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Grid Satellite Rainfall Products Potential Application for Determining Rainfall Thresholds for Landslide Occurrences over Bali Island

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A B S T R A C T

Grid Satellite Rainfall Products (GSRPs) present rainfall data on global spatial coverage and different temporal resolution have the potential to identify rainfall conditions for landslide occurrences because the rain gauge observations need to maintain, the coverage observation is not widespread enough, and limited in the mountain area. The current study represents the potential application of Global Satellite Mapping of Precipitation (GSMaP), the Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG), and Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) in determining the mean rainfall intensity-duration (I-D) and cumulated rainfall-duration (E-D) thresholds for landslide occurrences on Bali Island. The power-law method was used to represent the I-D and E-D thresholds. The result shows that I-D and E-D thresholds established by GSRPs are generally lower than the threshold defined by rain gauge observation. Among the three GSRPs, IMERG is performing the best to determine the rainfall threshold for landslide occurrences. The GSRPs be allowed to be an essential additional data source that potentially to be used to establish a regional early warning system for landslide occurrence.

1. Introduction

The landslide triggered by rainfall is a popular natural hazard regularly occurring around the world with serious impacts on property losses, fatalities, and environmental damages [1] [2]. Conforming to the World Health Organization in the range from 1998-2017, landslides have an impact on approximately 4.8 million population and cause more than 18 thousand mortalities [3]. The occurrences of landslides primarily provoked by rainfall infiltration are associated with rainfall duration, cumulative rainfall, and antecedent rainfall causing a rise in the soil pore pressure so that the shear stress of the soil decreases [4][5]. This is the main factor in the occurrence of landslides. To mitigate landslide hazard risk, early warning systems for the forecast of landslide-triggering rainfall were established at global and regional scales derived from different procedures and input raw data [6][7]. The prediction of rainfall-generated landslides calculates on physical or empirical approaches [8][9][10].

The physical approach can forecast the failures by examining the terrain information, soil formation, and environmental condition of the study region. Whereas in the empirical method, to evaluate the possibility of landslide occurrences is determined by analyzing previous rainfall events that resulted in landslides. Recently, empirical rainfall thresholds have been used to establish the early warning system of landslide occurrences on a global and regional scale [6]. The rainfall thresholds are categorized into three parts: (i) mean rainfall intensity-duration (I-D), (ii) cumulative rainfall-duration (E-D), and (iii) cumulative -mean intensity rainfall (E-I) [4][8]. The frequent rainfall thresholds used on a global and regional scale are the I-D and E-D thresholds [11]. Hence, the I-D and E-D thresholds are chosen in the current study.

The accuracy of I-D and E-D thresholds is highly dependent on the quality of rainfall data as a primary input [12]. Reliable rainfall data used to define rainfall thresholds are obtained from rain gauge measurements. However, the spatial coverage of rain gauge stations which are very rare in remote areas and high terrain is a major issue in their use to develop rainfall thresholds for landslide occurrences. Recently, remote sensing platforms are capable to present global grid satellite rainfall products (GSRPs) at high spatial and temporal resolution. Various SPDs are accessible for their different retrieval algorithm, coverage areas (global or regional), spatiotemporal resolution, and utilized sensor instruments (visible, infrared, passive microwave, and combinations). GSRPs have the potential to be used to determine rainfall thresholds for landslide occurrences because it provides global rainfall estimates over remote areas, and complex topography, and have a high temporal resolution [13][14].

The first potential GSRPs used to obtain the framework of global rainfall intensity-duration threshold for global landslide occurrences was the use of the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) datasets [15]. The first framework was upgraded by [16], who emphasize several issues in the original derivation because of the susceptibility map spatial resolution and the need to re-analyze the I-D threshold for a finer assessing regional climatology. A further study was achieved by [17] who used the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks

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(PERSIANN) to establish the global landslide forecast model. Moreover, [18] determined I-D thresholds from the TRMM dataset over the Garhwal Himalaya region in India. Afterward, [18] analyze the accumulative rainfall probability for landslide occurrences using a grid rainfall dataset from the global Hydro-Estimator of the National Oceanic and Atmospheric Administration (NOAA). In [19] compare the E-D threshold between rain gauge with TMPA and Climate Prediction Center morphing technique (CMORPH) datasets for debris flow occurrences in eastern Italian. Furthermore, [12] assess the performance of TMPA, PERSIANN, CMORPH, and Soil Moisture TO RAIN-Advanced SCATterometer (SM2RASC) datasets to determine the E-D threshold for landslide events over Italy. More currently, [11] used CMORPH to calculate the E-D threshold over the whole of China. The previous studies highly emphasize the potential of GSRPs in determining rainfall threshold. However, the past studies only derived I-D and E-D separately so that in the current study will analyze both I-D and E-D thresholds by using IMERG, GSMaP, and PERSIANN.

Bali Island which is bordered by the sea has a complex terrain, where the border is a beach or flat area while the center part has a higher terrain with several mountains and hills [13]. Based on the National Disaster Management Agency of Indonesia, Bali is one of the provinces in Indonesia that has a high risk of natural disaster vulnerability. Landslide events are frequently occurring in Bali. The number of landslides in Bali took the first position in 2017-2019 compared to other natural disasters (floods, earthquakes, volcanic eruptions, and strong winds) based on data from the Regional Disaster Management Agency of Bali Province. Therefore, it is important to develop the rainfall thresholds for landslide occurrences in Bali Island by using satellite-based rainfall datasets because the coverage of rain gauge stations in Bali Island is not widespread enough and is limited in the high terrain areas. Based on our knowledge, there are no previous studies in determining the rainfall threshold for landslide events using either rain gauge data or GSRPs over Bali Island. The main contribution in the current study is the development of the mean rainfall intensity-duration (I-D) and cumulated rainfall-duration (E-D) thresholds for landslide occurrences over Bali Island by using the different spatial-temporal resolution of GSRPs (IMERG, GSMaP, and PERSIANN).

2. Research Method

2.1. Area of study

Bali is a province of Indonesia, and it is located to the east of Java and the west of Lombok Island. Geographically, it is situated 8° south of the equator. Bali measures approximately 140 km by 80 km and has a total area of 5620 km^2 (**Figure 1**). Bali Island is

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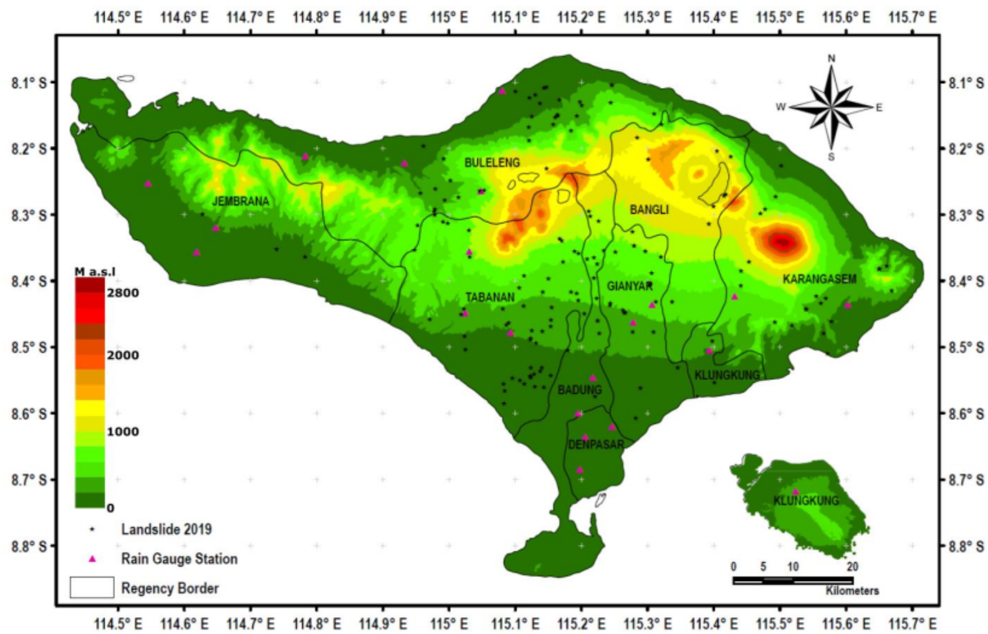
extremely susceptible to landslides because of its complex topography and frequent heavy rainfall. Rainfall in Bali is classified as monsoonal. Bali experiences a wet season from November until April and a dry season from May to October; this is the same seasonal pattern as in Indonesia in general [20]. Based on the 2015–2017 rain gauge data from Balai Wilayah Sungai Bali-Penida (BWSBP), the average rainfall in Bali was determined to be approximately 180 mm/month; the highest rainfall occurs from December to February, whereas the lowest rainfall occurs from July to August [13].



Source: Author's Compiles (ArcGIS, 2022).

Figure 1. Elevation Map of Bali and Landslide Events Position

2.2. Landslide data

The landslide events data is obtained from the Regional Disaster Management Agency of 8 regencies over Bali province. In this study, collected 66 landslide events were triggered by rainfall in 2019. For each landslide, the corresponding information includes the location (village or site) and the occurrence time (hour or date). The latitude and longitude of the landslide events were acquired by field surveying. **Figure 1** shows the locations of landslide events and elevation distribution in Bali.

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2.3. Rainfall data

Two kinds of rainfall datasets were used to determine the rainfall thresholds: (i) rain gauge observations and (ii) grid satellite rainfall products (IMERG, GSMaP, and PERSIANN). The hourly rain gauge data were obtained from the BWSBP Ministry of Public Works and Human Settlements of Indonesia. They only can provide 18 hourly rain gauge observation data for the completion in 2019. Since rain gauges are not always located close to landslide sites, we selected the nearest rain gauges for each landslide event's location.

The IMERG dataset is an improvement of TRMM-TMPA that was later published and data available in global coverage from June 2000 to the present. Its algorithm is inter calibrations of all available satellite microwave precipitation measurements, microwave-calibrated infrared measurements, surface rain gauge analyses, and other possible rainfall estimates at high temporal and spatial scales over the entire quasi-global [21]. The present study used the latest Level-3 IMERG half-hourly and 0.1° spatial resolution data from version-06B of the final run dataset. The IMERG dataset is available online at https://gpm.nasa.gov/data/directory.

The GSMaP is a satellite rainfall dataset built by the Core Research for Evolutional Science and Technology (CREST) program under the authority of the Japan Science and Technology Agency from 2002 to 2007, and the program was extended by the Japan Aerospace Exploration Agency (JAXA) [22][23]. The GSMaP algorithm combines passive microwave sensors and infrared sensors to get high precision precipitation dataset [22][23][24]. The GSMaP_Gauge version 7 was used in the present study with the hourly temporal resolution, 0.1° spatial resolution, and can be accessed from the JAXA website (ftp://rainmap:Niskur+1404@hokusai.eorc.jaxa.jp/standard/v7/hourly_G/).

The PERSIANN was established by the Center for Hydrometeorology and Remote Sensing at the University of California Irvine in association with the National Aeronautics and Space Administration (NASA), NOAA, and the United Nations Educational, Scientific and Cultural Organization (UNESCO) program for the Global Network on Water and Development Information for Arid Lands (G-WADI). PERSIANN retrieval algorithm rainfall estimates based on infrared imagery by an artificial neural network method [14]. In this study, the PERSIANN-CCS dataset with 0.04° spatial resolution and hourly time resolution was used, this dataset is available online at https://chrsdata.eng.uci.edu/.

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2.4. Methods

A frequently used equation form of rainfall thresholds for landslide occurrences is the power-law relationship, defined as [4][25]:

$$I = \alpha \cdot D^{-\beta}$$

$$E = \alpha \cdot D^{\beta}$$

With:

I = the rainfall mean intensity (mm/hour)

E = the rainfall accumulation (mm)

D = the duration of the triggering event (hour)

α = the scaling factor

β = the shape/slope parameters

Based on the above formulation, this study used the frequentist estimation method proposed by [9] to estimate the I-D and E-D thresholds for all rainfall datasets. The rainfall thresholds, in the present study, are estimated at a 5%, 10%, 20%, 30%, 40%, and 50% exceedance level, which means that the probability of a landslide due to rainfall events not exceeding the rainfall thresholds is less than 5%, 10%, 20%, 30%, 40%, and 50%.

The preprocessing of rainfall datasets for the identification of landslides triggering rainfall events involved two main steps. First, landslide locations available from the catalog were spatially matched to satellite pixels and rain gauges. For the GSRPs, the pixel covering the landslide initiation point was considered while for the rain gauges, the single nearest neighbor to the location of the landslide was considered, following what is commonly done in gauge-based landslide-triggering rainfall estimation [26]. Second, the time series extracted for each gauge/pixel were processed to identify and separate the rainfall events that triggered the landslide events. Events covering the date of occurrence of the landslide were considered and a 24-hour no-rain threshold was used as the minimum interevent duration [19]. Several past studies obtained 7 days of antecedent rainfall as an essential factor for initiating landslide occurrences [27][28]. Hence, the present study further analyzed rainfall total for 7 days (168 hours) before the start of rainfall events that initiated landslide occurrences.

3. Results and Discussions

The I-D and E-D threshold were inferred from the rain gauge, IMERG, GSMaP, and PERSIANN datasets by using the landslide occurrences during 2019 in Bali Island.

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3.1 Rainfall event conditions

Table 1 shows the mean intensity, rainfall duration, cumulative rainfall, and antecedent rainfall to trigger the landslide occurrences. Mean rainfall intensity for rain gauge ranged from 0.41 to 6.68 mm/h with an average of 2.16 mm/h, IMERG ranged from 0.20 to 2.66 mm/h with an average of 1.12 mm/h, GSMaP ranged from 0.12 to 2.12 mm/h with an average of 0.66 mm/h, and PERSIANN ranged from 0.31 to 4.83 mm/h with an average of 1.08 mm/h. The minimum rainfall duration triggers landslides of rain gauge and PERSIANN is equal, while IMERG and GSMaP are more longers. The average rainfall duration of all GSRPs was confirmed higher with rain gauge observation. The maximum cumulative and antecedent rainfall of the rain gauge shows the highest compared to all satellite rainfall datasets.

Table 1. Rainfall events conditions

Dataset	Rainfall condition	Mean Intensity (mm/h)	Duration (h)	Cumulative rainfall (mm)	Antecedent rainfall (mm)
Rain Gauge	Average	2.16	64.73	105.80	36.63
	Max.	6.68	339.00	334.30	309.50
	Min.	0.41	2.00	5.60	0.00
IMERG	Average	1.12	132.58	116.26	44.42
	Max.	2.66	341.00	268.95	126.04
	Min.	0.20	6.00	5.97	0.00
GSMaP	Average	0.66	128.20	77.64	53.85
	Max.	2.12	347.00	244.36	136.76
	Min.	0.12	5.00	3.68	0.00
PERSIANN	Average	1.08	114.05	102.24	65.65
	Max.	4.83	326.00	317.00	182.00
	Min.	0.31	2.00	3.00	0.00

Source: Author's Analysis

Figure 2 reports the box plots of the rainfall duration (**Figure 2a**), the mean rainfall intensity (**Figure 2b**), the cumulative rainfall (**Figure 2c**), and the antecedent rainfall (**Figure 2d**) calculated using the rain gauge and GSRPs responsible for the landslide occurrences. Inspection of **Figure 2a** reveals that the GSRP's rainfall duration has long duration compared with the rain gauge duration. **Figure 2b** shows that all satellite datasets generally underestimate the mean rainfall intensity that induces landslides measured by the rain gauge. From **Figure 2c** the cumulative rainfall for PERSIANN is comparable to that of a rain gauge, while IMERG and GSMaP show overestimate and underestimate, respectively. All satellite rainfall datasets depict an overestimated antecedent rainfall (**Figure 2d**). This indicates that cumulative and antecedent rainfall is a dominant influence on the occurrence of landslides [5][27].

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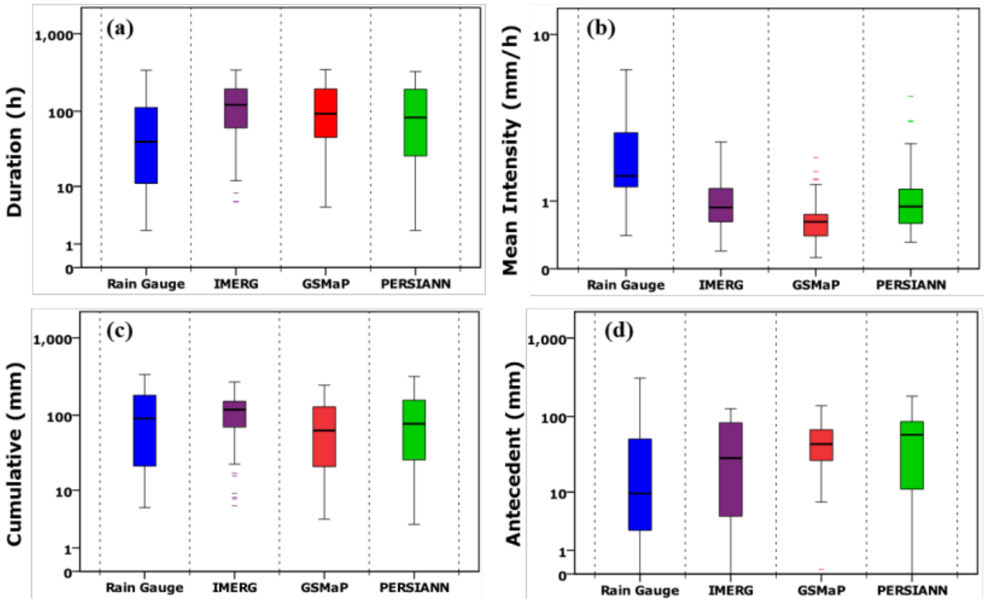

Source: Author's Analysis

Figure 2. Box Plots of Rainfall Condition: (a) Duration, (b) Mean Rainfall Intensity, (c) cumulative rainfall, and (d) Antecedent Rainfall

3.2 Rainfall thresholds

Figure 3 displays the I-D threshold at exceeding probabilities from 5% (T5%) to 50% (T50%) for the rain gauge (**Figure 3a**), IMERG (**Figure 3b**), GSMaP (**Figure 3c**), and PERSIANN (**Figure 3d**) datasets. The probability of every I-D threshold represents the potentiality of landslides when rainfall above the I-D curve happens. As presented in **Figure 3**, the I-D threshold of the GSMaP dataset is lower than other datasets. The IMERG threshold is relatively close to the I-D threshold determined by the rain gauge dataset, this might be due to the highest temporal resolution of the IMERG dataset. The accumulated half-hourly rainfall may produce a noteworthy overestimation of the rainfall needed to induce the landslide [12]. The slope of the PERSIANN demonstrated relatively similar to the rain gauge observation, this is might due to the highest spatial resolution of the PERSIANN dataset.

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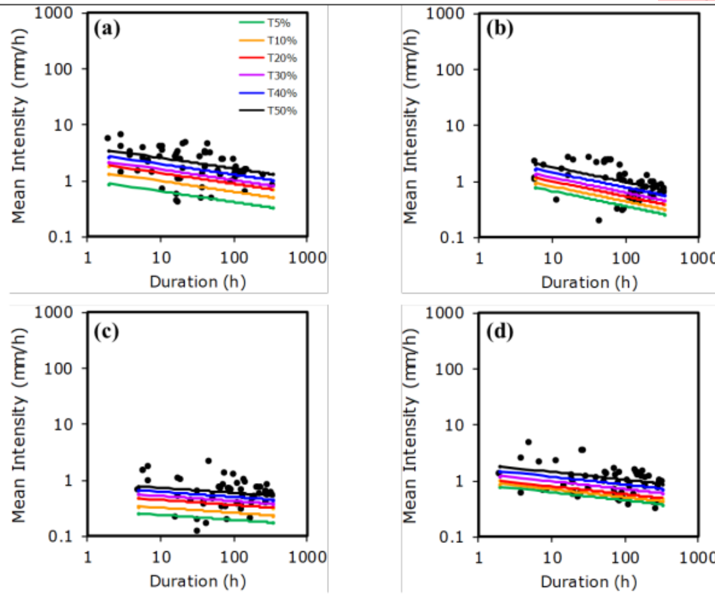
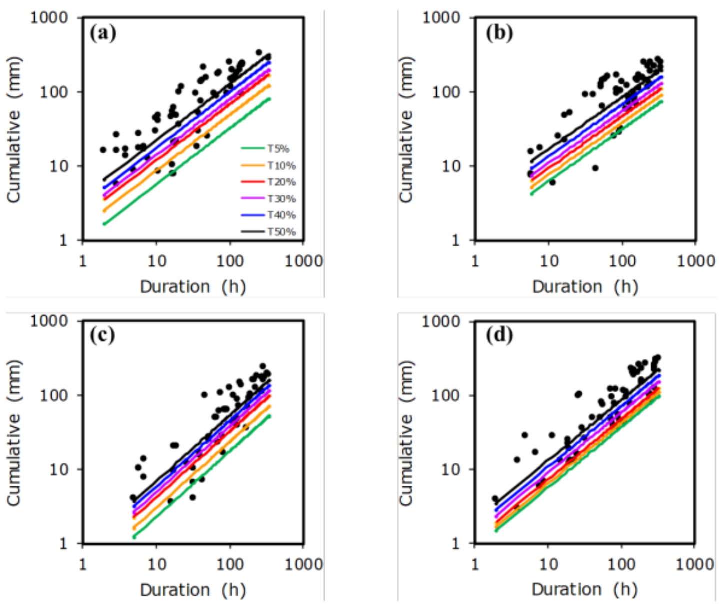


Source: Author's Analysis.

Figure 3. (a) I-D thresholds for the rain gauge. (b) I-D thresholds for IMERG. (c) I-D thresholds for GSMaP. (d) I-D thresholds for PERSIANN



Source: Author's Analysis.

Figure 4. (a) E-D thresholds for the rain gauge. (b) E-D thresholds for IMERG. (c) E-D thresholds for GSMaP. (d) E-D thresholds for PERSIANN

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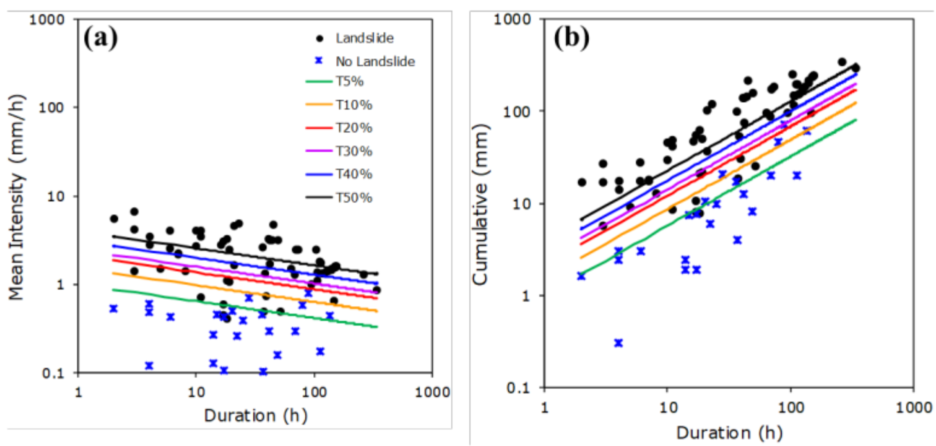
The E-D threshold at exceeding probabilities from 5% to 50% for the rain gauge, IMERG, GSMaP, and PERSIANN datasets are shown in **Figure 4a**, **Figure 4b**, **Figure 4c**, and **Figure 4d**, respectively. The slope of the E-D threshold of all GSRPs is comparable to that of a rain gauge, while the E-D thresholds of the three GSRPs tend to be lower compared to the rain gauge observation.

3.3 Verification and prediction accuracy

The verification of landslide and no landslide occurrences for I-D and E-D thresholds at different exceeding probabilities are shown in **Figure** **5a** and **Figure** **5b**, respectively. Most of the landslide events occur above the I-D and E-D lines for a probability of 20% (red line in **Figure 5a** and **Figure 5b**).



Source: Author's Analysis.

Figure 5. (a) Verification landslide and no landslide for I-D threshold. (b) Verification landslide and no landslide for E-D threshold

The I-D and E-D thresholds equation derived from the rain gauge and GSRPs over Bali Island is tabulated in **Table 2**. **Table 2** also despite the relative differences of the threshold parameters in estimating mean rainfall intensity, cumulative rainfall, and rainfall duration. The differences between the GSRP's threshold parameters from the rain gauge threshold parameters are within 75%, with some datasets showing differences lower than 10%. All GSRPs underestimate the intercept parameter (α), while for the slope parameter (β) the IMERG dataset

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overestimates the I-D thresholds. The slope parameter of the E-D thresholds indicates that the IMERG underestimates, while both GSMaP and PERSIANN overestimate. Among the three GSRPs, IMERG has the lowest relative deviation of α compared with other datasets. PERSIANN dataset exhibited better accuracy of β in the I-D threshold, while IMERG demonstrated better performance in the E-D threshold.

Table 2. Rainfall threshold equation and relative differences of intercept and slope parameters to the rain gauge

Threshold	Dataset	Equation	The relative deviation of α (%)	The relative deviation of β (%)
I-D	Rain Gauge	I=2.126D-0.191	0.00	0.00
	IMERG	I=1.860D-0.269	-15.94	40.84
	GSMaP	I=0.551D-0.091	-75.10	-52.36
	PERSIANN	I=1.108D-0.141	-49.92	-26.18
E-D	Rain Gauge	E=2.126D0.753	0.00	0.00
	IMERG	E=1.860D0.701	-15.94	-6.91
	GSMaP	E=0.551D0.886	-75.10	17.66
	PERSIANN	E=1.108D0.817	-49.92	8.50

Source: Author's Analysis

3.4 Comparison of rainfall thresholds

The I-D thresholds comparison with other regions of the world is shown in **Figure 6a** by [8], [29], and [30] have developed the world's I-D threshold for landslides with symbols in the form of dots, dash lines, and long dash lines, respectively. Furthermore, [31] and [32] established regional I-D thresholds in Taiwan (dash-dot lines) and Japan (dash double-dot lines), respectively. The I-D threshold calculated based on four rainfall datasets in the current study for the whole of Bali Island is lower than the I-D threshold in past studies, including the world thresholds [29][30], and the regional threshold in Taiwan [31], but higher than the world's I-D threshold was determined by [8]. The slope of the I-D threshold curve established in this study is similar to the slope examined in Japan by [32] but quite different from the slope revealed in [8], [29], [30], [31]. Among of three GSRPs, the IMERG dataset demonstrated the closest I-D threshold to the rainfall threshold set by [32] in Japan.

The E-D threshold curves are incomparable with other areas around the world as expressed in **Figure 6b**. In [29] and [33] established the world's E-D threshold for landslides as shown in **Figure 6b** with symbols in the form of dots and dash lines, respectively. Additionally, [12] and Brunetti et al. (2018) and [11] developed regional E-D thresholds over Italy (dash-dot lines) and China (dash double-dot lines), respectively. Comparing the present E-D threshold with other regions of the world displays that the E-D threshold for Bail Island is relatively close to the threshold for the world and Italy, but higher than the E-D threshold for

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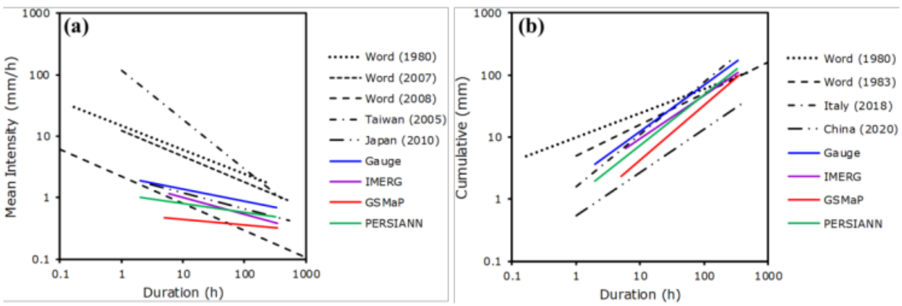
China. The slope of the E-D threshold developed in the current study is relatively similar to the slope calculated in Italy and China, but slightly different from the E-D threshold reported by [29] and [33]. Comparison of the I-D and E-D thresholds in this study with previous studies shows that the E-D threshold can reduce the uncertainty in satellite-based rainfall products, this indicates a high possibility of using the satellite rainfall datasets to establish the E-D thresholds.



Source: Author's Analysis.

Figure 6. Comparison rainfall thresholds with the past studies: (a) I-D thresholds, (b) E-D thresholds

4. Conclusion

The major advances in satellite remote sensing precipitation estimation over the last few decades has to lead the availability of various GSRPs with different coverage areas and space-time resolution. However, some previous assessment studies have demonstrated that GSRPs can be correlated with several errors [34], but they present the rainfall information on a global scale that is a possibility to use for assessing high-impact weather and natural disaster monitoring, such as landslides and flood monitoring. The intercomparison of three GSRPs (IMERG, GSMaP, and PERSIANN) to address the I-D and E-D threshold for the landslide occurrences in Bali Island was represented in this study. The I-D and E-D thresholds established by GSRPs are generally lower than the threshold defined by rain gauge observations. Among the three GSRPs, IMERG is performing the best to determine the rainfall threshold for landslide occurrences. The GSRPs be allowed to be an essential additional data source to establish a regional early warning system for landslide occurrence.

The accuracy assessment of GSRPs to determine the I-D and E-D thresholds in this study only uses the relative deviation of intercept and slope parameters. Further studies are needed to analyze the accuracy more objectively by using skill scores and receiver operating

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characteristic (ROC) analysis. The present study has limitations in the number of landslide events. Further studies are required for a large number of landslide events.

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