Evaluation of the accuracy level of landslide vulnerability maps for various rainfall models

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Abstract. The Regional Disaster Management Agency (BPBD) and Communication and Information Agency (Diskominfo) of Garut Regency recorded seven landslide events in 2020 and nine in 2023 in the Banjarwangi District. These events were triggered by steep to very steep slopes with landslide-prone soil and rock types, and heavy rainfall. This study aimed to evaluate the accuracy of landslide hazard maps for various rainfall models, including daily, decadal, monthly, and annual rainfall, validated landslide occurrence points with the DVMBG 2004 method. The evaluation results showed that the maximum rainfall model had a hazard classification of 12,055.3 ha. The average rainfall model showed a less vulnerable classification, covering an area of 9,253.45 ha. Rainfall levels affect the classification of vulnerability, thereby impacting the accuracy. The results of evaluating the accuracy of landslide vulnerable suitability for various rainfall models showed a low accuracy of 45.5%. Therefore, further analysis is required to improve the accuracy of landslide vulnerability maps.

1 Introduction

Indonesia is located in the Pacific Ring of Fire, characterized by a tropical climate and high levels of seismic activity, making it highly vulnerable to hydrometeorological disasters. This situation is due to high levels of exposure and vulnerability, particularly to events such as landslides [1]. Data from the National Disaster Management Agency (BNPB) in 2024 showed that 98.84% of the 1,117 disaster events were hydrometeorological natural disasters, with 86 landslide events [1]. Additionally, in West Java, BNPB also recorded 185 landslide events out of a total of 843 hydrometeorological disasters in 2023 [1]. Landslides occur as a result of the destabilization of slopes, which is influenced by determining factors such as slope gradient, land use, and environmental and hydrological conditions [2]. The primary trigger of landslides is the increase in soil moisture due to rainfall infiltration, which elevates pore water pressure and reduces soil shear strength, ultimately leading to slope instability [3].

In Indonesia, Garut Regency has a high disaster risk index score of 147.39, and a high landslide risk score of 16.11 [1]. In 2024, 11 natural disasters struck, including floods,

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extreme weather, drought, forest fires, earthquakes, and landslides, with a total of 9,087 fatalities and 1,382 houses damaged, ranging from minor to severe damage [1]. In addition, there were 75 landslides in Garut Regency in 2020 [1, 4]. This vulnerability is caused by its topography, which consists of hills and mountains, so that landslides often occur during the rainy season, with Garut Regency identified as one of the most affected areas [4]. One of the areas that is often affected is Banjarwangi District, which has a landslide alert status [4]. The slope inclination in Banjarwangi is in the moderate slope inclination class (10°-25°), which is generally found in hilly areas, and in the steep slope inclination class (25°-60°), which is spread across the upper parts of the hills, making it highly vulnerable to ground movement [5]. During rainfall, the steeper the slope, the less surface water infiltration and the greater the surface runoff, thereby increasing the risk of slope instability and potentially increasing the likelihood of slope failure and landslides [3].

The Garut Regency Disaster Management Agency (BPBD) reported that the Banjarwangi District experienced seven landslides throughout 2020, one of which occurred on January 9 and affected three villages, namely Talagasari, Bojong, and Tanjung Jaya, threatening 10 houses and cutting off access to village roads. Additionally, the Garut Communication and Information Office (Diskominfo) reported nine landslides in the same area throughout 2023. The intensity of these landslides was influenced by high levels of rainfall. Based on the rainfall map from the Directorate of Environmental Geology, Garut Regency has relatively high annual rainfall, reaching approximately 6,000 mm per year in some locations, thereby increasing the potential for landslides [4].

The vulnerability to landslides using the Directorate of Volcanology and Geological Disaster Mitigation (DVMBG 2004) method, on The Cisarua subdistrict showed results that in 2014 and 2018, the vulnerable classification dominated the potential for landslides with a percentage value of 82.54% and 64.59% [6]. The results of this study validate the 2004 DVMBG method. However, there was an inaccuracy between the results of the very high landslide potential map and the actual situation in which no landslides occurred. Gumilang (2021) research results show that there were 9 landslide points that actually occurred in zones mapped as less prone [6]. The discrepancy between the potential map and reality in the field may be due to the limited amount and quality of landslide data, environmental data, and the selection of analysis or modelling methods that depend on the inventory of past landslide locations, which are difficult to collect and are often unrepresentative [7]. Therefore, this study aimed to evaluate and vary rainfall data into daily, decadal, monthly, and annual models using the DVMBG 2004 method in the Banjarwangi District, which was then validated with landslide occurrence points to assess the level of accuracy.

2 Research methods

2.1 Time and location

The landslide study in the Banjarwangi District, Garut Regency, was conducted from February to June 2025. The research area was located at coordinates 7°24'02″ " S and 107°52'48"″ E. A map of the study area is shown in Figure 1.

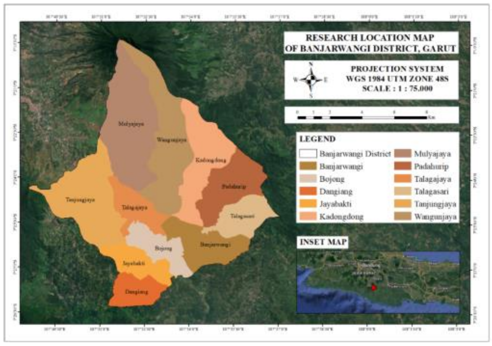

Fig. 1. Research location

2.2 Tools and materials

This study utilised ArcGIS 10.8.1, Microsoft Word, Microsoft Excel, and Google Earth. The research materials consisted of secondary data, including RBI maps, DEMNAS, rainfall data with return periods of 10 and 1 years, as well as monthly, decadal, and daily rainfall data, and soil type and geological maps of the Garut Regency. All data were processed using the 2004 DVMBG method [8]. The DVMBG method is a GIS-based model that evaluates vulnerability parameters to classify landslide potential [6, 8]. The specifications and sources of all spatial data used in this study are listed in Table 1.

Table 1. Spatial data used in the study

No	Data	Specifications	Description	Source
1	RBI Map	SPOT Imagery	1:50000	tanahair.indonesia.go.id
2	DEMNAS	0.27 arcsecond	1:50000	tanahair.indonesia.go.id
3	Rainfall Data	Annual	2014 - 2023	dataonline.bmkg.go.id
4	Soil Type	Soil Type Map	1:3000000	www.fao.org
5	Rock Type	Geological Map	1:50000	Indonesia-geospasial.com

2.3 Weighting and scoring

Each parameter was assigned a score and weight according to its potential contribution to landslide occurrence, allowing us to determine of area affected by each parameter. The scoring and weighting table for the landslide parameters based on the 2004 DVMBG method is presented in Table 2.

Table 2. Landslide parameter scores

Parameters	Description	Score	Code	Weight (%)
Annual Rainfall (mm/year)	< 1000	1	A	30
	1000 - 2000	2		
	2000 - 2500	3		
	2500 - 3000	4		
	> 3000	5		
Geology	Volcanic rock	1	B	20
	Sedimentary rock	2		
	Alluvial rock	3		

Parameters	Description	Score	Code	Weight (%)
Soil Type	Alluvial, Planosol, Hydromorphic	1	C	20
	Latosol	2		
	Brown Forest Soil, Mediterranean	3		
	Andosol, Laterite, Grumosol	4		
	Regosol, Lithosol, Organosol	5		
Land Cover	Forest/dense vegetation and water bodies	1	D	15
	Plantations and mixed shrubs	2		
	Plantations and irrigated rice fields	3		
	Industrial and residential areas	4		
	Bare land	5		
Slope Gradient (%)	< 8	1	E	15
	8 - 15	2		
	15 -25	3		
	25 - 45	4		
	> 45	5		

The total score was calculated as follows:

$$\text{Total score} = (30\%\times A) + (20\%\times B) + (20\%\times C) + (15\%\times D) + (15\%\times E) \quad (1)$$

2.4 Landslide susceptibility index classification and landslide validation

Data analysis was performed by overlaying all the parameters that were assigned scores. The overlay results were then classified using the 2004 DVMBG model to produce a landslide susceptibility map consisting of three classes: low vulnerable, vulnerable, and high vulnerable. The classification of these classes was based on the cumulative total scores presented in Table 3. Furthermore, rainfall evaluation was conducted using empirical data from the past 10 years by modelling rainfall into daily, decadal, monthly, and annual models to analyse its influence on landslide occurrence. The resulting maps from these rainfall models were used to validate the accuracy of the 2004 DVMBG model by comparing them with the actual landslide occurrence points. If the mapped landslide potential at a given location corresponded to moderate or high susceptibility classes, the landslide point was considered validated in accordance with actual field conditions [9].

Table 3. Landslide susceptibility level classification

No	Classification	Total score
1	Low Vulnerable	≤ 2.5
2	Vulnerable	2.6 ≤ 3.6
3	High Vulnerable	≥ 3.7

3 Result and discussion

3.1 Slope gradient

The Slope gradient and surface elevation play significant roles in increasing landslide susceptibility [2]. The classification results indicate that the Banjarwangi District is predominantly characterised by steep slopes, accounting for 40.78% or approximately 4,956.46 ha of the area. This condition reflects the regional geographical characteristics of the Banjarwangi District, which consists mainly of hilly terrain with moderate to high relief (25% to >45%), thereby categorising the area as highly prone to landslides. This finding is consistent with previous studies, including Muntohar *et al.* (2022) [3], which indicate that steep slopes in hilly and mountainous terrains are more susceptible to landslides, especially under rainfall-induced conditions [3]. Setyadji *et al.* (2025) reported that Garut Regency exhibits slope variations ranging from 0 to 40%, with 71.42% of the area having slopes between 8 to 25%, whereas slopes exceeding 40% account for approximately 2.46%. These conditions correspond to extreme vulnerability, dominating 65.25% of the regency, and very high susceptibility, covering 30.03% of the Garut Regency [4]. The slope of the Banjarwangi District is shown in Figure 2.

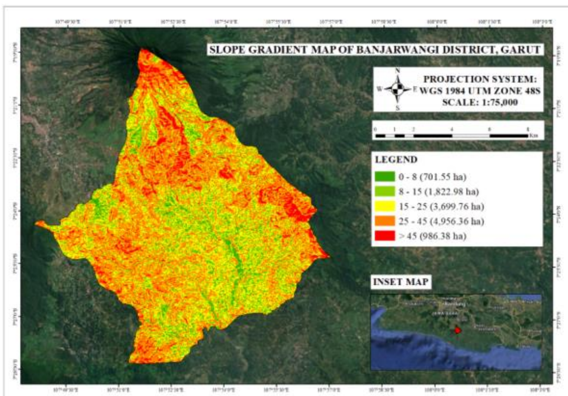

Fig. 2. Slope gradient of Banjarwangi District

3.2 Geology

The likelihood of landslide occurrence is closely associated with the physical characteristics of surface and subsurface materials, particularly their strength and permeability [9]. Geological maps compiled from data provided by the Geological Agency of the Ministry of Energy and Mineral Resources (ESDM) indicate that Banjarwangi District is predominantly composed of tuff and breccia, old volcanic rocks, and products of ancient volcanic activity, covering areas of 3,681.18 ha, 2,532.81 ha, and 1,962.94 ha, respectively. These lithologies are classified as volcanic rocks that are highly susceptible to weathering, which can significantly increase landslide potential under humid climatic conditions [3]. Furthermore, Banuzaki and Ayu (2021) reported that the Salawu District, based on a landslide study conducted along the Garut-Tasikmalaya Road, is situated within an unfavourable geological setting. The roadway in Salawu District extends along river corridors and steep mountainous slopes, is composed of highly eroded volcanic materials, and is intersected by both normal and strike-slip faults. The combined influence of these geological and geomorphological factors plays a critical role in triggering landslides in this area [5]. The types of rocks found in the Banjarwangi District are shown in Figure 3.

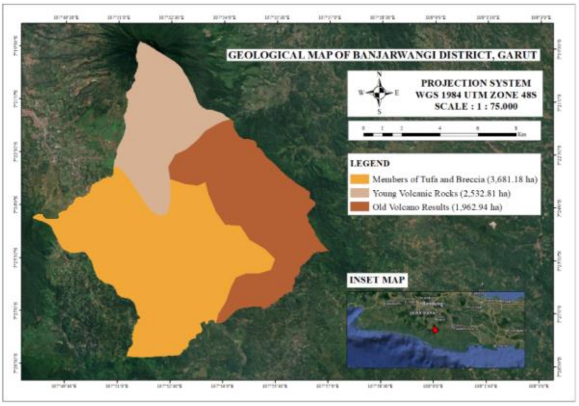

Fig. 3. Geological of Banjarwangi District

3.3 Soil type

Each soil type exhibits distinct characteristics that influence slope stability depending on its mechanical properties, water content, and hydraulic behaviour within the soil layers [3]. The Banjarwangi District is predominantly underlain by Andosols, covering an area of 10,795.77 ha, and Lithosols, which occupy approximately 1,372.09 ha. According to the FAO soil classification adapted to Indonesian conditions, both soil types are derived from volcanic processes and possess physical properties that can potentially trigger landslides [10]. Andosols are characterised by sandy loam textures with high moisture retention, whereas lithosols generally exhibit clayey textures with significant clay and silt contents [10]. Soils with high clay mineral content and sandy loam textures, such as andosols and lithosols, tend to lose stability when saturated, resulting in a higher susceptibility to landslides [10]. Furthermore, a study reported by Suharini et al. (2021) in Banjarnegara Regency revealed that areas classified as having high landslide hazard levels accounted for approximately 25% of the total study area, encompassing seven land units dominated by mediterranean soils, lithosols, and andosols. These high-hazard zones pose significant threats to several villages, including Slatri, Paweden, Gumelar, Sampang, Ambal, Pagerpelah, Pasuruhan, Karanggondang, Jlegong, Binangun, and Karangkobar [10]. The soil types in Banjarwangi District are presented in Figure 4.

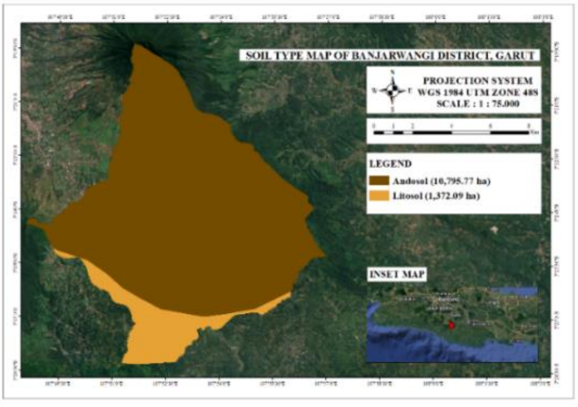

Fig. 4. Soil type of Banjarwangi District

3.4 Land cover

Land cover type significantly contributes to the spatial distribution of landslides through variations in vegetation cover [3]. In the Banjarwangi District, the land cover is predominantly forested, covering an area of 3,372.15 ha (27.71%). Vegetated land cover dominated by forests generally exhibits a lower frequency of landslide occurrences than non-forest areas, as strong root systems provide both mechanical reinforcement and hydrological regulation, which often enhance slope stability [5]. However, the Banjarwangi District faces a high potential risk of land conversion for settlement development. Changes in land-use patterns from forested areas to residential zones can induce slope instability and increase its occurrence [12]. Land use reflects anthropogenic activities that contribute to alterations in land function and surface morphology. According to Banuzaki and Ayu (2021), land-use classes with the greatest influence on landslide distribution are settlements, which exert the highest impact on landslide potential, followed by bare land, agricultural land, and forests [5]. The land cover types in the Banjarwangi District is shown in Figure 5.

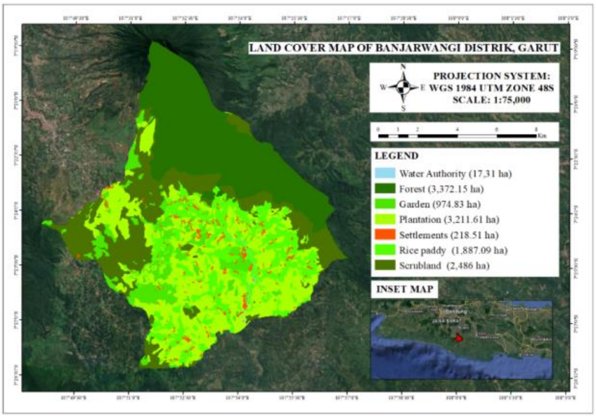

Fig. 5. Land cover of Banjarwangi District

3.5 Rainfall

Landslides are frequently triggered by rainfall, which induces changes in groundwater levels and pore water pressure, thereby disrupting slope stability [11]. The rainfall data used in this study were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) and collected from five BMKG stations across West Java over a ten year. The rainfall records were processed and modelled at daily, ten-day (decadal), monthly, and annual temporal scales. The result of the modelled rainfall data are shown in Figure 6.

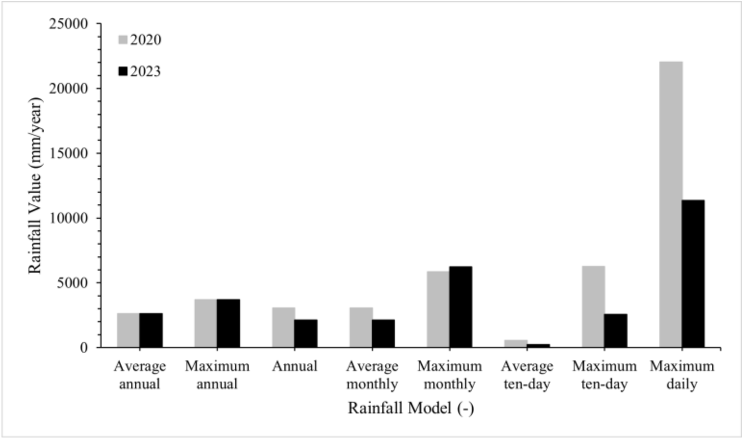

Fig. 6. Rainfall data model

The accuracy of landslide prediction exhibits a strong correlation with rainfall conditions. Frequent high-intensity rainfall disrupts soil stability on sloping terrain, substantially increasing the likelihood of landslides [12]. Based on the processed rainfall data, the highest recorded value was the maximum daily rainfall in 2020, reaching 22,045.55 mm/year, whereas the lowest value corresponded to the average decadal rainfall in 2023, amounting to 235.66 mm/year. Considering the geological setting and soil types, the Banjarwangi District, which is predominantly composed of sandy loam and clayey soils, is highly sensitive to variations in pore-water pressure, rendering the soil mass unstable under high-intensity rainfall, which leads to saturation [10]. Extremely high rainfall can rapidly increase the soil moisture content and add to the load acting on the soil mass. While such effects may be relatively minor in flat areas, they become significantly amplified in hilly and mountainous regions, where gravitational forces enhance the downslope movement of saturated soil materials, potentially triggering landslides [12].

Previous studies have reported that Garut Regency experiences very high annual rainfall, reaching up to 2,589 mm/year [4]. Similarly, rainfall ranging from 2,668 to 3,228 mm/year has been associated with landslide occurrences in the Bogor Regency [12]. The DVMBG (2004) method assigns rainfall the highest influence weight of 30%, indicating that rainfall intensity is the primary triggering factor of landslides. Rainfall characteristics, including temporal patterns, spatial distribution, and intensity, particularly during extreme rainfall events, can induce slope instability and ultimately lead to slope failure [13].

3.6 Landslide susceptibility index classification and landslide validation

3.6.1. Landslide susceptibility index classification

Analysis of the 2004 DVMBG landslide vulnerability index in Banjarwangi District showed that the maximum daily rainfall model (2020 and 2023), maximum decadal rainfall (2020), and maximum monthly and annual rainfall models produced a classification of 11,590.9 ha as vulnerable and 569.21 ha as highly vulnerable. In the 2023 maximum decadal rainfall model, 2020 average monthly model, and 2020 annual model, the classification of vulnerable areas dominated an area of 12,055.3 ha, highly vulnerable areas covered 0.503 ha, and less vulnerable areas covered 104.23 ha. In the average annual rainfall model as a control, the vulnerable classification covered 10,149.4 ha, and the less vulnerable classification covered 2,010.62 ha. The dominance of high vulnerability classes reflects elevated landslide hazard, which is largely influenced by steep to very steep slope gradients within hilly and mountainous topography [5], the presence of Andosol and Lithosol soils derived from volcanic materials with sandy loam to clay textures that are highly sensitive to landslide processes and prone to rapid saturation [10], and high maximum daily rainfall that induces slope instability and ultimately leads to slope failures [13].

Conversely, the average decadal rainfall model (2020 and 2023), average monthly model (2023), and annual model (2023) were dominated by the less vulnerable classification, covering areas of 9,253.45 ha, 9,253.45 ha, 9,246.61 ha, and 9,247.85 ha, respectively, and the vulnerable classification covered areas of 2,906.62 ha, 2,906.62 ha, 2,913.46 ha, and 2,912.22 ha, respectively. This condition can be attributed to the relatively lower rainfall compared to that recorded in 2020, as well as the extensive presence of forest land cover, which plays a crucial role in reducing landslide potential through strong root systems that enhance slope stability [5]. Accordingly, the maximum rainfall model is considered the most effective factor in landslide susceptibility mapping, as it adequately represents extreme rainfall intensity as the primary triggering mechanism for landslide occurrence [13]. The landslide vulnerability map results are shown in Figure 7. The specific landslide vulnerability results with various rainfall models are presented in Figure 8.

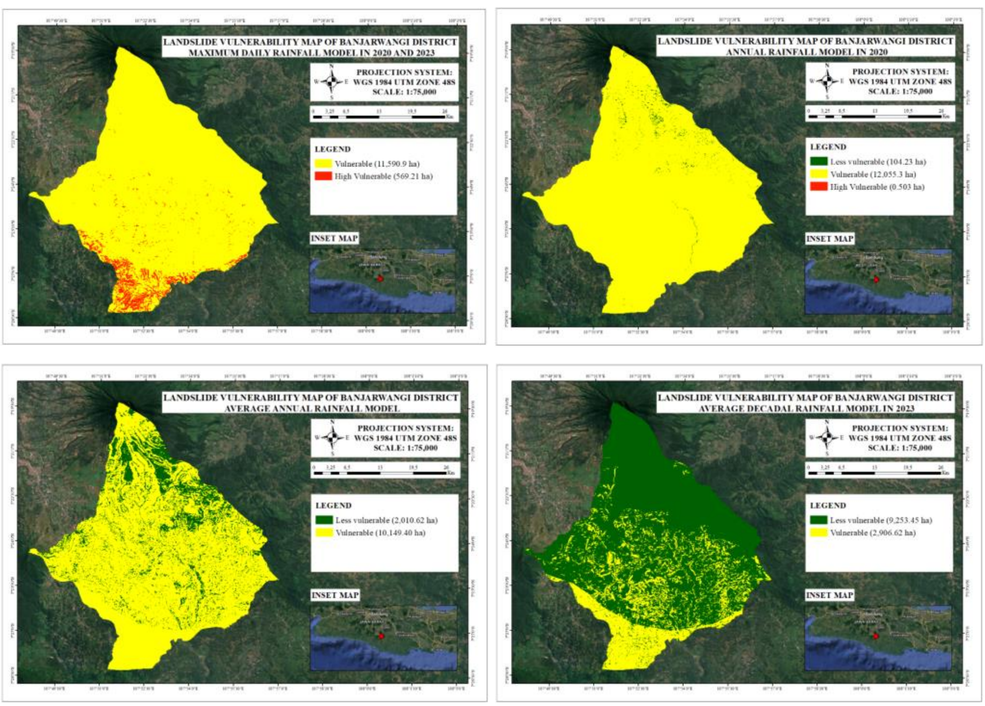

Fig. 7. Map of landslide vulnerability for various models

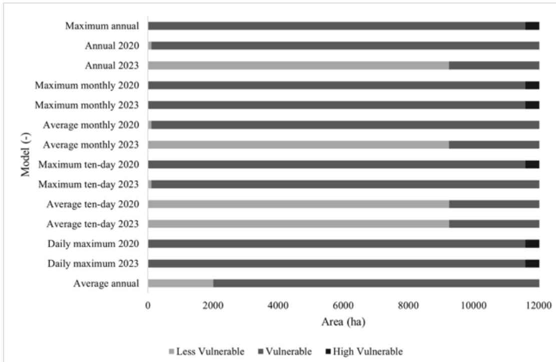

Fig. 8. Classification of landslide vulnerability areas for various rainfall models

3.6.2 Landslide event validation

Landslide occurrence data were validated by comparing the landslide susceptibility maps generated using the DVMBG (2004) method with multiple rainfall models against recorded landslide event locations from 2020 and 2023. This validation aimed to assess the accuracy of landslide-prone area mapping based on actual field conditions. According to Tara and Bhandari (2025), a landslide location is considered validated if it falls within the susceptible or highly susceptible classes on a landslide susceptibility map. Conversely, areas classified as having low susceptibility and exhibiting no recorded landslide events were also regarded as validated [9].

The landslide susceptibility map generated using the DVMBG (2004) method was validated against landslide occurrence data recorded from 2020 and 2023. Seven landslide events were documented in 2020, and nine events were recorded in 2023. These landslide locations were overlaid onto the DVMBG (2004) landslide susceptibility maps incorporating various rainfall models to evaluate the accuracy of landslide prediction in the Banjarwangi District. The analysis results indicate that most landslide occurrences fall within the low vulnerable and vulnerable classes. The landslide susceptibility maps showed a dominance of high-susceptibility zones, particularly in models that accounted for variations in the maximum rainfall. However, several inconsistencies were identified between the classified susceptibility zones and the actual field conditions, wherein certain areas classified as susceptible did not experience landslide events. These findings suggest that although landslide susceptibility maps can provide a general overview of potential landslide risk, their predictive accuracy requires improvement through more comprehensive field validation. The validation process is essential for evaluating the effectiveness and predictive capability of the developed model and demonstrating its applicability in landslide hazard assessment studies [9]. The validation of the landslide-vulnerable areas is illustrated in Figure 9.

The validation analysis indicated that the accuracy of the landslide susceptibility maps for the Banjarwangi District in 2020 and 2023 remained relatively low. A comparison between the DVMBG (2004) susceptibility maps and recorded landslide events revealed notable discrepancies, with only three to five villages showing agreement for each rainfall model. These inconsistencies occur in areas classified as susceptible or highly susceptible that lack documented landslide occurrences in areas categorised as having low susceptibility that nevertheless experienced landslides. Overall, the validation results showed that 54.5% of the study area is not validated, whereas only 45.5% is validated. The average rainfall model, which is commonly applied as a control in the DVMBG (2004) method, demonstrated low validity, with only three villages classified as validated. This limitation arises because the use of ten-year rainfall data does not sufficiently represent the actual spatial and temporal variability of the rainfall intensity observed in the field. In contrast, alternative rainfall models exhibited marginal improvements, although only two additional villages were validated. This improvement can be attributed to the use of various rainfall modelling approaches, which better capture the relationship between estimated rainfall patterns and observed landslide occurrences [9]. Discrepancies between landslide susceptibility maps and landslide validation data may result from limitations in the quantity and quality of landslide inventory data, environmental datasets, and the selection of analytical methods that are insufficiently representative of local conditions [7].

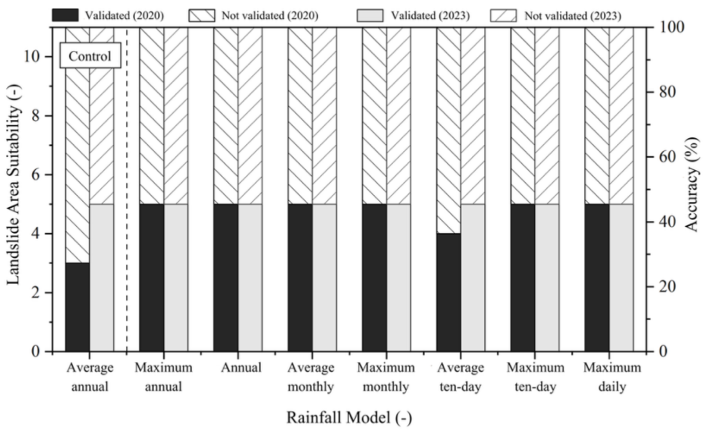

Fig. 9. Landslide event validation data

Figure 9 shows the validation maps of landslide susceptibility zones and landslide occurrence points generated using various rainfall models. As illustrated in Figure 9, the DVMBG (2004) landslide susceptibility model demonstrated relatively low accuracy, with a validated accuracy of 45.5% and a non-validated rate of 54.5%. These results indicate that the model requires further improvement, as several areas classified as susceptible did not experience landslides, whereas some areas categorised as having low susceptibility were affected by landslide events [9]. Machine learning-based landslide susceptibility approaches, such as the Frequency Ratio (FR) and Random Forest (RF) models, have been shown to outperform the DVMBG (2004) method. The Frequency Ratio and Random Forest models are among the most widely applied techniques and generally yield higher success rates and improved predictive accuracy, with reported accuracies of 78.94% for the Frequency Ratio model [9] and 93% for the Random Forest model [12]. GIS-based weighted overlay approaches, such as the DVMBG (2004) method, are inherently limited because of the subjective classification of parameters and the complexity of spatial processes used to assess the contribution of predictive factors to landslide occurrence [14]. Therefore, the DVMBG (2004) model requires enhancement through optimisation of its fundamental equations and/or modification of the applied formulations, as well as refinement of key controlling parameters, particularly rainfall variables and slope gradients, to improve landslide susceptibility assessment [6].

4 Conclusions

The evaluation results showed that the maximum rainfall model had a vulnerability classification of 12,055.3 ha. The average rainfall model showed a lower vulnerability classification, covering an area of 9,253.45 ha. Rainfall levels affect the vulnerability classification, thereby affecting accuracy. The results of the evaluation of the accuracy of landslide vulnerability suitability for various rainfall models showed that only three to five villages accurately matched each rainfall model, whereas the other areas did not match the daily, decadal, monthly, and annual rainfall models. The DVMBG (2004) vulnerability method showed low accuracy, with 45.5% of the classifications validated and 54.5% not validated. To improve accuracy, machine learning-based models are recommended, as they have shown superior predictive performance in landslide vulnerability mapping. In addition, the DVMBG (2004) method needs to be improved through optimisation or modification of its basic equations, as well as adjustment of key parameters, especially rainfall intensity and slope gradient. Rainfall modelling should also avoid converting diverse rainfall variations into annual values, because such simplification fails to represent the actual spatial and temporal variability of rainfall intensity in the field.

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