42

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Performance of high-resolution satellite rainfall datasets in developing rainfall-duration threshold for landslide incidents over Badung Regency

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Abstract. A dependable high-resolution rainfall dataset was potentially used in various fields of study. Satellite-based rainfall datasets provide high-resolution worldwide rainfall information, which has the potential to be used in identifying rainfall conditions that trigger landslides. Landslides can be forecasted by rainfall thresholds modeling which is used as an early warning system. The threshold model used needs to be validated to know the accuracy of the rainfall threshold in forecasting landslide occurrences provoked by rainfall events. The objective of this study is to assess the performance of three high-resolution satellite rainfall datasets (IMERG, GSMaP, and PERSIANN) in developing a rainfall thresholds model for landslide occurrences in Badung Regency. The recent study used cumulative rainfall events (1, 3, 5, 7, 10, 15, 21, and 30 days) before landslide occurrences. The determination of rainfall threshold values in the recent study used the statistical distribution namely: first quartile, second quartile, and third quartile. Validation of rainfall threshold results was conducted using receiver operating characteristic (ROC) curves and area under the ROC curve (AUC). The analysis results show that the first method (Q_1) shows the best accuracy compared to the others and this method gives a good estimation of landslide occurrence. Moreover, among all satellite rainfall datasets, the 15-day cumulative rainfall demonstrates the highest AOC value (> 0.75), implying a greater likelihood of triggering landslide events over Badung Regency.

Keywords: high-resolution, landslide, performance, rainfall threshold

1. Introduction

Landslides are natural disasters that often occur in tropical countries, one of which is in Indonesia [1]. One of the triggers for landslides is very high rainfall [2]. The high rainfall can cause soil conditions to become unstable and cause slope collapse [3]. Landslides often occur in areas with complex topography, one of which is Bali Province. This condition is supported by the existence of landslide disasters that reached an area of 3,354.4 ha. Of the total disaster cases that occurred in Bali Province, 250 cases occurred in Badung Regency [4]. Landslide-prone areas in Badung include Petang, Abiansemal, Mengwi, North Kuta, and South Kuta sub-districts [5]. When viewed from topographic conditions, Badung Regency has steep slopes with most of the soil classified as inceptisols made from intermediate volcanic ash and tuff, where this type of soil is a weathered soil that is easily eroded when it is above impermeable rock on hills/ridges with moderate to steep slopes. These conditions have the potential to cause landslides during the rainy season with high rainfall. Landslides have an impact on the loss of life and material as well as environmental damage, so to reduce the loss of life, mitigation is needed with an early warning system [6]. One of them is the method of applying rainfall thresholds in the early warning system.

Landslide-triggering rainfall can be predicted using rain threshold modeling used in the early warning system. Rain threshold modeling is made by evaluating rain intensity and rain duration from satellite rain data. Each threshold model created has a different level of accuracy in predicting landslide events. Therefore, evaluation of threshold models is often carried out using several methods, one of which is ROC analysis. Each rain threshold model created needs to be evaluated to know the accuracy level of the threshold in predicting landslide events due to rain. The accuracy level can be determined by the ROC analysis method. This method uses statistical index values and ROC curves that represent the accuracy level of the rain threshold model [7]. ROC analysis can provide better results in evaluating the level by using a contingency table and Area Under Curve (AUC) [3], [7]. This study uses ROC analysis to determine the accuracy of the rain threshold model in predicting rainfall events that trigger landslides or not.

Satellite rainfall data is one of the alternatives that can be used to produce data that is more accurate and relevant to the actual situation [8]. Some examples of satellite rainfall datasets that are often used in the analysis and prediction of landslide events are Tropical Rainfall Measuring Mission (TRMM), Global Satellite Mapping of Precipitation (GSMaP), Global precipitation measurement-The Integrated Merged Multi-satellite Retrievals (GPM-IMERG), Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), Climate Prediction Center Morphing Method (CMORPH), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), and so on [1], [9]–[14]. There has been a lot of research on the application of satellite rain data such as IMERG. This data has a good correlation with observational data on a monthly scale but has a moderate correlation on a daily scale. Assessment of the performance of IMERG data in Surabaya results in that the 10-day accumulation (dasarian) of the data has a good correlation, especially in the rainy season and dry season periods. However, it has a low correlation during the transition period from wet to dry season or vice versa [15]. Testing of GSMaP data in 14 cities in Indonesia shows a good correlation for monthly rainfall patterns with values between 0.82-0.92 and the resulting error is less than 100 mm/month [10] [11]. In addition, validation of GSMaP-MVK (Moving Kalman Filter) on several islands in Indonesia showed a good correlation coefficient value in the rainy season with the best probability of detection (POD) and false alarm ratio (FAR) values found on Kalimantan Island [18]. In addition, studies on the utilization of satellite rainfall products in Bali Province are still very few, including TRMM, CMORPH, PERSIANN, IMERG, GSMaP, and CHIPRS [17], [19]–[21]. One of these studies explained that IMERG and PERSIANN showed better performance in measuring average rainfall intensity compared to GSMaP. Cumulative rainfall for PERSIANN has a good correlation with rainfall stations, while IMERG and GSMaP show overestimate and underestimate. However, IMERG has a small deviation in measuring accumulated rainfall that triggers landslide events compared to other products [22]. IMERG shows better performance on daily, decadal, and seasonal time scales, while GSMaP has a negative bias for all observed time scales (daily, decadal, monthly, and seasonal) [23]. These previous studies show variations in the performance of satellite-based rain products according to the conditions of each region.

The use of rain threshold-based early warning systems has been widely used. The important thing about these systems is the availability of components related to rainfall forecasts [24]. Most slope collapses/landslides are triggered by rainfall. A number of researchers have tried to establish rainfall thresholds in accurately predicting slope collapse/landslide using the parameters of average rainfall, duration of the rainfall event, a ratio of rainfall to daily rainfall, previous rainfall to annual average rainfall, and daily rainfall to maximum previous rainfall ratio [2], [25]–[30]. The utilization of satellite rainfall products in determining the rainfall threshold for landslide occurrence is still little done especially in Bali Province [22]. Previous researchers have analyzed many landslide-triggering rainfall events for the determination of rainfall threshold values using daily, dasarian, and monthly rainfall data [6]. However, previous studies have not analyzed rainfall thresholds based on variations in rainfall accumulation, and variations in analysis based on statistical location measures. Therefore, in the current study determine the rainfall thresholds using variations of rainfall accumulation, as well as variations in the size of the statistical location. On the other hand, research on rainfall threshold analysis triggering landslides has never been conducted in Badung Regency. This study is expected to improve the performance of high-resolution satellite rainfall datasets, so that it can be used as an alternative in analyzing the rainfall threshold that triggers landslides and can be applied in the development of an early warning system in Badung Regency.

2. Materials and Method

2.1 Study Area

This research was conducted in Badung Regency - Bali. Geographically, Badung Regency has an area of 418.52 km^2, or about 7.43% of the total area of Bali Province. The geological conditions of Badung Regency are mostly young volcanic products consisting of volcanic breccia, passive tuff, and lava deposits. Most of the soils in Badung Regency are classified as Inceptisols made from intermediate volcanic ash and tuff. Meanwhile, when viewed from the topographic conditions, the slope of Badung Regency is grouped into 7 (seven), namely slope 0 - 3%, is a flat area, slope > 3 - 5%, is a gentle area, slope > 5 - 10% is an undulating hilly area, slope > 10 - 15% is a slightly sloping area, slope > 15 - 30% is a sloping area, and slope > 30 - 70% is a very steep area. The more to the north has a higher slope [31].

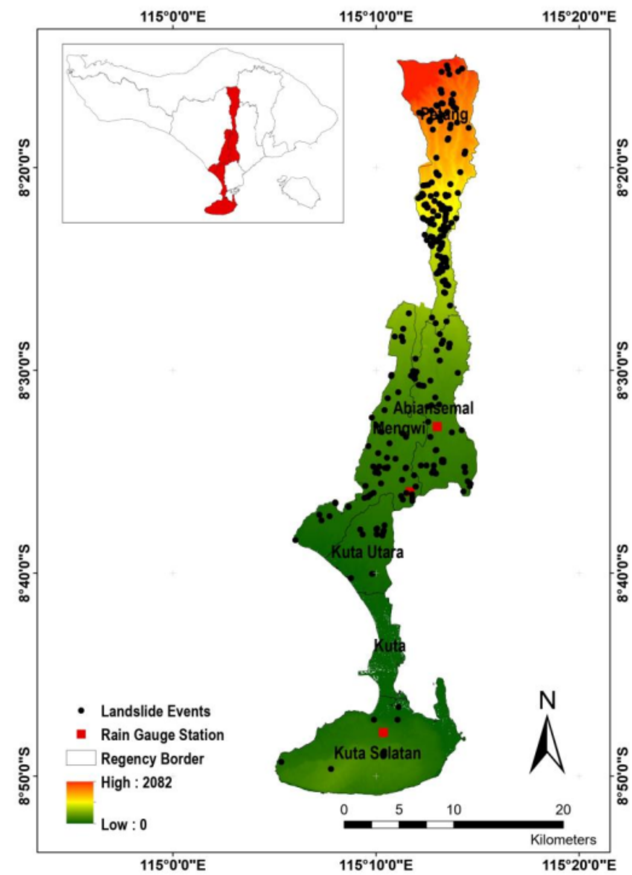

Figure 1. Research location

2.2 Data

2.2.1 Landslide Events

The data used in this research is landslide event data for the time interval of 2015 - 2022. Landslide event data required includes the location of the event, date of the event, coordinates of the event location, the area affected, and level of loss. The landslide data was obtained from the report of the Regional Disaster Management Agency (BPBD) of Badung Regency.

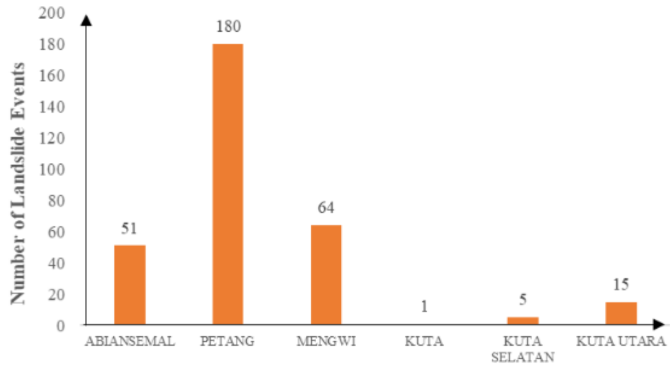

Figure 2. Number of landslide events per sub-district

In Figure 2, it is explained that the Petang sub-district has the highest number of landslide events with 180 events because the Petang sub-district which is located in the northernmost area of Badung regency has an area with a slope above 45% (very steep). Followed by Mengwi sub-district with 64 landslide events, then the Abiansemal sub-district with 51 events. Other sub-districts in the regency tend to be dominated by sloping areas (0-8% slope) especially Kuta, North Kuta, and South Kuta sub-districts. This also shows that the incidence of landslides in these areas is the least among other areas.

2.2.2 Rainfall Data

This research uses 2 (two) rainfall data, namely rainfall data consisting of hourly rainfall measurements obtained from the Bali-Penida River Basin with selected rainfall stations namely Mambal, Sading, and Unud. As for satellite rain data used are GSMaP, IMERG, and PERSIANN. GSMaP has a spatial resolution that reaches 0.1° x 0.1° or equivalent to 11.06 x 11.06 km so rain data can be obtained in all regions of Indonesia. Daily GSMaP data can be downloaded from the JAXA website https://sharaku.eorc.jaxa.jp/GSMaP/index.htm. IMERG data has a temporal-spatial resolution of 0.1° x 0.1° every 30 minutes. IMERG Global Precipitation Measurement (GPM) Final Precipitation data can be downloaded from https://giovanni.gsfc.nasa.gov/giovanni/. This study uses the PERSIANN-Cloud Classification System (CCS) which can estimate global rainfall with a spatial resolution of 0.04° (approximately 4x4 km). The PERSIANN satellite rainfall data was obtained from the PERSIANN website http://chrsdata.eng.uci.edu.

2.3 Method

2.3.1 Determination of Rainfall Thresholds

Thresholds are used to determine the limit of landslide occurrence and the minimum duration that triggers landslides. The relationship between rainfall and landslide in this study can be obtained by processing data in Microsoft Excel. The cumulative rainfall of rainfall events was calculated with various time variations of 1, 3, 5, 7, 10, 15, 21, and 30 days before the time of landslide occurrence. To determine the threshold value of rainfall, this study uses statistical location measures, namely the first quartile (Q_1), second quartile (Q_2), and third quartile (Q_3).

2.4 Performance Analysis of Rainfall Thresholds

This study uses ROC analysis to determine the accuracy of the rain threshold model in predicting rainfall events that trigger landslides or not. The ROC are consist two indices namely true positive rate and false positive rate (Table 1 and Table 2). While the area under the curve is the region that shows the accuracy of the empirical model and is calculated by a calculation method called Area Under Curve (AUC). AUC is a square-shaped area whose value is always between 0 and 1 [14]. The classification of AUC levels can be seen in Table 3 [14].

Threshold performance is calculated by a confusion matrix that contains actual landslide events with predicted landslide events which results in four conditions that can occur (Table 1). True positive occurs if rainfall triggers a landslide in both the actual event and the predicted event (1,1). True negative is when rainfall does not trigger landslides in the actual or predicted event (0,0). A false positive is when rainfall does not trigger landslides in the actual event, but according to the prediction, rainfall can trigger landslides (0,1). False negative is when rainfall can trigger landslides in the actual event, but according to prediction, it does not trigger landslides (1.0) [14].

Table 1. Contingency table

Rainfall Model Predictions	Landslide Events	
	Yes	No
≤ Threshold	True Positive (TP)	False Positive (FP)
> Threshold	False Negative (FN)	True Negative (TN)

Table 2. Statistical indices used to measure the performance of the thresholds

Statistical Indices	Equation
True Positive Rate (TPR)	$TPR = \frac{TP}{TP + FN}$
False Positive Rate (FPR)	$FPR = \frac{FP}{FP + TN}$

Table 3. AUC value classification

Value AUC	Description
$0.5 < AUC \leq 0.6$	Poor discrimination
$0.6 < AUC \leq 0.7$	Acceptable discrimination
$0.7 < AUC \leq 0.8$	Excellent discrimination
$0.9 < AUC$	Outstanding discrimination

3. Result and Discussion

3.1 Rainfall Threshold Results

Based on the method used in analyzing rainfall threshold values in this study, it was found that there was an increase in value for each cumulative rainfall variation. Based on the results of the rainfall threshold analysis for the entire cumulative rainfall of 1, 3, 5, 7, 10, 15, 21, and 30 days from three satellite rainfall products, the largest threshold value is obtained from the third method (Q_3), followed by the second method (Q_2) and finally the first method (Q_1). The threshold of the third method (Q_3) has values of 437.00 mm, 413.50 mm, and 406.25 mm. Followed by the second method (Q_2) thresholds of 285.50 mm, 284.71 mm, and 275.26 mm. Finally, the lowest threshold of the first method (Q_1), with threshold values of 205.00 mm, 208.31 mm, and 208.06 mm. Then for the smallest threshold value obtained from the 1-day cumulative rainfall of the three satellite rainfall products PERSIANN, IMERG, and GSMaP. The thresholds of the third method (Q_3) are 25 mm, 29.15 mm, and 27.28 mm. Then for the second method (Q_2) of 10.00 mm, 15.16 mm, and 11.43 mm. As for the values of 4.00 mm, 6.00 mm, and 4.34 mm for the first method (Q_1). More details can be seen in Table 4.

Table 4. Results Rain Threshold Value

Method	Threshold Line	Duration	Threshold (mm) GSMaP	IMERG	PERSIANN
1	Q_1	1	4.34	6.00	4.00
		3	19.16	19.07	18.00
		5	26.76	28.66	35.25
		7	40.90	44.24	48.00
		10	73.11	81.90	77.25
		15	114.03	129.09	116.25
		21	150.20	171.98	158.25
		30	208.06	208.31	205.00
2	Q_2	1	11.43	15.16	10.00
		3	37.67	38.75	32.00
		5	60.01	62.55	66.00
		7	77.24	79.03	95.00
		10	114.61	114.61	111.50
		15	160.96	162.13	152.50
		21	204.79	218.11	213.00
		30	275.26	284.71	285.50
3	Q_3	1	27.28	29.15	25.00
		3	61.55	62.58	62.75
		5	91.35	91.75	95.00
		7	119.20	122.08	132.25
		10	173.22	167.42	167.75
		15	244.04	240.12	239.00
		21	309.96	307.62	325.00
		30	406.25	413.50	437.00

1

Landslide thresholds derived from cumulative rainfall vary from less than 17 mm to more than 400 mm. This shows that landslide thresholds are highly dependent on location, climate, and the method used to determine the threshold line [8]. Highland areas with steep slopes and lowlands with fairly flat slopes will have different rainfall intensities before landslides, resulting in different rainfall thresholds. In addition, the determination of landslide threshold in a location should consider the differences in season, climate, land cover, and soil conditions compared to other locations, which will result in different threshold values, even though the locations under review are the same.

3.2 Threshold Performance Analysis

Based on 316 landslide events spread across Badung Regency, the number of rainfall events that caused landslide (TP), no landslide (TN), and false positive (FP) were obtained. The ROC curve shows that the accuracy of various cumulative rainfall (1, 3, 5, 7, 10, 15, 21, and 30 days) from the three satellite rainfall products (IMERG, GSMaP, and PERSIANN) is quite good because the results obtained are above the diagonal line (Figure 3). Figure 3 illustrates that the Q_1 approach has the best performance in determining the rainfall threshold for landslide occurrences over Badung Regency at various cumulative rainfall levels. This is evident from the position of Q_1 on the ROC curve, which is much closer to the upper left corner.

The AUC of the rainfall threshold indicates the level of accuracy in detecting landslide-triggering and non-landslide-triggering rainfall events. The cumulative rainfall of 1, 3, 5, 7, 10, 15, 21, and 30 days for the three satellite rainfall products (IMERG, GSMaP, and PERSIANN) shows that the 15-day rainfall produces better performance. Based on the Area Under Curve obtained from the ROC curve, the rain threshold has a pretty good accuracy, where the results obtained for each satellite rainfall product are AUC = 0.755 (75.5%) for PERSIANN, AUC = 0.777 (77.7%) for IMERG, and AUC = 0.760 (76%) for GSMaP. This result is reinforced by research that has been done that the rainfall threshold 15 days before the landslide event has the highest accuracy (86%) [32]. However, for this research, it is necessary to optimize rainfall data both in the correction of rain station data and satellite rain products. The Table 5 is the result of the Area Under Curve (AUC) analysis for the threshold model analyzed in this study.

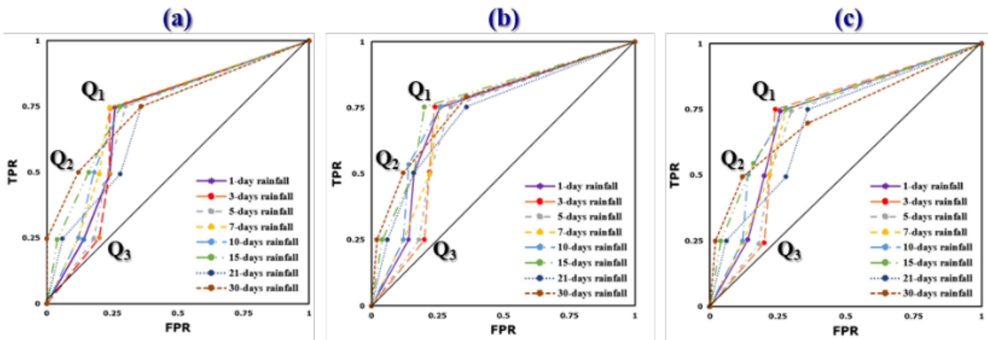

Figure 3. ROC curve

Table 5. AUC rainfall threshold

Satellite Rainfall	Cumulative rainfall (days)							
	1	3	5	7	10	15	21	30
PERSIANN	0.713	0.701	0.697	0.733	0.729	0.755	0.722	0.753
IMERG	0.734	0.710	0.700	0.725	0.747	0.777	0.730	0.767
GSMaP	0.723	0.709	0.698	0.719	0.741	0.760	0.699	0.726

If the accuracy value obtained is > 50%, it can be said that the rain threshold can be used as an early warning system [14]. Based on the AUC obtained from the ROC curve, the rain threshold has good accuracy and can be used as an early warning system for landslides although it still has a considerable error rate. From the AUC analysis, it can be determined that IMERG is the best rain product among GSMaP and PERSIANN that can be used especially in Badung Regency.

4. Counslusion

Based on the analysis, it can be concluded that of the three methods used, the first method (Q_1) performed well for all statistical indices (TPR and FPR) for all three satellite rain products (IMERG, GSMaP, and PERSIANN). In addition, among all satellite rainfall datasets, the 15-day cumulative rainfall demonstrates the highest AOC value (> 0.75), implying a greater likelihood of triggering landslide events over Badung Regency. These thresholds provide good predictions for landslide events with low error rates. Further studies are required to perform bias correction and integrate rain gauge observations in order to enhance accuracy prior to implementation in the early warning system.

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42

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