positive downward (m);
Z = vertical coordinate direction (m).

The factor of safety is calculated by Equation 8. Downward flow direction above water table generates a new ground water table and develops positive water pressure. Thus, the factor of safety will change with the depth and time.

$$FS(Z,t) = \frac{\tan\varphi'}{\tan\delta} + \frac{c' - \psi(Z,t)\gamma_w \tan\varphi'}{\gamma_s Z \sin\delta \cos\delta} \qquad (8)$$

where c' is effective cohesion, ϕ' is effective internal friction angle, γ_s is soil unit weight, and γ_w is water unit weight.

III. METHODS AND ANALYSIS

A. *Site location*

The study area is shown in Fig. 2. Landslide spots were identified along the sloping road as shown in location 4, 5, 6.

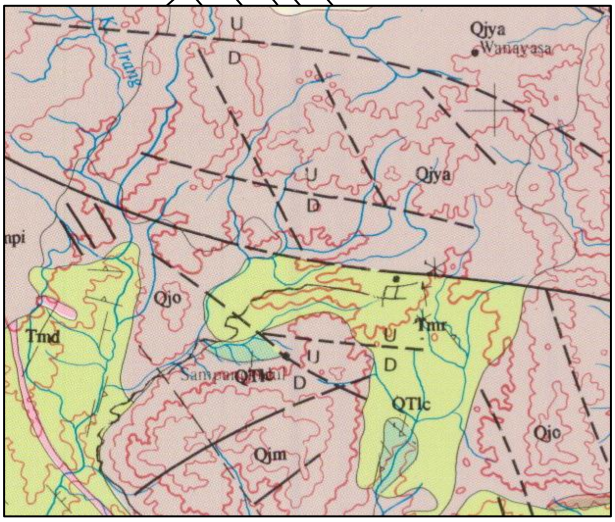

Fig. 3. Geological setting of the landslide area

A slope failure followed by debris flow occurred at Jemblung. The geological setting of the area is predominantly shale, marl, calcareous sandstone, which is part of Rambatan Formation (Tmr) as shown in Fig. 3. Field observation found a soften clay. Its thickness can be greater than 300 mm. The landslide area and its surroundings are formed by unit Qiya, Qjm, Qjma, which is the andesite lava and the volcanic clastics rocks of the volcano sliced from the Jembangan Mountains, especially andesithic; locally contains hornblende and olivine basalt. Qiya and Qjma are alluvium lava and sediment composed of weathered volcanic rock, as well as a few amounts of lava flow and breccia flow. The Qjm and Qjo units are lava flows, breccia, pyroclastic breccias, soil and alluvium deposits.

B. *TRIGRS Modelling*

This study uses TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis) Version 2.0 to the model of slope stability in a spatial. The main input parameters in TRIGRS are precipitation intensity (*cri*), slope (°), soil depth (*Z*), initial water table depth (*depthwt*), saturated vertical hydraulic conductivity (k_s), hydraulic diffusivity (*D*), three-parameter soil-water characteristic curve, cohesion for effective stress (*c*), angle of internal friction for effective stress (ϕ), and total unit weight of soil (γ_s).

1) *Digital Elevation Model (DEM)*

Fig. 2 shows boundary area and the locations. The area represented by a grid with 25x25 each cell size. In this study, the area is divided into three zones (see Fig. 6). Each zone has different hydrological properties. Landscape digital of location is transformed into ASCII text as DEM file. This ASCII text underlies every input data in this research.

2) *Soil Water Characteristic Curve*

The soil water characteristics curve (SWCC) is used to determine the residual (θ_r) and saturated (θ_s) volumetric moisture content. These two parameters are the input parameter in TRIGRS model. In this study, the SWCC was obtained from the suction measurement using tensiometer in the field. Fig. 4 shows the SWCC of the soil layer. The SWCC is fitted on the van Genuchten – Mualem model of SWCC [9].

3) *Precipitation*

The precipitation record was collected from rainfall station in Karangkobar. The daily rainfall and cumulative

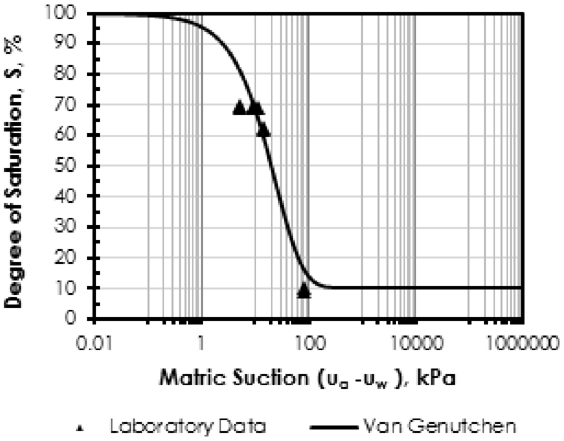

Fig. 4. The SWCC of the soil layer

rainfall in December 2014 is shown in Fig. 1. The arrow indicates the time of landslide occurrence on 12 December 2017. The average hourly rainfall triggering slope failure is calculated about 136 mm/h (3.79×10^{-5} m/s).

4) Input Parameters

Field observation shows that the variation of geotechnical properties is almost similar for each zone. The shear strength properties were obtained from the direct shear test. The hydraulic properties of soil, which represented by the coefficient of permeability k_{sat}, and diffusivity D_1, at each zone relatively varied. The input parameter of this simulation is presented in Table 1.

TABLE 1. VARIABLE INPUT IN TRIGRS

Parameter		Zones		
		1	2	3
c'	N/m^2	1.1×10^3	1.1×10^3	1.1×10^3
ϕ'	^{o}	13.810	13.810	13.810
γ_s	N/m^3	1.4×10^4	1.4×10^4	1.4×10^4
k_{sat}	m/s	4.0×10^{-7}	4.0×10^{-5}	4.0×10^{-4}
θ_s	-	0.873	0.87	0.873
θ_r	-	0.09	0.09	0.09
α	-	-0.5	-0.5	-8.0
D_1	m/s	6.0×10^{-6}	8.68×10^{-4}	4.12×10^{-2}
i	m/s	3.79×10^{-5}	3.79×10^{-5}	3.79×10^{-5}

IV. RESULTS AND DISCUSSION

A. Results

Fig. 5 present the spatial factor of safety at the initial condition, before rainfall infiltration. The FS values vary from 1 to 10. The lowest FS value ranges from 1 to 1.2, where is distributed at the steep slope area near the Jemblung. Theoretically, the area is initially almost stable, but the area is potential to slide. This study concerns about the change of slope stability during a rainfall event. The slope stability is represented by the modification of safety factor with the elapsed time of rain. Fig. 6 illustrates that the minimum factor of safety varies with the elapsed time rainfall. The simulation determined that the minimum factor of safety range from 0.2 to 10. Use the criteria proposed by Ward et al. [10]; the relative spatial hazard level can be divided into three regions, that is low if the FS > 1.7, medium if the FS ranges from 1.2 to 1.7, and high if the FS < 1.2.

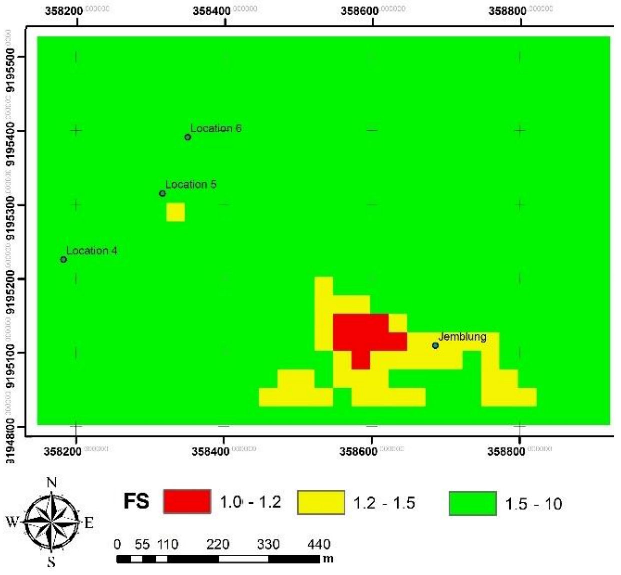

Fig. 5. Initial spatial safety factor of the slope.

In the Fig. 6, high hazard level is shown by red colour region, while medium and low hazard level is noticed by yellow and green colour areas. The figure shows clearly that high hazard area is gradually wider with the elapsed time of rainfall. The map shows that unstable area is initiated in the first three hours. After 24 hours precipitation, the hazards area majorly occurs at the steep slope, which the slope angle is greater than 30^o (see Fig. 7). The simulation result shows that the predicted landslide area (FS < 1.2) has been confirmed by field observation points in location 4, 5, 6, and Jemblung.

B. Discussion

Theoretically, in limit state equilibrium, a slope failure is defined if the factor of safety value is lesser than one (FS < 1) for the one or two-dimensional stability slopes, model. Some researchers apply this criterion for spatial analysis such as Baum et al. [4], Alvioli and Baum [5], Chen et al. [8], Alvioli et al. [11]. However, Ward et al. [9] state that erroneous determination of FS in spatial areas ranges from 20% to 30%, thus the high hazard area is determined for the FS < 1.2. At this condition, the probability of landslide (FS < 1) is approximately 60 percent and more. The results in Fig. 6 and 7 present the predicted time and location of landslides. Prediction of location and time of landslides using TRIGRS is subject to the limitation resulting from the interacting grid cell. Baum et al. [4] mentioned that the model results are sensitive to the physical properties and hydraulic soil layers, which it may vary and anisotropic in the model area. Saturated permeability controls the velocity of water flow. The velocity influences to debris flow and induce slope movement caused by water flow inside soil layer. Diffusivity impacts to water storage of soil. Soil capacity of pore water determines the maximum saturated of soil. If the soil moisture peaks, the soil becomes slurry and water will be routed as run off.

In the prediction of the time of landslides occurrence, there is some notice from Alvioli et al. [11]. The application of the physically-based model revealed the presence of both scaling properties of landslides, i.e., of the intensity of the driving forces (the mean rainfall intensity and the rainfall duration responsible for the slope instabilities) and the magnitude of the consequences (the relative proportion of landslides of different sizes). The result was obtained selecting reasonable values for the model parameters, without changing or optimizing them. This result indicates a functional link between rainfall and landslides and opens to the possibility to quantify the link. Muntohar et al. [12] found that the occurrence time of landslides is affected by rainfall pattern. A well predicted time of landslide needs a complete hourly precipitation record from the nearest rainfall measurement.

In this study, the model is validated through the back-analysis of a reference landslide event in Karangkobar area. In general, the model is useful for predicting the landslide potential, although there are few parts of the predicted high hazard area are not collapse yet, the soil movement still exists around the area. It was observed in the field [13] that a new slope failure took place a year after the disaster. A successful prediction was also summarized by Zhuang et al. [7].

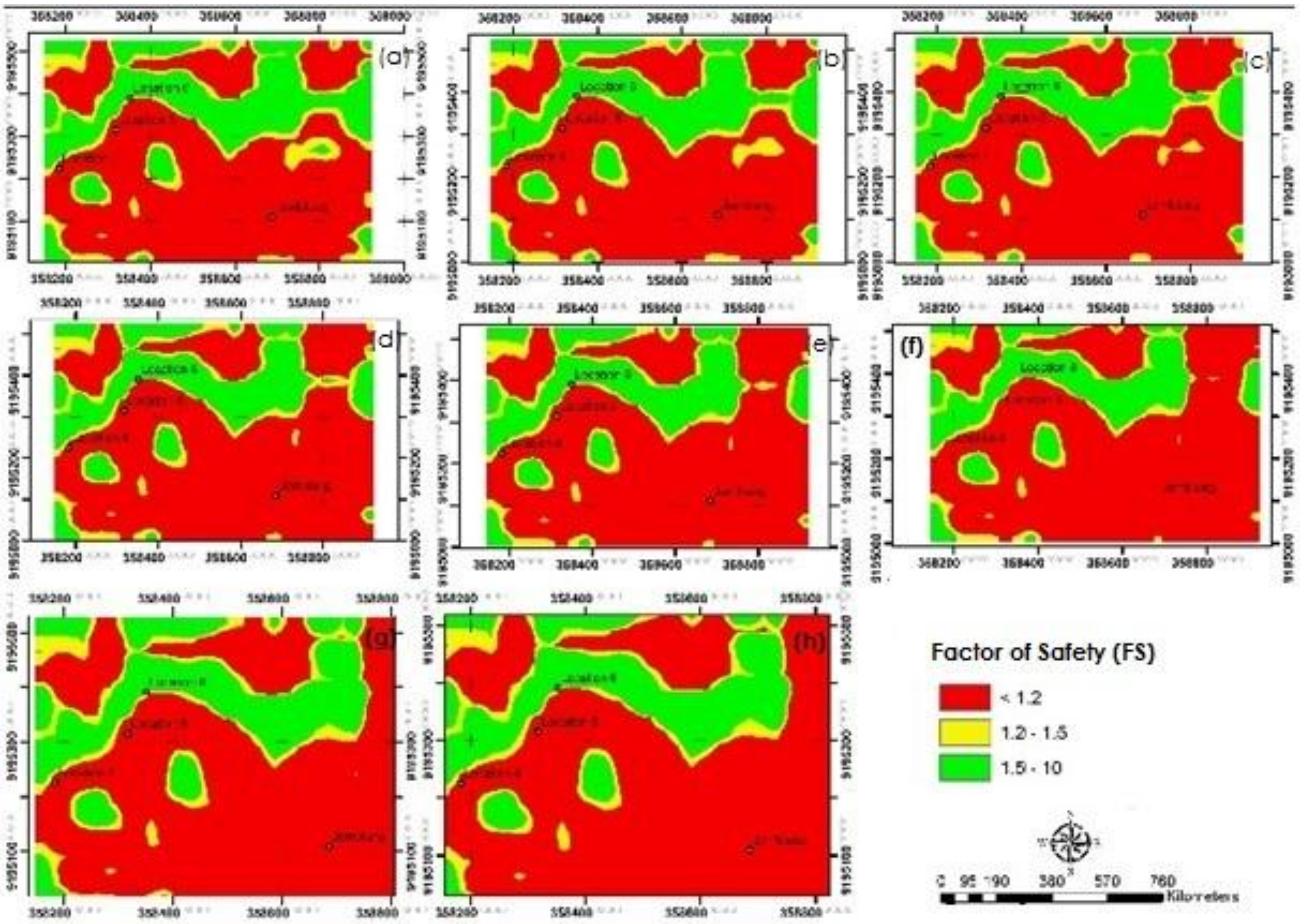

Fig. 6. Slope stability conditions, represented in terms of safety factor (SF), during the rainfall event according to the TRIGRS model (a) 3 hour, (b) 6 hour, (c) 9 hour, (d) 12 hour, (e) 15 hour, (f) 18 hour, (g) 21 hour, and (h) 24 hours of rainfall.

Comparison results showed that TRIGRS is more useful for landslide prediction for a certain precipitation threshold, also in the regional scale. Differences between the predicted landslide area and field observation can be contributed by the effect of vegetation cover and its roots in subsurface soil layer. Bordoni et al. [14] concluded that the role played by wine plant roots on soil reinforcement will be considered, allowing for the development of optimal prediction of slope instability area and agricultural management in practice.

V. CONCLUSIONS

The landslide triggered rainfall has been simulated using TRIGRS 2.0 for a mountainous area in Karangkobar sub-district, Banjarnegara district, Central Java. The physical based model describes the stability conditions of natural slopes in response to specific rainfall events. The model has been validated through the back analysis of a reference landslide event. The prediction shows that unstable area is initiated in the first three hours of rainfall. After 24 hours of rain, the hazards area majorly occurs at the steep slopes, which the slope angle is greater than 30o. At this area, the safety factor was simulated from 0.20 to 1.20. A higher elevation and steeper area have the lowest safety factor. The result of from TRIGRS was compared with observation at the study site, indicating that the modeling performed had a good lever of accuracy. Therefore, TRIGRS modeling to predict rainfall-induces spatial landslide can be developed as a predictable model for early warning.

NOMENCLATURE

c'	effective cohesion	kPa
d	steady-state depth water table	m
D_0	saturated hydraulic diffusivity	ms^{-1}
d_{LZ}	depth of impermeable boundary	m
I_{ZLT}	steady (initial) surface flux	ms^{-1}
K_S	saturated hydraulic conductivity	ms^{-1}
n^{th}	time interval infiltration	
S_S	specific storage	
t	time	s
z	positive downward	m
Z	vertical coordinate direction	m
δ	slope angle	degree
γ_s	soil unit weight	kNm^{-3}
γ_w	is water unit weight	kNm^{-3}
ϕ'	effective shear angle	degree
ψ	ground water pressure head	m

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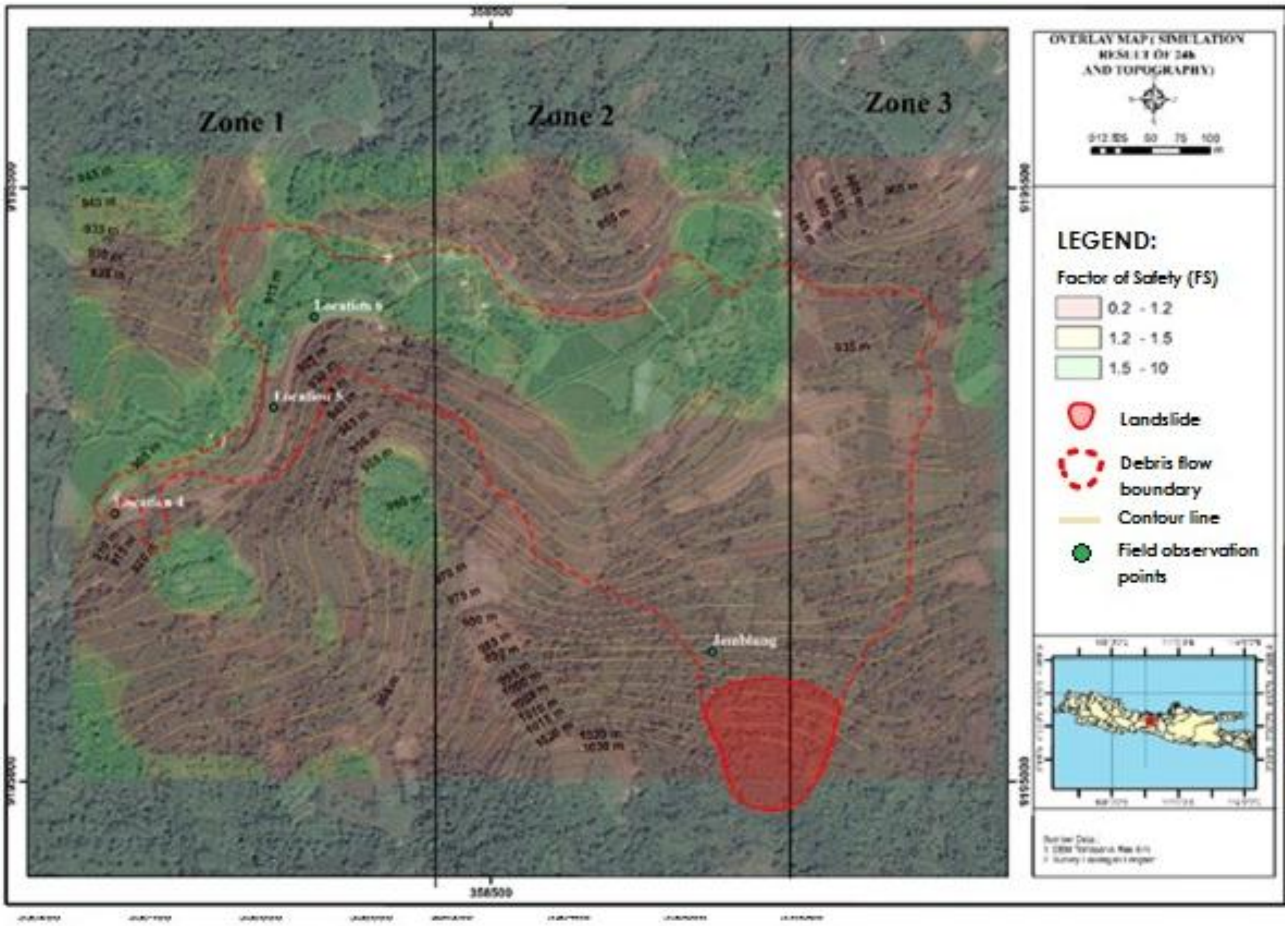

Fig. 7 Predicted slope failure potential from TRIGRS simulation and observed landslides location and debris boundary.

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