

Rainfall Thresholds Analysis for Early Warning of Landslides in The Bompon Watershed

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ABSTRACT

The transitional zone between the central and southern morphologies of Java is characterized by steep slopes and thick soil. On the other hand, high rainfall in the area poses a potential threat of landslide hazards. This research is conducted in the Bompon Watershed, located in the transitional zone between Mount Sumbing and the Menoreh Mountains. This study aims to examine the rainfall dynamics leading to landslides in the Bompon Watershed using rainfall threshold analysis. Intensity and duration are selected as parameters to establish the rainfall threshold model. The research findings indicate that long-duration rainfall is the dominant cause of landslides in the Bompon Watershed. High-intensity rainfall can trigger landslides when lasting for more than one day. The established rainfall threshold equation in the Bompon Watershed is $I = 263,29D^{-1,113}$, where I is intensity and D is duration. The effects of long-duration rainfall include raising the groundwater level, thereby increasing the slope load. The presence of clay in the Bompon Watershed can hinder proper rainwater infiltration. Poorly infiltrated water adds to the slope load and induces slope instability. The calculated rainfall threshold can serve as the basis for early landslide warning systems.

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1. INTRODUCTION

Landslide can divine by material movement down a slope (BNPB, 2012). Landslides can be caused by various factors, such as steep slopes, thick soil, and rainfall (Chen & Lan, 2021; Huang et al., 2022; Pamungkas & Sartohadi, 2018). As a tropical country, Indonesia has a high potential for landslide frequency due to extreme rainfall (Basofi et al., 2015). Events such as the Madden Julian Oscillation (MJO), Asian Monsoon, Tropical Cyclones, and other climatological phenomena can induce anomalies in high rainfall in Indonesia. Developing early warning systems based on rainfall that triggers landslides can be an effective method to mitigate the impacts of landslides.

The rainfall threshold represents the minimum and maximum rainfall limits that can trigger landslides (Setyo Muntohar, 2008). This threshold is utilized as the foundation for the development of early warning systems for landslides. The current value of the rainfall threshold is employed to represent the locally and regionally threshold. The regional application of the threshold introduces more significant uncertainty compared to its local counterpart. Non-linear variations in rainfall across extensive areas contribute to the precision advantage of using the rainfall threshold at a local scale.

Parameters such as intensity, duration, and presence of rainfall are frequently employed in establishing the rainfall threshold (Chikalamo et al., 2020). High-intensity rainfall can retrigger landslide activity (Purwaningsih et al., 2020).

Prolonged rainfall duration can lead to prolonged infiltration, inducing slope instability (Sun et al., 2022). Both intensity and duration of rainfall are crucial factors in the occurrence of landslides due to rainfall.

This research is situated in the Bompon Watershed, located in the transition zone between the Southern Mountains and Mount Sumbing. Being in a transitional zone result in the Bompon Watershed having a hill-shaped morphology with thick soil (Faozi Malik & Sartohadi, 2018). Rainfall in the Bompon Watershed can exceed 3000 mm/year, with extreme daily intensities reaching up to 50 mm/hour (Pratiwi et al., 2019). These conditions contribute to the high landslide hazard potential in the Bompon Watershed. This study aims to determine the rainfall threshold in the Bompon Watershed based on rainfall intensity and duration.

2. MATERIALS AND METHODS

2.1. Location and Data

Bompon Watershed was situated in the Central Java Province, Magelang Regency, encompassing the Salaman and Kajoran Sub-districts (Figure 1). The Bompon Watershed fell within the boundaries of 9 hamlets, namely Tubansari, Salakan Kwaderan, Salakan Wonogiri, Bompon, Sabrang, Ngemplak, Tuanan, Bleber, and Kalisari (Figure 2).

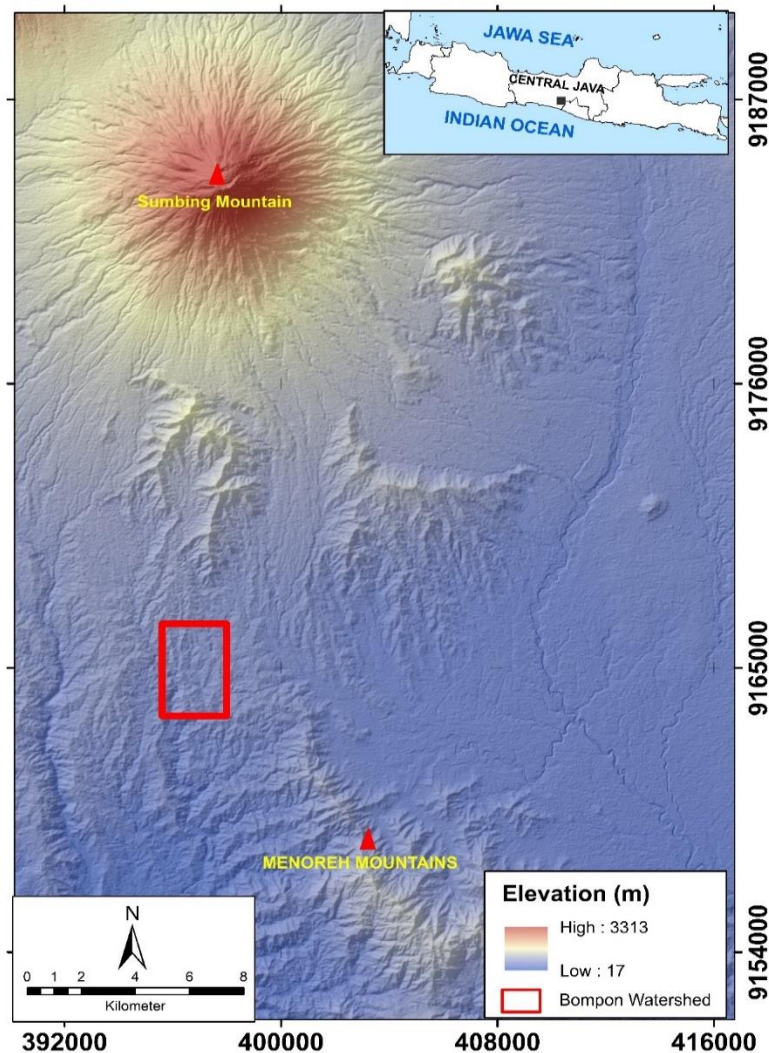


Figure 1. Location of the Bompon Watershed Area (red box)

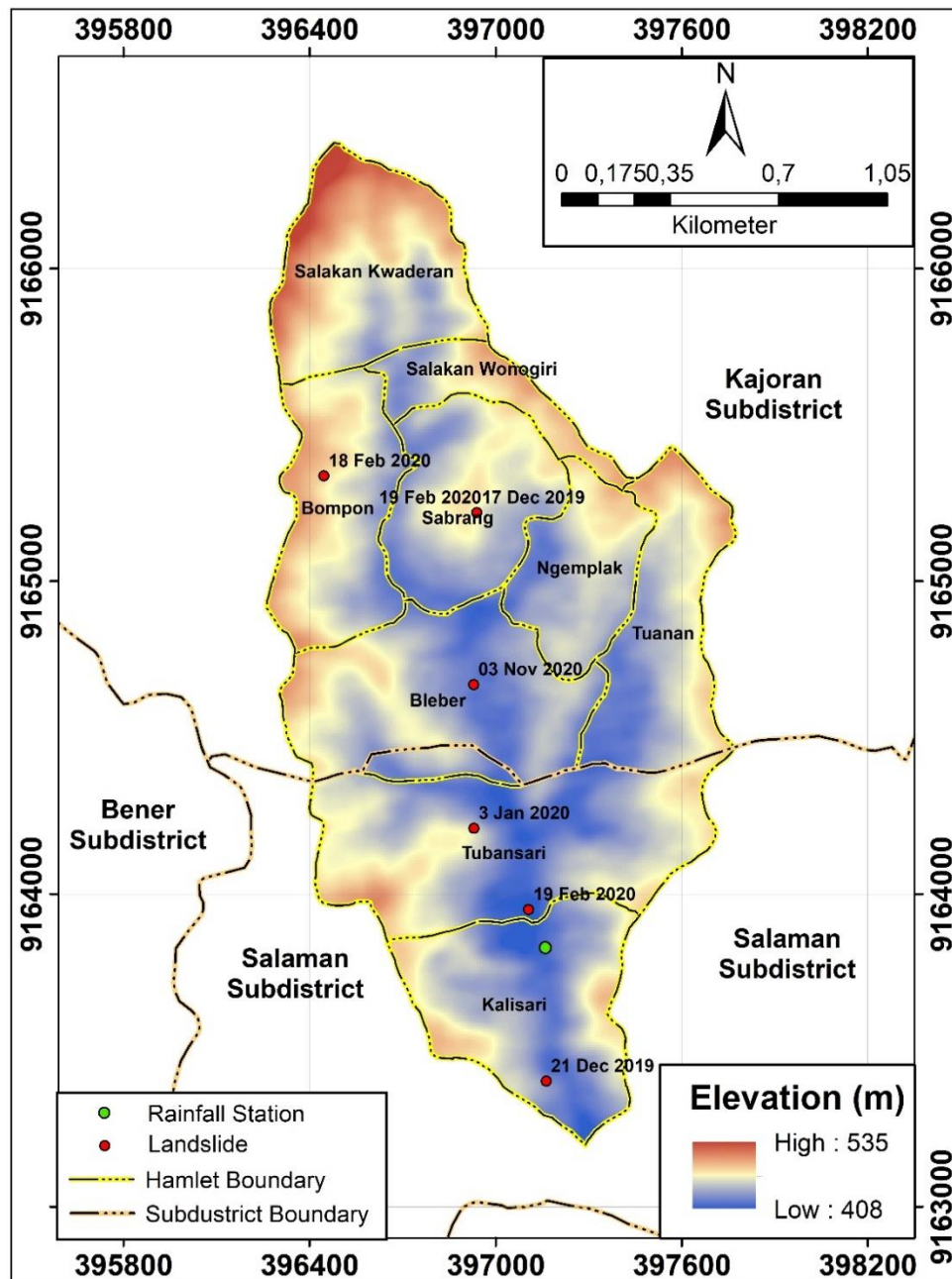


Figure 2. Locations of landslide 2018-2022 period and rainfall recording stations

Physiographically, the Bompon Watershed was positioned between the Central Java Physiography Zone, characterized by volcanic mountain alignments, and the Southern Java Physiography Zone, characterized by uplifted zones. Due to its location in the transitional zone, the Bompon Watershed receives a substantial supply of materials (Faozi Malik & Sartohadi, 2018). In addition to the abundant material supply from Mount Sumbing and the Southern Mountains, the Bompon Watershed was rich in clay minerals. The presence of clay in the Bompon Watershed originated from the hydrothermal alteration of andesitic breccia (Pratiwi et al., 2019). The existence of clay layers could act as potential slip surfaces for landslides (Sartohadi et al., 2018). Moreover, the water-absorbing yet non-permeable nature of clay could trigger slope instability.

The data utilized in this research was divided into two categories: rainfall recording data and landslide occurrence data. Rainfall recording data were obtained through direct rainfall measurements at the Kalisari rain gauge station (Figure 2). The daily rainfall depth was extracted as the recorded data value. Range of rainfall data recording utilized in establishing the rainfall threshold extended from February 2018 to September 2022. Historical landslide occurrence data were collected from two sources: field activities (2023) and information from the Regional Disaster Management Agency (BPBD) Magelang (2023). The landslide occurrence history includes details regarding the location points and timing of landslide events. There were a total of 7 landslide events in the Bompon Watershed between February 2018 and September 2022 (Figure 2).

2.2. Quality Control (QC) Data

Data checking, or Quality Control (QC), was conducted to determine whether there were any missing or irregularities in the rainfall data series. The rainfall data utilized in this study consists of a daily time series of rainfall depth from February 2018 to September 2022. Any missing data were filled using a moving average calculation according to Equation (1).

$$\text{the MA} = \frac{1}{N} \sum_{i=1}^N D_t \quad (1)$$

where D_t represents the time data at t , N is the prediction period, and MA is the prediction result or moving average. The moving average is a method to smooth, refine, and interpolate the data series (Akrami *et al.*, 2014).

2.3. Rainfall Threshold

The rainfall threshold was determined by calculating the correlation between the intensity and duration of rainfall that could lead to landslides. Daily rainfall thickness records were tabulated to determine the intensity and duration of rainfall. The durations and average daily rainfall intensities during landslide occurrences were categorized. This data was then computed using Equation (2), a power-law equation, to establish the rainfall threshold that triggers landslides.

$$I = \alpha D^\beta \quad (2)$$

where I is the daily rainfall intensity (mm/day), D is the duration of rainfall (days), α and β are constant obtained through determining the characteristics of the threshold.

3. RESULTS AND DISCUSSION

3.1. Rainfall Pattern in Bompon Waterhed

The rainy season for each period is calculated from November to April. The highest rainfall occurred during the 2018-2019 rainy season (Table 1). During this period, rainfall was influenced by the Madden Julian Oscillation (MJO) event that occurred at the end of 2018 (BMKG, 2018), and at the beginning of 2019, tropical cyclone seeds formed (BMKG, 2019). No landslides were recorded in the Bompon Watershed during this rainy season. The intensity and duration of rainfall in this period did not lead to landslides in the Bompon Watershed.

Table 1. Annual Rainfall Depth in Bompon Watershed

Year	Rainfall depth (mm/year)
2018-2019	2912,55
2019-2020	2082,60
2020-2021	1920,40
2021-2022	1900,30

Landslide events in the Bompon Watershed were concentrated during the rainy season of 2019-2020. There was one landslide occurrence during the 2020-2021 rainy season. The characteristics of rainfall intensity and duration during the 2019-2020 rainy season were identified as the cause of landslides in the Bompon Watershed. The rainy season during this period was influenced by the Asian Monsoon event (BMKG, 2019). The impact of the Asian Monsoon event increased rainfall from December 2019 to February 2020. During this period, the average monthly rainfall depth reached 430 mm per month, with the highest monthly rainfall depth occurring in February 2020 at 545.2 mm per month (Figure 3).

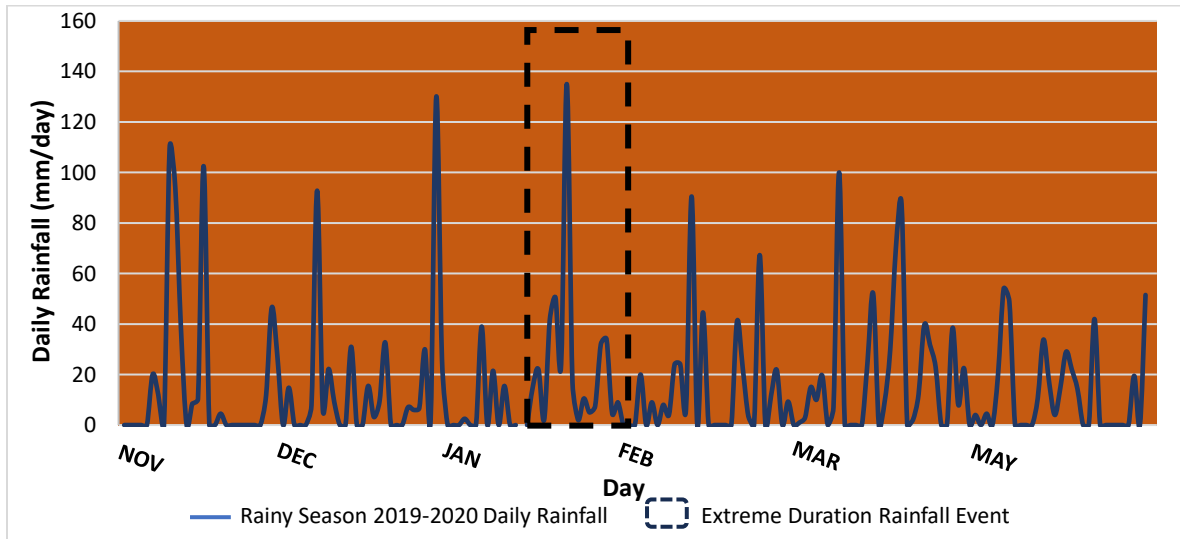


Figure 3. Daily rainfall during the 2018-2019 rainy season

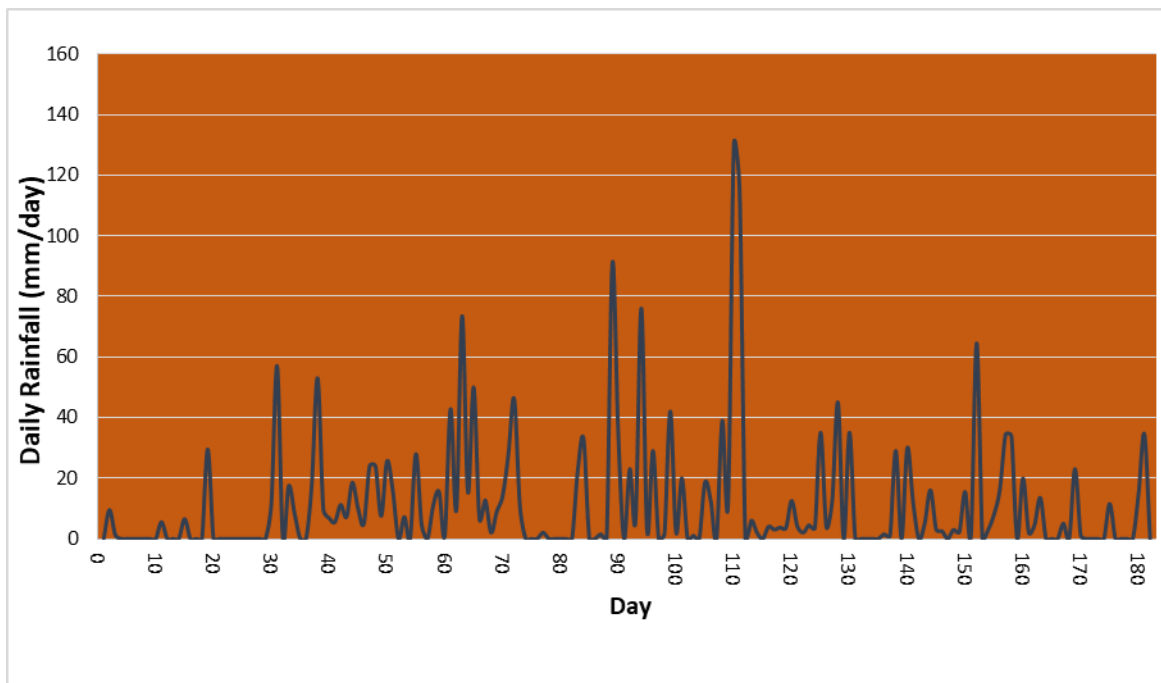


Figure 4. Daily rainfall during the 2019-2020 rainy season

Extreme rainfall during the 2018-2019 rainy season was compared to identify the characteristics of rainfall that led to landslides. Extreme events were distinguished based on the duration of rainfall lasting more than 10 consecutive days and daily rainfall intensity exceeding 100 mm/day. Extreme rainfall intensity occurred 5 times, and extreme rainfall duration occurred once during the 2018-2019 rainy season (Figure 3). Rain with extreme duration occurred for 16 days from January 12, 2019, to January 27, 2019. During this event, the average daily rainfall intensity was 25.72 mm/day, with the highest daily intensity reaching 50.5 mm/day on January 16, 2020. Rain with extreme intensity and duration during the 2018-2019 rainy season did not trigger landslides. Despite the occurrence of heavy rainfall with extreme intensity, landslides did not occur. This indicates that rainfall with intensity exceeding 100 mm/day, even if it occurs only for 1 day, does not induce landslides in the Bompon Watershed.

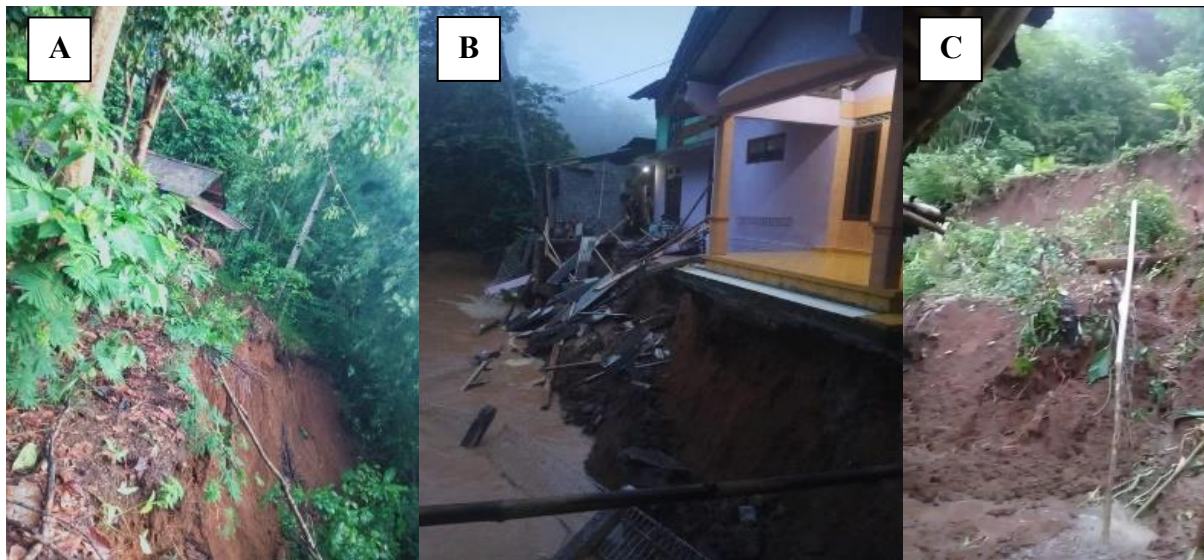


Figure 5. (A) Landslide on February 18, 2020, in Bompon Hamlet (396446.09, 9165336.99). (B) Landslide on February 19 in Sabrang Hamlet (396939.16, 9165219.61). (C) Landslide on February 19 in Tubansari Hamlet (397106.15, 9163950.28).

Rainfall with extreme intensity in the 2019-2020 rainy season occurred twice (Figure 4). This event occurred sequentially on 18 February 2020 until 19 February 2020. Intensity of rainfall on 18 February 2020 was 130 mm/day and on 19 February 2020 was 115 mm/day. As a result of these 2 extreme rainfall intensities, 3 landslides occurred. First landslide occurred on 18 February 2020 (figure 5), then was followed by two other landslides on 19 February 2020. The first landslide occurred after 3 consecutive days of rainfall with average daily intensity of 60,17 mm/day. As a result of this landslide, the road between hamlet in Bompon was closed. Two landslide that occurred on 19 February 2020 occurred in Tubansari and Sabrang. The landslides event occurred after 4 consecutive days of rainfall with an average daily intensity of 73,88 mm/day. The landslide in Tubansari affected resident's houses buried be landslide material (Figure 5) and landslide in Sabrang resulted the collapsing resident's house (Figure 5). The characteristics of rainfall with extreme intensity during the 2019-2020 rainy season differ from the 2018-2019 rainy season. Extreme rainfall intensity lasting for one day during the 2018-2019 rainy season did not result in landslides in the Bompon Watershed. However, extreme rainfall intensity lasting for more than one day during the 2019-2020 rainy season led to landslides in the Bompon Watershed. This indicates that extreme rainfall intensity capable of triggering landslides occurs when the duration of rainfall persists for at least 2 consecutive days.

In total, there were 3 incidents of extreme-duration rainfall during the 2019-2020 rainy season (Figure 4). The first incident of extreme-duration rainfall occurred for 15 days from December 7, 2019 to December 21, 2019. During this period, two landslide events occurred on the 11th and 15th days. On the 11th day, the landslide occurred with an average daily intensity of 15.33 mm/day, and on the 15th day, the landslide occurred due to rainfall with an average daily intensity of 16.12 mm/day. The second incident of

extreme-duration rainfall occurred for 16 days from December 18, 2019, to January 12, 2020. On the 7th day, a landslide occurred with an average daily intensity of 24.1 mm. The third incident of extreme-duration rainfall occurred for 13 days from February 24, 2020, to March 5, 2020. During this period, rainfall did not trigger landslides.

During the period of 2018-2020, rainfall with extreme intensity occurred more frequently than rainfall with extreme duration. The frequency of landslide events is equal when considering incidents of extreme rainfall duration and extreme rainfall intensity. Despite having the same frequency, landslides only occurred during extreme rainfall intensity events with a duration of 2 days. Therefore, rainfall with extreme intensity alone cannot trigger landslides in the Bompon Watershed. The duration of rainfall plays a crucial role in landslide occurrences (Sun et al., 2022). The determination of the rainfall threshold, considering both the duration and intensity, is calculated in the rainfall threshold graph.

3.2. Rainfall Threshold in the Bompon Watershed

The rainfall threshold in the Bompon Watershed is represented by the equation $I = 263,29D^{-1,113}$ (Figure 6) with coefficient determination (R^2) 0,7724 (Figure 6). The coefficient determination value 0,7724 classed in strong class (Chin W. Wynne, 1998). The value of coefficient determination shows that duration of rainfall (variable dependent) has an influence around 77% on the rainfall intensity (variable independent) which triggering landslides. On other hand comparison of the power graph and point from landslides data set do not in one line for rainfall low duration. It indicates that the result of graph does not follow the nature phenomena fully (Haryanto et al., 2021; Pinchuk & Kuzmin, 2019). It is reasonable because Other landslide trigger such as physical properties of soil, land cover, drainage can be a contributing factor of landslides (Murali & Katsumi, 2020; Setyo Muntohar, 2008).

When compared to the rainfall threshold in the surrounding areas, namely the Tinalah Watershed with the equation $I = 111,62D^{-0,779}$ (Arrisaldi et al., 2021) and in the Loano District (Purworejo) with the rainfall threshold equation $I = 92,679D^{-0,13}$, the empirical equation values for the rainfall threshold in the Bompon Watershed have a higher duration coefficient. This indicates that when rainfall lasts for less than 3 days, landslides in the Bompon Watershed will be triggered with higher rainfall intensity compared to the Tinalah Watershed and Loano District. In terms of duration, when compared to the Tinalah Watershed and Loano District, landslides in the Bompon Watershed will occur when rainfall persists for a longer duration but with lower intensity.

The effect of high-intensity rainfall is the reactivation of landslides on a slope. High-intensity rainfall results in surface runoff on the slope. Surface runoff on the slope can accelerate the erosion process, starting from channel erosion and eventually forming gullies (Almeida et al., 2021). Gully erosion is one of the processes that occur in the landslide body and can trigger the reactivation of landslides (Purwaningsih et al., 2020).

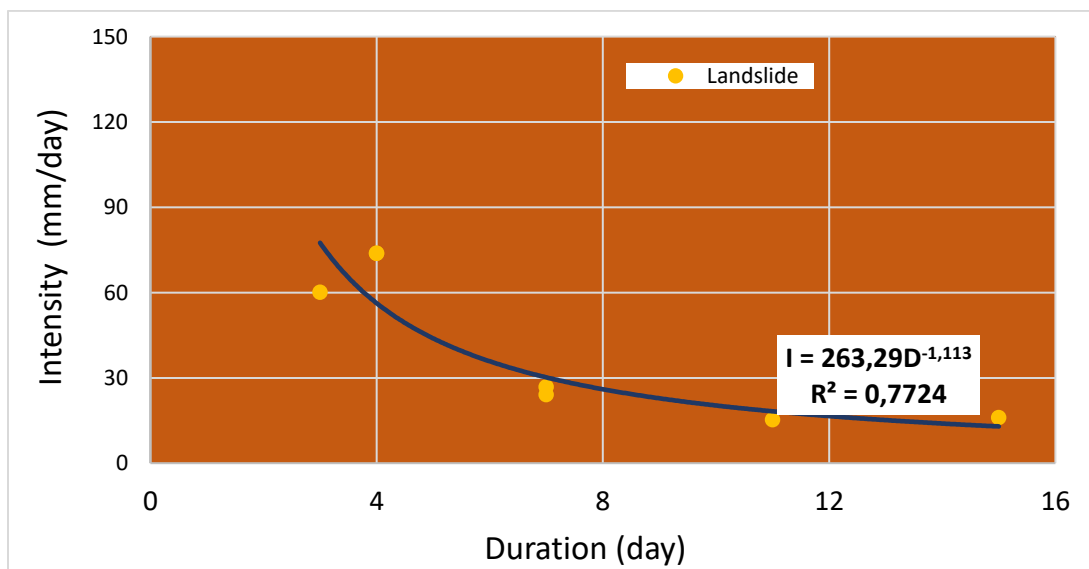


Figure 6. Bompon Watershed rainfall threshold graph

Long-duration rainfall raises the groundwater table, leading to slope instability (Guo et al., 2022). When prolonged rainfall occurs, water has sufficient time to infiltrate the soil. The water infiltrating the soil causes the groundwater table to rise. As the groundwater table approaches the slope's surface, it imposes a load that the slope cannot sustain, resulting in slope instability (Setyo Muntohar, 2008; Setyo Muntohar et al., 2013).

The Bompon Watershed has soil characteristics with clay layers (Yoesep, 2016). The occurrence of clay in Bompon was result of Breccia Andecite alteration (Pratiwi et al., 2019) can be the sliding surface of landslides (Sartohadi et al., 2018). The properties of clay, which absorb water and do not allow water to pass through, make the duration of rainfall a crucial factor in the landslide process. Long-duration rainfall is a distinctive precursor to landslides in the Bompon Watershed. Therefore, the threshold value for rainfall in the Bompon Watershed can be used as a reference in the development of early warning systems for landslides.

4. CONCLUSIONS

The characteristic of rainfall that triggers landslides in the Bompon Watershed is prolonged-duration rainfall. The rainfall threshold in the Bompon Watershed, represented by the empirical equation, is $I = 263,29 - 1,113$. characteristics of prolonged-duration rainfall contribute to slope instability in the Bompon Watershed. Rainfall with high intensity leads to the reactivation of landslides in the Bompon Watershed.

For future research, it is recommended to conduct more detailed mapping for landslide data inventory. The data from the BPBD only covers landslide events impacting settlements and not those occurring far from residential areas. Hazard modeling for landslides should be undertaken, involving parameters such as rainfall intensity or duration, to map areas at risk of landslides.

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