Rainfall threshold and soil moisture indexes for the initiation of landslide in Banjarmangu sub-district, central Java, Indonesia

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Abstract. Rainfall is an identified trigger of landslides, and researchers have long attempted to ensure the total precipitation that can trigger slope failures under different local climate condition, a problem of scientific interest. In this study, we propose new empirical rainfall thresholds combining with antecedent soil moisture indexes for analysing the initiation of landslides in Banjarmangu districts, located in Central Java. Daily rainfall and landslide information were obtained from Banjarnegara Geophysical Station and Regional Agency for Disaster Management (BPBD); evapotranspiration data were obtained from the United States Geological Survey (USGS). We plotted the mean rainfall intensity (mm per hour) and rainfall duration values in logarithmic function. For the results, we found that the increase of rainfall duration led the decrease of rainfall intensity defined by intensity-duration (ID) threshold \( I=43.2D^{0.87} \). In addition, we determine a formula for a cumulative rainfall threshold (CT), \( P_3=120.75-0.475P_{15} \), recognized by rainfall amounts (in mm) during the last 3 days and previous 15 days, was constructed from landslides historical data from 2011 to 2017. Both thresholds have to be used with the combination of soil moisture index for failure above 0 mm at positive pore pressure for developing a landslide warning.

1. Introduction
Banjarmangu districts in Central Java was recognized as a landslide-prone area [1] and was studied in previous research [2, 3]. Historical records showed that landslide disasters in Banjarmangu caused not only significant losses of property but also human life [4, 5]. Banjarmangu that has monsoonal type of rainfall, generally experienced a peak of rainy season in December or January [6]. High rainfall intensity was considered as one of landslide-trigger factors besides high slope, the presence of faults, geological conditions in several previous landslide disasters in this region [7]. Thus, rainfall-induced and Earthquake-induced landslides are the two types of landslide that possible to occur in this region.

Rainfall-induced landslides occur as a response to hydrological processes that come from the accumulation of precipitation for a specific period of time [8]. Heavy rainfall may introduces high force exerted by raindrops to the upper layer of soil that will increase the pore pressure[9]. The impact of precipitation in triggering landslides is difficult to quantify precisely because of the indirect impact on slope stability which generally also involves soil properties [10]. Determination of the rainfall threshold is necessary to help distinguish between rainfall-induced landslides and Earthquake-induced landslides. Nevertheless, rainfall threshold that can cause rain-
induced landslides is likely to vary at each location depending on the characteristics of the land and the topography [11].

Most commonly used rainfall threshold is the empirical intensity-duration threshold that first introduced in a study by Caine [10]. This empirical intensity-duration method developed later by Guzzetti et al. [12, 13] using minimum and normalised intensity-duration. Cumulative rainfall threshold also used in addition to the empirical intensity-duration threshold to assess the impact of accumulated rainfall 3-day to 15-day prior to the landslides occurrence [14, 15]. Although this method provides robust analysis in certain places, physical processes that potentially cause rainfall-induced landslide are hardly explained using intensity-duration threshold due to absence in soil-related variables in the model [16]. Soil-moisture model proposed by Crozier [17] is used in this study together with empirical intensity-duration threshold to overcome the absence in soil-related variables as suggested by Gabet et al. [16].

Past studies related to rainfall threshold to assess rainfall-induced landslides in Banjarmangu have been done, for instance, study done by Muntohar [18] that calculated rainfall threshold only based on intensity-duration and cumulative-intensity relationship without involving soil-related variables. This study aims to identify local empirical rainfall thresholds coupled with antecedent soil moisture indices as soil-related variables for analysing the initiation of landslides in Banjarmangu districts. Cumulative rainfall thresholds for 3 days and 15 days prior to the landslide occurrence are constructed from landslides historical data from 2011 to 2017. The result can be applied to the development of landslide early warning system to reduce damages and losses caused by future landslides in Banjarmangu.

2. Data and Methods

2.1 Study Site

In this study, Banjarmangu districts, Banjarnegara, East Java, Indonesia, was chosen as the study site. We assessed the rainfall thresholds and soil moisture indexes for the initiation of landslide around this site.

![Figure 1. Site location](image)

This area is an example of a populated highland that is extremely vulnerable to landslide which is mainly caused by rainfall. The worst landslide disaster occurred in Grumbul Gunung Raja, Sijeruk village, Banjarmangu district, in January 2006, in which more than 100 residents
were killed after being buried alive [4]. In addition, during a storm, heavy rain not only caused flooding but also initiate landslide at Clapar village, Banjarnegara on 27 March 2017 [19]. Banjarmangu sub-district is located on the Banjarnegara district on the middle Java. Parts of Banjarnegara barely exhibit higher rainfall than other locations in central Java, especially in the north and west. The area on the northern side of Banjarmangu is employed by high annual average precipitation approximately at 3500 – 4000 mm/year. In addition to arable land, forest and grassland grow in some areas.

2.2 Data Collection

The landslide historical dataset compiled for this study consists of information on 30 reported landslides that occurred in the study area during the period 2011–2017. It was obtained from the Regional Agency for Disaster Management (BPBD). All the landslide events in this dataset were triggered by rainfall. The collected information includes the landslides location and the amount of rainfall that triggered a landslide. Daily rainfall data from 2011 to 2017 has been collected from Banjarnegara geophysical station, Indonesia Agency for Meteorology, Climatology, and Geophysics (BMKG) branch, central Java. It was taken from a single rainfall station located at Banjarmangu sub-district. Furthermore, evapotranspiration data to calculate soil moisture indexes were obtained from the United States Geological Survey (USGS).

2.3 Determination of Rainfall Thresholds

In this study, empirically based model was applied to determine a threshold for the initiation of landslides. As the study area is a small district (46 km²), it can be classified as a local extent. Regional and local thresholds perform well in the location where the models were developed but cannot be easily applied to the other areas [20]. Empirically based rainfall thresholds can be analysed using rainfall data that triggering a landslide. Hourly rainfall data, which are derived from daily rainfall data (mm per hour), and the duration of the rainfall have been plotted using the logarithmic function of Intensity-Duration (ID). Then, the equation of Cumulative Rainfall Threshold (CT) as a threshold calculated from 3 days and 15 days before the 3 days’ period (in mm) has been reconstructed from historical landslide dataset. The ID thresholds have the general form:

\[ I = c + \alpha D^\beta \]  

where \( I \) is (mean) rainfall intensity, \( D \) is rainfall duration, and \( c, \alpha, \) and \( \beta \) are empirical parameters. Since the rainfall threshold is defined as an empirically based, the threshold equations are varying from one location to the other. We used local empirical equation models proposed from several scientists in various locations compiled by Guzzetti [12] to be plotted in a graph to compare the rainfall threshold in the study area and other local thresholds.

2.4 Determination of Soil Moisture Indexes

The soil moisture index is an important factor to constructs a hydrological model related to landslide event (including calculation for the interception of rainfall by vegetation) [17]. Groundwater system and soil moisture index that initiate a landslide event in this research are determined by two basic rules based on Crozier [17]: (i) positive pore pressures (one of the physical factors that triggering landslides) do not expand until the moisture exceeds the soil field capacity, and (ii) moisture in excess of field capacity is drained fast. The initial value of soil moisture index (\( M_0; \) mm) is a negative value of the soil field capacity (\( F_c; \) mm) at the end of the dry season. Furthermore, the soil moisture index is calculated as follow [16]:

\[ M_0 = -F_c \]
The effective rainfall that contributes water to the hillslope is calculated with

\[ R_t = P_t - I \]  \hspace{1cm} (3)

where \( R_t \) is effective rainfall at time \( t \), \( P_t \) is total daily rainfall (mm) at time \( t \) and \( I \) is intensity of rain (mm) intercepted by vegetation. Then, daily moisture values \( (M_t) \) are determined with

\[ M_t = M_{t-1} + R_t - D_t - E_t \] \hspace{1cm} (4)

where \( M_{t-1} \) is the previous day’s value of the moisture index, \( D_t \) is the drainage and \( E_t \) is the daily evapotranspiration (mm). The drainage \( (D_t) \) term is determined as

\[ D_t \begin{cases} \frac{k}{M_{t-1}} & \text{if } M_{t-1} \leq 0 \\ \frac{k}{M_{t-1}} & \text{if } M_{t-1} > 0 \end{cases} \] \hspace{1cm} (5)

where \( k \) is a dimensionless constant. The drainage is calculated for water that drains quickly from the soil after the field capacity has been exceeded.

3. Results and Discussion

3.1 Cumulative Rainfall Thresholds (CT) for Banjarmangu Area

We utilised the daily rainfall average, landslide history and local climate condition to define rainfall thresholds for the initiation of landslides as an impact threshold-based warning in the Banjarmangu site. We determined cumulative rainfall thresholds (CT) condition during landslides from 2011 to 2017 and we defined the formula based on the linear trend characteristic. As illustrated in figure 2, the formula of this CT threshold is \( P_3 = 120.7 - 0.475P_{15} \). The solid red line is a lower-bound threshold for the initiation of landslide when 15-day antecedent rainfall is lower than 200 mm. The solid dark green line is the proposed lower-bound threshold that possibly triggering landslide for the intensity of 15-day antecedent rainfall exceeding 200 mm.

![Figure 2](image_url)

**Figure 2.** Plot of cumulative 3-day and previous 15-day rainfall threshold (CT) associated with the newest additional rainfall history in 2018 period (filled red circles).
A level of antecedent rainfall before landslide occurred is required to predict landslide induced by rainfall. In this study, we determine cumulative 3-day and previous 15-day rainfall threshold (CT) based on the landslide history from 2011 to 2017 and compared with additional landslide phenomenon in 2018 as shown in figure 2. This CT was defined visually from the scatter plot by interpreting the lower-bound rainfall threshold under which rainfall-induced landslide phenomenon occur under certain conditions. The landslide activity that occurs only rarely were not included in this equation. For instance, the landslide phenomenon below solid dark green in figure 2A is included as rare condition because it is outside from the dominant landslide cluster. That a rare landslide occurred on 13 October 2018 at Sijenggung village, Banjarmangu and that phenomenon occurred when 3-day previous rainfall is 19.2 mm and 15-day rainfall condition during landslide is 455.9 mm.

As can be seen in figure 2, we define a lower-bound threshold formula into two parts i.e. when 15-day antecedent rainfall below 200 mm and for the intensity of 15-day antecedent rainfall exceeding 200 mm. Based on figure 2, an estimation for lower-bound cumulative threshold was explained by the formula \( P_3 = 120.75 - 0.475P_{15} \). For the 15-day antecedent rainfall below 200, the lower-bound threshold shows the decreasing 3-day rainfall shape over 15-day antecedent rainfall, taking a minimum value of previous 15-day rainfall from 57.9 mm to 494.8 mm. As demonstrated on that downward trend threshold, the cumulative 3-day rainfall presents its highest value of 3-days rainfall lower-bound threshold of 94.8 mm when 15-day cumulative rainfall exhibits value approximately at 57.9 mm. For the previous 15-day cumulative rainfall above 200 mm, we define the threshold of 3-day cumulative rainfall at 40 mm as a lower rainfall value that possibly to initiate landslide.

3.2 Rainfall Intensity Duration (ID) Threshold

30 landslides phenomenon, in this study, with the known date that obtained from Regional Agency for Disaster Management (BPBD) database have been checked for the amount of rainfall that occurred during and before the landslide events. We collected the daily rainfall data from the nearest rain gauge to landslide event from 2012-2016 at Banjarmangu districts. The rainfall event that triggered the landslide is considered as the cumulative amount of rain that fell during consecutive wet days directly during and before the landslide. In this study, the rainfall durations (D) are in the range of from 24 hours to 384 hours (16 days). Furthermore, the rainfall intensities are in the range of 0.5 mm/hours to 4.2 mm/hours.

![Figure 3](image-url)  
**Figure 3.** Rainfall intensity and duration threshold (ID) for Banjarmangu, Central Java, Indonesia
As demonstrated in figure 3, we plotted the rainfall intensities on the y-axis against rainfall duration on the y-axis. Furthermore, the threshold is drawn as a lower boundary line to the scatter plot. We define the threshold formula based on the lower-bound threshold line as a power function of $I=43.2D^{-0.87}$. As shown by the graph, the threshold line for mean rainfall intensity decreases sharply to approximately 1.2 mm per 24 hours period reaching down to 0.4 mm per hour in the 200 hours. It then decreases slightly and exceeds 0.2 mm/hour in 400 hours. After that, the downward trend starts to slow down until it starts to stabilize. Local rainfall intensity-duration (ID) thresholds from other local sites in the world obtained from Guzzetti et al. [12] are also plotted in a logarithmic coordinate in Figure 4, compared to the ID threshold for Banjarmangu area.

As illustrated in figure 4, the proposed ID thresholds extend a considerable range of rainfall durations and intensities. However, most of the thresholds cover the range of durations below 200 hours and the range of intensities from 1 to 100 mm per hour. All of the local ID thresholds exhibit a simple power formula showed by $c = 0$ at equation (1). For figure 4, all the listed power laws have a negative scaling exponent [12] where the threshold formula in this work at Banjarmangu employed the highest negative scaling exponent up to -0.87. The function of negative power law employs the decline rate of rainfall behaviour against duration that initiates slope failures. For $\alpha$ parameter, they exhibit the range from 1.7 to 85.58 [12].

![Figure 4. Rainfall intensity-duration (ID) thresholds in a logarithmic scale. Legend: The gray lines are other local ID thresholds obtained from Guzzetti et al. [12]; thick blue line employs local threshold for Banjarmangu; very thick black line shows local thresholds for Oregon area proposed by Montgomery et al. [21] that visually also seem to be fit for Banjarmangu; the solid red dots show Banjarmangu historical landslides.](image)

Analysis of figure 4 discloses that ID thresholds at Banjarmangu are slightly lower than other local thresholds in duration more than 100 hours. This interprets that, in general, ID thresholds at Banjarmangu predict the initiation of rainfall-induced landslides for a slightly lower average rainfall intensity for rainfall duration excess 100 hours than another local threshold. Generally, local thresholds are influenced by varied topography so that causes for more varied ranges of rainfall duration, especially when compared to the regional and global thresholds [12]. In this research, we attribute the observed rainfall in a geographical districts scale, which influences better rainfall sampling resolution compared to the regional or global scale that affected by regional averaging. Rainfall intensity adjuncts as the increasing of sampling resolution, resulting in more extreme – but more realistic – ID relationships that initiate landslides. Furthermore, for the local thresholds pattern, the threshold equation proposed by Montgomery et al. [21] also visually seem to be fit to be the threshold for the Banjarmangu in this study area although seems there are two observation point of rainfall average fall above the threshold in the duration of 24 hours.
3.3 Soil Moisture Index

We calculate soil moisture index based on equation (4) to estimate the antecedent rain that feel and exceeds soil regolith field capacity at Banjarmangu area. This moisture in excess of regolith capacity is quickly drained. This soil moisture index calculation for landslide model is coarse without any physical criterion. For instance, the drainage term overly facilitates the subsurface flow process and does not calculate for the impact of hillslope angle. In addition, we ignored the effect of bedrock topography on subsurface drainage convergence [22]. As a consequence, we assume that the highly weathered bedrock and the soil have similar hydrologic and hillslope properties. However, this soil moisture index can capture the essence of hillslope hydrology criterion although not details.

Figure 5. The instance of changes in the soil moisture index started from the end of dry season from 27 August 2016 to 30 September 2016 according to the model. Columns bar indicate daily rainfall and the red line represents soil moisture index (M). Positive pore pressures (above dashed line area) represent the soil moisture index exceeds the regolith field capacity. In this soil moisture model, we defined the interception = 2 mm/day, k = 0.9, and field capacity = 150 mm.

As is illustrated in figure 5, at the beginning of rain season, soil moisture index rises sharply between storms once field capacity is reached. In figure 5, When soil moisture index is in negative value, the moisture index exhibits slight reduction due to evapotranspiration (represented by small arrows). Furthermore, the sharp reduction events happened in the positive pore pressure, when moisture index exhibits positive value, as an impact of evapotranspiration and drainage (explained by large arrow in figure 5). In addition, this soil moisture index duplicates well the observation data that not always the cumulative rain that falls within the landslide area triggers a landslide. Landslide occurrences possibly happen if the pore pressure employing value exceeds 0 mm in this soil model.

During September 2016, based on the BPBD database information, there is one landslide occur in Banjarmangu area on 27 September 2016. This landslide occurrence can be detected in this soil moisture index at the positive pore pressure area. However, as showed in figure 5, there are some events in the end of September that exhibits positive pore pressure but there were no landslides. It is proved that this model cannot stand alone and need the use of both ID and CT thresholds for developing a landslide warning model.
4. Conclusions
This contribution explored the new rainfall threshold combined with the soil moisture model for detecting the initiation of landslide in the Banjarmangu area. We define the threshold formula based on the lower-bound threshold line as a power function of $I=43.2D^{-0.87}$. This formula represents that with increased rainfall duration, the rainfall intensity likely decreases linearly against time. Cumulative rainfall threshold also identified in this study as $P_{3}=103-0.29P_{15}$ in addition to the empirical intensity-duration threshold to assess the impact of accumulated rainfall 3-day to 15-day prior to the landslide occurrence. Furthermore, for developing a landslide warning, both thresholds have to be utilised with the use of soil moisture index for failure above 0 mm at positive pore pressure.

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