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Spatial multi-parameter analysis of landslide susceptibility with geological structure integration

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ABSTRACT

Background: Based on the 2022-2026 disaster risk assessment, nearly all districts in Bali Province are at a high risk of landslides. The Tukad Oos Watershed is one of the river basins in Bali Province, spanning two districts: Gianyar District and Bangli District. Mapping and analysing landslide potential is an important step in disaster mitigation efforts. The objective of this study is to identify the locations of landslide-prone areas in the Tukad Oos Watershed and to assess the impact of the development of the Ubud and Kintamani tourist areas on these landslide-prone areas. **Methods:** The method used is multi-parameter scoring. This study analyzes landslide potential in Tukad Oos Watershed, Bali, using rainfall, slope, geology, soil, landform, and land use parameters with a weighted scoring method. **Findings:** The results of the landslide potential estimation analysis indicate a high landslide potential class covering 4.87 hectares or 0.03% of the basin area, a moderate potential class covering 72.97 hectares or 0.5% of the watershed area, a low potential class covering 829.98 hectares or 6.74% of the watershed area, and a non-potential class covering 11,406.05 hectares or 92.62% of the upstream Tukad Oos watershed area. **Conclusion:** The results of the landslide potential analysis from this study are quite similar to the Inarisk BNPB data, with the difference lying in the level of detail produced, which is influenced by the spatial resolution of the Digital Elevation Model (DEM) used for the analysis. The development of tourism activities in the Ubud and Kintamani areas does not significantly increase the landslide potential in the Tukad Oos watershed. **Novelty/Originality of this article:** Studies on landslides in Indonesia use several parameters; the main parameter that is often used is slope inclination, but this study adds geological structure parameters as a determining factor in landslide estimation.

KEYWORDS: landslide; GIS; overlay; scoring; watershed.

1. Introduction

Natural disasters are among the most pressing challenges for sustainable development in Indonesia and globally. The frequency and intensity of disasters have increased significantly, largely due to environmental degradation, climate change, and anthropogenic pressures (Rakuasa et al., 2023). Several types of natural disasters occur frequently with considerable frequency and intensity, namely floods and landslides. Landslides, in particular, are geological hazards that have severe environmental, social, and economic consequences (P. Latue et al., 2023; Somae et al., 2022; Bai et al., 2021; Fariz et al., 2023).

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Within the Indonesian context, landslides are recurrent in many watersheds, particularly in upstream catchments where topographic conditions are steep and geomorphological processes are highly dynamic. According to the National Disaster Management Agency (BNPB, 2021), landslides are among the most lethal natural hazards, accounting for significant loss of life annually (Isnaini, 2019). By definition, a landslide is the downslope movement of rock, soil, sediment, or man-made debris under the influence of gravity (Iskandarsyah et al., 2022; Hungr et al., 2014). Multiple factors interact to trigger slope instability. Arsyad (2012) and Indarto (2010) emphasize that topography, particularly extremely steep slopes, constitutes the most critical determinant of landslide occurrence in Indonesia. Complementing this view, Cook & Doornkamp (1994) distinguished between passive and active factors. Passive factors include slope morphology, soil types, lithology, hydrology, and vegetation cover, while active factors are primarily human activities and climatic variability. Deforestation, expansion of settlements, road construction, and poorly managed agricultural activities can destabilize slopes and accelerate erosion (Feronika et al., 2023). Climatic extremes such as high-intensity rainfall, increasingly linked to climate change, further exacerbate these risks.

Recent studies highlight that degraded river basins in Indonesia experience landslides at increasing rates, particularly in upper catchments (Badwi & Baharuddin, 2023). Degradation processes—such as deforestation, loss of vegetation cover, and uncontrolled land conversion—accelerate hydrological responses, thereby intensifying slope failure probability (Dwiastuti et al., 2021). Bali Province provides a critical example. The 2022–2026 National Risk Assessment Document identifies nearly all districts in Bali as highly susceptible to landslides. The Oos River Basin, which extends across Bangli and Gianyar Districts with an area of 115 km^2 and a river length of 51.96 km, is classified as a perennial river system and is particularly relevant in this context (Suryati et al., 2023). Given this vulnerability, landslide susceptibility mapping becomes an indispensable tool for risk reduction. Previous research demonstrates that spatial mapping of hazard-prone areas provides essential baseline information for disaster mitigation strategies and community preparedness (T. Latue et al., 2023; Pakniany et al., 2023; Hamida & Widyasamratri, 2019). Such mapping efforts not only identify potential hazard zones but also support disaster education, community awareness, and emergency response (Damanik & Restu, 2012; Rahmad et al., 2018).

In this study, a multi-parameter scoring/assessment method is applied, referencing the guidelines developed by the UGM Natural Disaster Study Centre (PSBA UGM, 2001). This method is widely recognized as effective for landslide susceptibility analyses, as it integrates various determinants such as rainfall, geological conditions, fault proximity, vegetation cover, and slope steepness (Wang et al., 2017). Recent findings also confirm that soil type remains a dominant factor shaping landslide-prone zones (Amin et al., 2023). Despite significant progress, some Indonesian studies on landslide susceptibility mapping remain limited by methodological simplifications. For example, Rahmad et al. (2018), Ramdani et al. (2020), Santoso et al. (2022), Muin & Rakuasa (2023), and Rakuasa et al. (2024) provide valuable insights but often emphasize slope gradient as the primary driver, while overlooking critical geological parameters. Yet, lithological composition and structural geology substantially influence slope stability and landslide processes (Krisnandi et al., 2021; Lanto et al., 2022). Accordingly, the present study addresses this gap by incorporating geological parameters into landslide susceptibility mapping for the Tukad Oos watershed.

This research is also positioned within the broader framework of the United Nations Sustainable Development Goals (SDGs). First, it aligns directly with SDG 15: Life on Land, which emphasizes the protection, restoration, and sustainable use of terrestrial ecosystems, as well as the prevention of land degradation and biodiversity loss. Landslides, as a form of land degradation, threaten ecosystem services, biodiversity, and agricultural productivity. Second, the study supports SDG 11: Sustainable Cities and Communities, since hazard mapping informs spatial planning policies, guides infrastructure development, and reduces disaster risk to settlements and livelihoods. Third, it addresses SDG 13: Climate Action, as landslides are increasingly linked to climate-induced extreme rainfall events. By providing localized susceptibility assessments, this research contributes to climate adaptation strategies at the watershed scale. Moreover, landslide hazard and risk assessments should be viewed as fundamental components of disaster risk management and land-use planning (Hadmoko et al., 2010; Bucała-Hrabia et al., 2022). Bucała-Hrabia et al. (2022) emphasize that disseminating knowledge on landslide-prone areas and integrating this information into spatial planning frameworks is one of the most effective strategies for minimizing losses. Hence, beyond technical mapping, effective communication and community-based awareness programs are critical for transforming scientific assessments into actionable risk reduction measures.

Experiences from other regions confirm the importance of participatory governance and knowledge dissemination. Community involvement ensures that hazard maps are not only scientifically robust but also socially relevant and trusted. Spatial planning authorities, local governments, and traditional institutions must work collaboratively to ensure that development trajectories, particularly in rapidly transforming areas such as Bali's tourism regions, do not exacerbate landslide hazards. Integrating scientific assessments with local knowledge and policy frameworks can help balance development with disaster resilience. In light of these considerations, this study examines the Tukad Oos watershed in Bali Province to identify landslide-prone areas through spatial analysis, integrating topographic, hydrological, vegetation, and geological parameters. By doing so, the research contributes both theoretically and practically: it refines susceptibility mapping methodologies and simultaneously provides critical input for land-use planning, climate adaptation, and sustainable watershed management. Ultimately, effective landslide risk reduction in the Tukad Oos watershed is not only a scientific necessity but also a developmental imperative, contributing directly to SDGs 11, 13, and 15.

2. Methods

2.1 Research location

The location studied in this research is in the Tukad Oos Watershed. With coordinates between 115° 17' 42.865‘ E - 115° 20' 9.859’ E and 8° 38' 12.534" S - 8° 15' 33.957" S as shown in Figure 1. The Tukad Oos Watershed spans two districts in the Province of Bali: Bangli District in the upstream area and Gianyar District in the downstream area, covering a total study area of 115 km². The research was conducted in 2025.

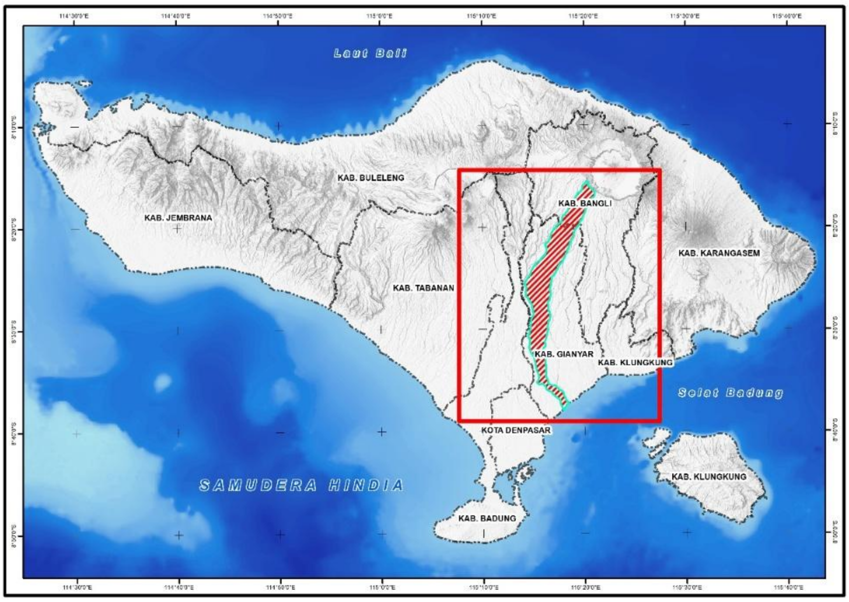

Fig. 1. Research location

2.2 Data

The data used in this study were rainfall data for 2023, Digital Elevation Model (DEMNAS) data with a resolution of 8 metres, and thematic maps consisting of geological maps of Bali sheets 1707 and 1807 at a scale of 1:250,000, FAO soil type maps, and BIG (Geospatial Information Agency) landsystem maps at a scale of 1:250,000, as well as land use data from medium-resolution Sentinel satellite imagery with a spatial resolution of 10 metres, recorded in 2024-2025 with a cloud cover percentage of 10%.

2.3 Method

In this study, the parameters required are rainfall, slope gradient, geological structure, land use, landform, and soil type. These parameters refer to those developed by the Centre for Natural Disaster Studies (PSBA UGM, 2001). The parameters used are not significantly different from those employed in studies conducted by Dwiastuti et al. (2021) and Feronika et al. (2023). The analysis of landslide potential was determined using a parametric approach with a scoring method. Each parameter used was classified into several classes and assigned a score or rating for each class. A score of 1 means the least contribution to landslides, while a score of 5 means a very high contribution to landslides.

Table 1. Rainfall intensity value

No	Rainfall (mm/year)	Score	Weight
1	<1500	1	5
2	1500- 1800	2	5
3	1800- 2100	3	5
4	2100- 2400	4	5
5	>2400	5	5

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

Based on Table 1, the scores determined in the rainfall parameters are divided into five score values. These score values are divided based on the rainfall intensity values within one year. Score 1 is the minimum score used to represent low rainfall intensity, i.e., rainfall intensity < 1500 mm/year, and according to Feronika et al. (2023), this is the rainfall that has the least impact on landslides. Meanwhile, high rainfall intensity, with a score of 5, refers to rainfall intensity exceeding 2400 mm/year, which can trigger landslides if it occurs frequently. The score results will then be multiplied by the weight of each parameter to obtain the analysis results per parameter.

Table 2. Slope intensity value

No	Slope (%)	Score	Weight
1	0- 8	1	5
2	8- 15	2	5
3	15- 30	3	5
4	30- 45	4	5
5	>45	5	5

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

In Table 2, the scores determined by the slope inclination parameter are divided into 5 classes, each with 5 score values. This division of slope inclination classes is based on the general division of slope inclination classes and is often used in certain analyses. According to Dwiastuti et al. (2021), slope inclination classes have a significant weight and can influence the occurrence of landslides. Accurate scoring of each slope gradient class provides an accurate and useful landslide potential mapping for the community. The slope class with a gradient of 0-8% has the lowest score because it has a low slope gradient, resulting in a low landslide potential.

Table 3. Geological structure intensity value

No	Geology structure	Score	Weight
1	Horizontal	1	3
2	Horizontal/ Tilted	2	3
3	Tilted	3	3
4	Cracks	4	3
5	Lean steep	5	3

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

Geological structure is an important parameter that influences landslide potential. Geological structure is determined by rock type and fault line conditions that can trigger landslides. In addition to soil type, landslides are also triggered by rock type and geological structure conditions. These geological structure conditions can influence the strength of landslides. Based on Table 3, geological structure scores are divided into five levels, with the lowest score corresponding to horizontal geological structures. According to Dwiastuti et al. (2021) and Feronika et al. (2023), horizontal geological structures are the safest in terms of landslide occurrence, as they tend to have more stable rock types.

Table 4. Landuse intensity value

No	Landuse	Score	Weight
1	Forests, mangroves, swamps, irrigated rice fields, ponds, salting, sand	1	4
2	Rainfed rice fields	2	4
3	Buildings, settlements	3	4
4	Shrubs, gardens/plantations	4	4
5	Grass, bare land, moor/fields	5	4

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

In Table 4, land use classes are divided based on the level of land cover. The level of land cover refers to whether the land cover still has a lot of vegetation and minimal human intervention in land conversion, in which case it will have a low score. For example, forest areas have a low score because there is minimal human activity in the use of this land, so the potential for landslides is still very low. This condition will be different if the level of land cover is mostly open land, such as grass and open shrubs, which greatly influence the increase in the potential for landslides in that land use.

Table 5. Landform intensity value

No	Landform	Score	Weight
1	Alluvial Plains	1	6
2	Limestone Hills, Caldera, Volcanic Foot Slopes, Hills, Lower Slopes	2	6
3	Lower Volcanic Slopes, Lower Hills Slopes, Middle Slopes, Inter-Mountain Plains, Rugged Slope Mountains	3	6
4	Middle Volcanic Slope, Upper Hills Slope, Volcanic Slope	4	6
5	Volcanic Cones, Upper Volcanic Slopes, Volcanic Lungur, Valleys, Caldera	5	6

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

Table 5 contains the landform class values, where the landform parameter has the highest score. Landform greatly influences landslides. The landform score values are divided into five levels. The lowest score in the landform parameter is alluvial landform, which usually has a low slope and very low landslide susceptibility. Meanwhile, the highest score is for volcanic cone landform, which usually has a very steep slope with rock material and soil types that are easily carried away by water in the event of a landslide (Feronika et al., 2023).

Table 6. Soil type intensity value

No	Soil type	Score	Weight
1	Mediterranean Brown, Mediterranean Reddish Brown	1	2
2	Yellowish Brown Latosol, Reddish Brown Latosol, and Litosol	2	2
3	Chocolate Latosol and Litosol, Brown Gray Alluvial, Alluvial Hydromorph	3	2
4	Brown Regosol, Yellowish Brown Regosol, Grey Brown Regosol, Regosol Humus, Grey Regosol	4	2
5	Grey Brown Andosol	5	2

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

The soil types in Table 6 are important parameters in determining landslide potential. The type of soil material components and soil properties found in areas with high landslide potential usually have low water absorption properties, making it difficult for the soil to absorb water. However, there are some types of soil, such as andosol soil, which have high water absorption properties.

Table 7. Landslide potential classification value

No	Landslide potential value	Landslide class
1	<90	No potential
2	90- 96	Low potential
3	97- 99	Medium Potential
4	>100	High Potential

(PSBA UGM, 2001; Dwiastuti et al., 2021; Feronika et al., 2023)

However, when combined with rock types that have impermeable properties, this will also affect the landslide potential. Therefore, in terms of soil type parameters, andosol soil has the highest score of 5. The landslide potential classification is divided into four classes, as shown in Table 7. These classes are determined based on the total score of each parameter derivative and the weight value of each parameter.

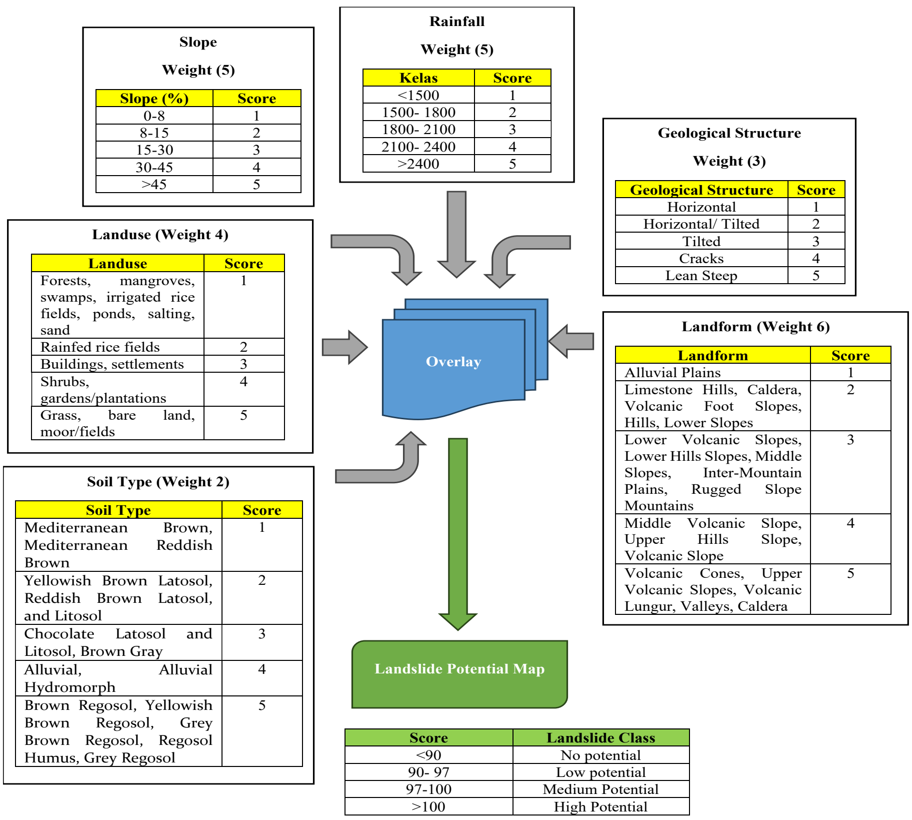

Fig. 2. Data processing and analysis flow diagram

The weighting assessment is based on research by PSBA UGM (2001), Dwiastuti et al. (2021), and Feronika et al. (2023), and these values are considered to be appropriate for describing landslide conditions. However, it is possible to create separate landslide classification values based on field findings, using several statistical methods to produce more accurate classification values. If you want to create your own classes, according to Arcana et al. (2021), you can use a method to determine the class intervals first, by independently determining the class intervals to be used, using the formula Class interval = (Highest total score – Lowest score) divided by the desired number of classes. The desired number of classes corresponds to the levels to be produced, which can be determined by referring to the literature on classes in previous studies or by independently determining the number of classes according to the expected results.

3. Results and Discussion

Administratively, Tukad Oos Watershed is bordered by Buleleng Regency to the north, Bangli Regency, Gianyar Regency, and Denpasar City to the east, the Indian Ocean to the south, and Tabanan Regency to the west. The total area of the Tukad Oos watershed is approximately 119.95 km^2 with a river length of 51.963 km. Most of this watershed is situated in Gianyar Regency, covering about 97.68 km^2, while the portion in Badung Regency covers 22.271 km^2 (Handari, 2016). The Gianyar Regency landscape is largely characterized by altitudes ranging between 250–950 meters above sea level, accounting for 20.25% of its total land area. This region is traversed by 12 rivers, the majority of which are utilized for agricultural irrigation. Unlike other regencies in Bali, Gianyar does not contain any volcanic mountains. The total area of Gianyar Regency is 36,800 hectares, representing 6.53% of the island of Bali. As of the end of 2011, the land cover distribution included 14,732 hectares of rice fields, 21,879 hectares of dryland, and 171 hectares of other land uses such as swamps, fishponds, and small water bodies (Handari, 2016). Water resources in Gianyar Regency rely heavily on the Tukad Oos watershed. When the watershed is in a healthy condition, its reliable flow can sustain water demand even during the dry season. Currently, the river serves as a vital source for various purposes, including raw water supply, drinking water, irrigation, and domestic needs (Handari, 2016).

A watershed is a spatial ecosystem unit comprising abiotic, biotic, and human components that interact (Rafidah et al., 2024), functioning as a precipitation collector defined by topographic boundaries (Fariz et al., 2024). In tropical regions like Indonesia, upstream and midstream areas face landslide risks influenced by rainfall, slope, land use, soil, landform, and geological structure. The rainfall data used in the study for landslide potential analysis is the average rainfall data for the year 2023. The results of rainfall interpolation were classified into four classes based on average rainfall values. The dominant rainfall in the Oos watershed is an average rainfall of <1500 mm/year with an area of 7247.89 Ha located in the upper part of the watershed, as shown in Figure 3.a. Rainfall in the Oos watershed for the middle and lower parts falls into the moderate class with an average rainfall of 1500–1800 mm/year. Based on the analysis of rainfall parameters in the Oos watershed, the low to moderate score class dominates. Therefore, the influence of the rainfall parameter is low, even though it has a high weight. The slope parameter has the same weight as the rainfall parameter, both having high weights. The slope data was obtained from the processing of DEM (Digital Elevation Model) data, specifically DEMNAS. DEMNAS data is in the form of a DSM (Digital Surface Model). It should be noted that when determining slope classes using DSM data, surface objects can affect the accuracy of slope measurements, making them inconsistent with field conditions. Slope gradients in the Oos watershed are dominated by flat to gentle slopes in the downstream section, and moderately steep to very steep slopes in the middle to upstream sections, as shown in Figure 3.b. The area of the Oos watershed with very steep slope gradients covers an area of 169.12 hectares. The very steep slope is located on the banks/edges of the Tukad Yeh Katung and Tukad Oos rivers in the middle of the watershed. Slopes with a very steep class will have a high final score weight. Based on the results of the slope analysis, the Oos watershed is dominated by low to moderate score classes, with a percentage of 92.38% of the total area of the Oos watershed.

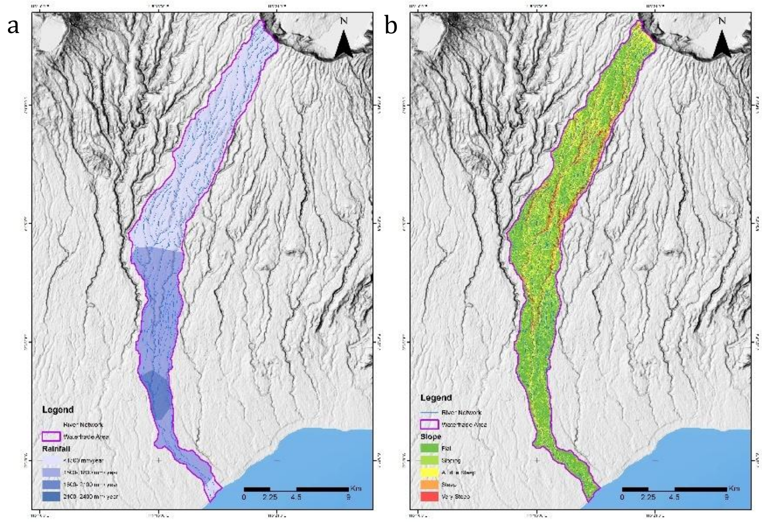

Fig. 3 (a) Rainfall map of the Oos watershed; (b) Slope map of the Oos watershed

Land use is also included as one of the parameters determining landslide estimates with a fairly high weight. Data processing to extract land use data uses Sentinel-2 level 1C image data. Sentinel level 1C satellite images were chosen because the image data processing used does not utilise spectral reflection, so only radiometric correction of the image to TOA (Top of Atmospheric) is required. Land use classes are classified based on the BIG (Geospatial Information Agency) land cover classification. The land use classification method uses supervised classification. Land use in the Oos watershed is dominated by plantations with 29% and settlements with 30% spread across the downstream and middle sections, as shown in Figure 4.a. The land use with the highest landslide estimation influence score is farmland, where in the Oos watershed, farmland is distributed in the upstream area with an area of 1,342.74 Ha. Farmland is a land use factor with a high score because farmland/fields can reduce soil stability and accelerate soil water saturation caused by intensive human activities. The weight of the land use parameter is quite high and significantly influences the estimation of landslide potential. In the Oos watershed, the forest area accounts for only 0.5% or 66.96 hectares, meaning that the area used for water absorption and soil retention is very limited, and most of it has already been utilised, which can trigger a high level of landslide potential (Rahmania et al., 2019).

The soil type in the Oos watershed is dominated by andosol soil. The andosol soil in the Oos watershed is derived from volcanic deposits from Mount Batur. However, according to FAO data, the andosol soil in the Oos watershed is divided into three subtypes: vitric andosol, ochric andosol, and mollic andosol, as shown in Figure 4.b. These three subtypes of soil have differences in physical properties, chemical properties, and soil horizon morphology. The vitric andosol soil type in the Oos River Basin extends from upstream to downstream on the eastern side. Vitric andosol soil is a type of soil that is easily saturated with water and has a high volcanic glass content, making it less stable. Ochric andosol soil is located in the central part of the watershed on the southwestern side of the Oos watershed. This soil type has limited water retention capacity and is highly stable under dry conditions. Mollic andosol soil is located in the central part of the watershed on the northwestern side of the Oos watershed. This soil type has good water absorption capacity and a stable soil structure. Although the analysis results were improved based on soil subtypes, the soil type parameter class only includes andosol soil, so the score used is based on the soil type parameter. The soil type score in the Oos watershed is moderate because andosol soil is prone to waterlogging. The lowest soil type parameter weight affects landslide potential.

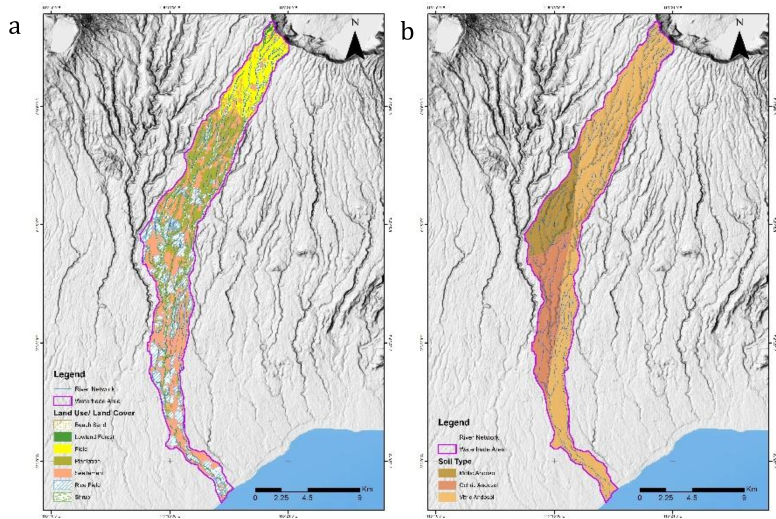

Fig. 4 (a) Map of land use in the Oos watershed; (b) Map of soil types in the Oos watershed

The landforms in the Oos watershed vary from upstream to downstream. Landform data was obtained from the analysis of BIG (Geospatial Information Agency) land system data, geological data, and topographical data. The landforms in the Oos River Basin are divided into four types: coastal alluvial plains, lower hillside slopes, middle volcanic slopes, and upper volcanic slopes, as shown in Figure 5.a. In the upstream area, the landforms are dominated by volcanic landforms due to the presence of Mount Batur, in the middle area they are dominated by hill slopes, while in the downstream area they are dominated by coastal alluvial plains. The landform parameter has the highest weight among other parameters. The Oos watershed is dominated by mid-slope volcanic landforms with an area of 6,556.36 hectares. The distribution of scores for landforms is relatively even, with almost all scores accommodated by the landform parameter. Upper-slope volcanic landforms have the highest scores, as these slopes are located in hilly topography with steep slopes.

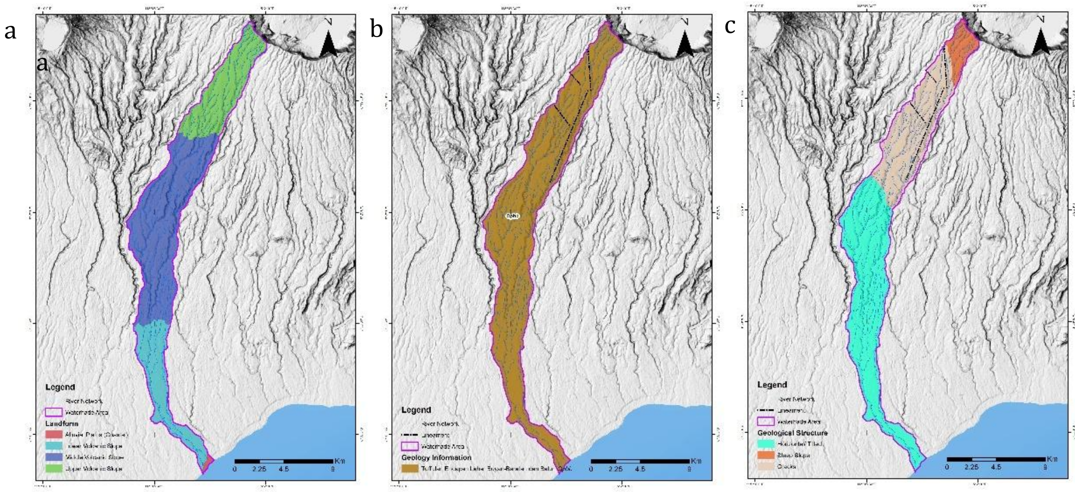

Fig. 5 (a) Topographic map of the Oos watershed; (b) Geological map of the Oos watershed; (c) Geological structure map of the Oos watershed

Geological data for the Oos watershed were obtained from geological maps at a scale of 1:250,000, sheets 1707 and 1807. It was found that the Oos watershed consists of Quaternary rocks of the Qpbb type, which were formed by the Buyan-Beratan and Batur volcanic rock formations composed of tuff and lahars, as shown in Figure 5.b. In addition to rock types, the geological data for the Oos watershed also includes information on faults located in the middle section towards the upstream part of the watershed. Based on the geological data, an analysis was conducted to determine the geological structure present in the Oos watershed. The results of the geological structure analysis in the Oos watershed are divided into three parts: horizontal/inclined, fractures, and steeply inclined, as shown in Figure 5.c. The geological structure analysis not only uses geological data but also employs a topographical approach. The fractured geological structure is located in the middle section towards the upstream part of the watershed, following the fault/line information. The highest score influencing the landslide potential in the geological structure parameter is steeply inclined. The weight of the geological structure parameter is moderate, so the geological structure conditions do not significantly influence the landslide potential.

Analysis to determine potential landslide areas using the overlay or superimposition method of all parameters. All parameters with assigned scores will be multiplied by their respective weights, resulting in a total weighted sum that serves as the outcome for the potential landslide area. The analysis of the Oos watershed's potential landslide areas is dominated by non-potential landslide areas, covering 11,406.05 hectares, which accounts for 92.62% of the total watershed area. Other potential landslide classes can be seen in Table 8. For high-potential areas in the Oos watershed, the affected area is very small, only 4.87 hectares or 0.03% of the total watershed area, and is located in part of the upper watershed, as shown in Figure 6.a. The distribution of high landslide potential is located along the banks or edges of the upper Tukad Oos river.

Table 8. Landslide potential in the Oos watershed area

No	Landslide potential value	Landslide class	Area (Ha)	Percentage (%)
1	<90	No potential	11406.05	92.62
2	90- 96	Low potential	829.98	6.74
3	97- 99	Medium potential	72.97	0.5
4	>100	High potential	4.87	0.03
Total			12313.87	100

Low and moderate landslide potential classes are spread throughout the Oos watershed, but the downstream section is dominated by non-landslide potential classes. In the upstream section, despite the steep slope, the landslide potential class is low. This is because the upstream section of the watershed has fairly stable soil types, even though there is considerable agricultural land use in the upstream section. Rainfall also plays a role, with the upper reaches having an average annual rainfall of <1500 mm/year. When compared with landslide risk data from the National Disaster Management Agency (BNPB) via Inarisk data, as shown in Figure 6.b, the high-risk landslide area in the Oos watershed based on Inarisk data is 386.62 hectares. Differences in the resolution levels used for analysis affect the discrepancies between Inarisk results and research findings. Inarisk data is more suitable for small-scale analysis, resulting in larger area outputs when compared with research analysis data, as shown in Figure 6.c. For detailed research studies, independent scoring analysis is more appropriate than using Inarisk data.

The development of tourism activities in the Ubud and Kintamani areas has not significantly increased the potential for landslides in the Oos watershed. Land use in Ubud, located on moderately steep to steep slopes, is still dominated by irrigated rice fields. This land cover type has a low score in the landslide susceptibility assessment, and therefore the expansion of tourism infrastructure in Ubud does not directly amplify slope instability. By contrast, the situation in Kintamani requires more careful attention. Much of the land on steep slopes is converted into fields or dry agricultural land, which receives a high score as a parameter for landslide potential. This land use pattern, combined with steep topography, creates conditions where the risk of slope failure is more likely to occur. Nevertheless, the current tourism development in Kintamani tends to follow road corridors along the northern side of the caldera, especially near Lake Batur, which lies outside the Oos watershed boundary. Despite this, the implications for the Tukad Oos watershed cannot be ignored. To minimise the increase in landslide-prone areas, regular monitoring of land-use change is essential, particularly in the upper watershed where water-absorbing areas play a crucial hydrological role. Preservation of these catchment functions ensures that slope stability can be maintained even under increasing pressure from agricultural expansion or tourism-related land conversion. While irrigated rice fields in Ubud act as buffers against slope instability, the agricultural practices in Kintamani highlight the need for stricter land-use regulation and sustainable farming techniques on steep terrain.

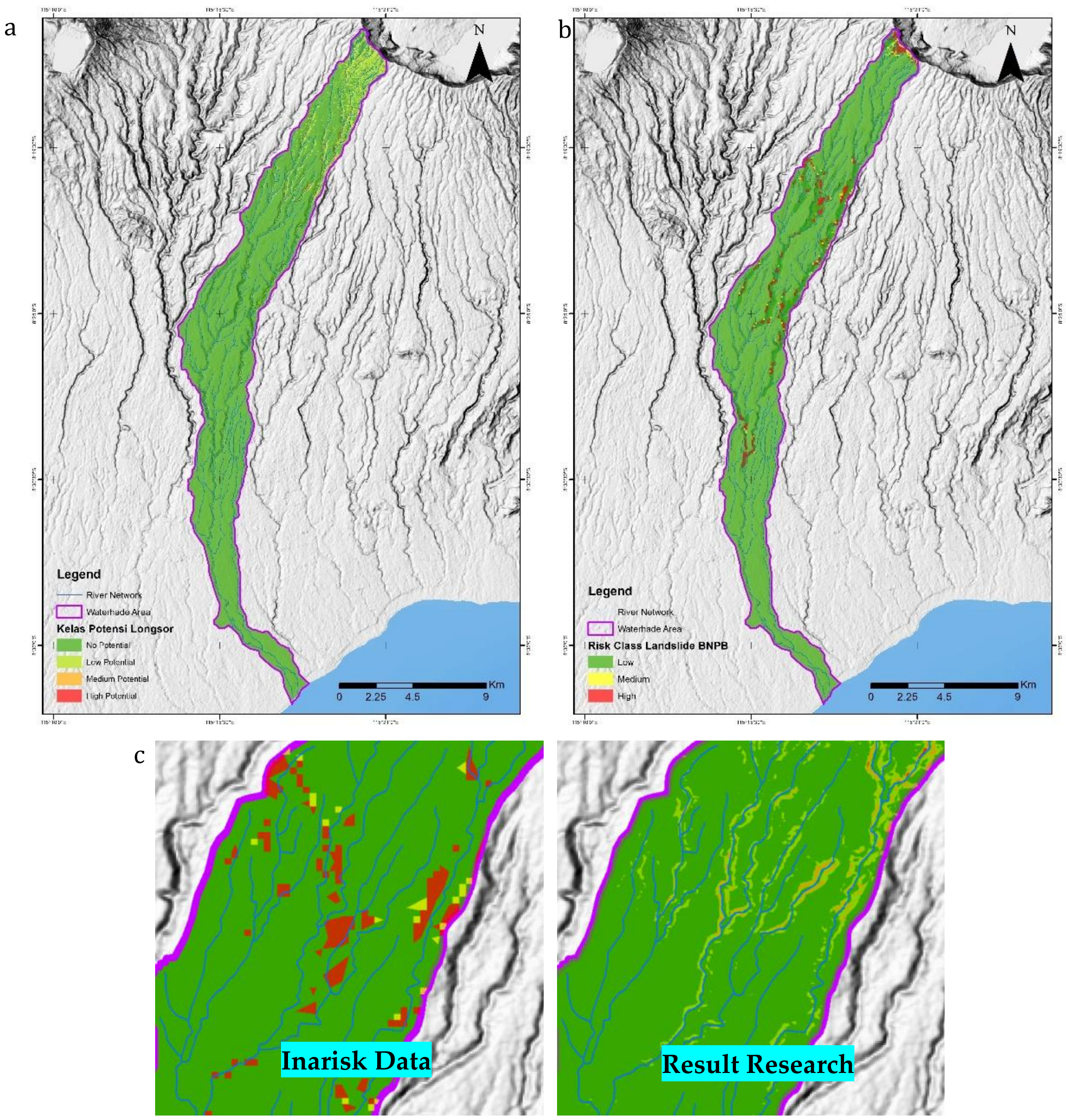

Fig. 6 (a) Map of landslide potential in the Oos watershed; (b) BNPB Inarisk landslide risk map; (c) Comparison of the resolution levels of Inarisk results and research results

This study also acknowledges its methodological limitations. The overlay and scoring methods applied, although widely used in spatial landslide assessment, have constraints in representing the complexity of slope processes. For future research, the integration of advanced modelling approaches such as machine learning is highly recommended. Several recent studies have demonstrated the potential of artificial intelligence techniques in enhancing landslide susceptibility mapping. Shahabi et al. (2023) and Agboola et al. (2024), for example, applied machine learning methods to classify slope instability with higher precision, reducing uncertainties associated with traditional scoring systems. Such approaches, if adopted in the Oos watershed context, could provide more accurate predictions and thus inform more targeted mitigation strategies. Furthermore, the integration of land-use dynamics through Google Earth Engine (GEE) offers a promising direction. Studies by Amalia et al. (2024), Fariz et al. (2020), and Aldiansyah & Saputra (2023) have shown the effectiveness of GEE in near real-time monitoring of land cover change, which is critical for proactive landslide risk management.

Beyond the methodological aspect, the interaction between tourism development and watershed sustainability should be viewed within a broader socio-ecological system. Arimbawa (2025) highlighted that the Mount Batur Geopark in Kintamani is categorized as a special-interest tourism destination, attracting not only casual visitors but also researchers and students who seek longer stays. The geopark integrates three major components, geodiversity, biodiversity, and culture, into a holistic tourism and conservation framework. The geodiversity of Mount Batur, as recognized by UNESCO since 2012, encompasses volcanic landscapes, caldera formations, and archaeological traces that serve both scientific and cultural values (Harini, 2021). The presence of Lake Batur, considered one of the largest and most beautiful calderas globally (Van Bemmelen, 1949), also provides vital ecosystem services, especially irrigation water that supports the Subak system, which itself has been designated as a UNESCO World Heritage site.

The biodiversity dimension of the geopark further enhances its ecological and economic importance. The Kintamani highlands are suitable for coffee cultivation, particularly organic coffee managed under agroforestry systems that minimize chemical inputs (Arimbawa, 2025). These agro-tourism practices, while beneficial for local livelihoods and conservation, also intersect with slope stability issues. Coffee plantations, if managed with soil conservation techniques, can mitigate erosion. However, if poorly managed, they can exacerbate surface runoff and increase landslide potential. The recognition of the Kintamani dog as a unique genetic resource further illustrates the intertwining of biodiversity conservation with local culture and tourism development. The cultural aspect is equally significant. The Subak system in Bali is not only an irrigation practice but also a manifestation of Tri Hita Karana philosophy, harmonizing relationships between humans, nature, and the divine. In Kintamani, cultural sites such as Ulun Danau Batur Temple and Terunyan Village reflect deep-rooted traditions that coexist with volcanic landscapes. However, these socio-cultural assets must be safeguarded against excessive land conversion or poorly planned infrastructure development, which could trigger ecological degradation and slope instability.

Experiences from other watersheds in Bali reinforce these concerns. I. Waridin et al. (2023) observed in the Ayung watershed that rapid tourism development has often led to severe land conversion and a decline in community awareness of environmental stewardship. Improper management of watershed resources, coupled with insufficient government socialization, has exacerbated risks such as landslides and pollution. Resort managers in Ayung who embraced the Tri Hita Karana concept and involved traditional villages in management practices were more successful in maintaining watershed sustainability (Waridin & Astawa, 2021). This highlights that strong community participation and customary law institutions play a decisive role in protecting watershed functions in Bali. Stakeholder analysis, as proposed by Stanghellini (2010), suggests that successful watershed management requires the integration of appropriators, providers, and producers. In the context of Oos watershed, this means aligning the interests of local communities, government agencies, and private tourism operators toward shared conservation goals.

The lessons from both the Ayung and Batur–Kintamani contexts provide crucial insights for managing the Tukad Oos watershed. Maintaining irrigated rice fields in Ubud as stable land cover, promoting sustainable agro-tourism practices in Kintamani, and ensuring community involvement in watershed monitoring represent key strategies for balancing tourism growth with slope stability. Ultimately, the sustainability of the Oos watershed depends on multi-stakeholder cooperation, technological innovation in monitoring, and the cultural wisdom embedded in Bali's traditional institutions. Future research should thus prioritize the integration of geospatial technologies such as GEE, predictive modelling with machine learning, and participatory approaches that empower local communities as active guardians of their environment. Only through such a multi-layered approach can the dual objectives of tourism development and watershed sustainability be achieved in the Tukad Oos watershed.

4. Conclusions

The results of the landslide potential analysis in the Oos watershed show that the high landslide potential class covers an area of 4.87 Ha or 0.03% of the total area, the moderate landslide potential class covers an area of 72.97 Ha or 0.5% of the total area, low potential class covering 829.98 hectares or 6.74% of the total area, and no landslide potential class covering 11,406.05 hectares or 92.62% of the total area. The high landslide potential area in the Oos watershed is located on the banks or edges of the upper Tukad Oos river. The results of the landslide potential analysis from this study are quite similar to the Inarisk BNPB data, with the difference being in the spatial resolution, where the Inarisk BNPB data is less detailed. The development of tourism activities in the Ubud and Kintamani areas does not significantly affect the increase in landslide potential in the Oos River Basin.

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