

Risk-Informed Settlement Development: A Landslide Mitigation Framework for Transmigration Areas in Polewali Mandar

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ABSTRACT

Landslides pose a major threat to settlements in transmigration zones, highlighting the need for a risk-based approach in sustainable land planning. This study introduces a Risk-Informed Settlement Development Framework to evaluate the landslide vulnerability in Ratte Village, Polewali Mandar Regency, which covers 625,000 km². A spatial analysis method was employed, combining various thematic layers, including geology, topography, land use, and rainfall intensity, to assess the risk levels using scoring and weighting techniques. The results show that much of the settlement area falls within moderate to high-risk zones, mainly due to steep slopes, heavy rainfall, and unsuitable land use practices. However, some low-susceptibility areas offer safer options for future settlement expansion. The novelty of this study lies in integrating landslide risk reduction with a proactive feasibility assessment for settlement development, shifting from traditional hazard mapping to forward-looking, adaptive land use planning. This research offers a decision-support tool that not only identifies risks, but also helps guide the strategic settlement relocation and development through multi-criteria spatial analysis. Future research should focus on enhancing the framework by including real-time monitoring data, socio-economic vulnerability indices, and climate change projections to improve the predictive accuracy and applicability across different geographic regions. The proposed framework serves as an essential tool for policymakers and planners to ensure the long-term safety and resilience of transmigrant communities in landslide-prone areas.

Keywords-landslide risk; transmigration settlement; spatial analysis; risk-informed planning; mitigation framework

I. INTRODUCTION

Landslides are among the most common and devastating natural disasters worldwide, resulting in significant

environmental damage, substantial economic losses, and numerous casualties. According to the United Nations Office for Disaster Risk Reduction (UNDRR), landslides impact around 4.8 million people each year, mainly in mountainous

and high-rainfall areas. The occurrence of landslides is influenced by various factors, including the geological conditions, topography, land-use practices, and climate change. Improper land use planning and human activities, such as deforestation and unregulated settlements, further increase the landslide risks [1–3].

Indonesia, located along the Pacific Ring of Fire, is highly vulnerable to landslides due to its complex geology and frequent heavy rainfall. According to data from the Indonesian National Board for Disaster Management (BNPB), landslides account for more than 40% of all natural disasters in the country. Several studies have shown that areas with steep slopes, heavy rainfall, and poorly managed land use are especially susceptible to landslides [4, 5]. Furthermore, the rapid urbanization and agricultural expansion into unstable terrains have greatly increased the frequency and severity of landslides in Indonesia [6].

Polewali Mandar Regency in West Sulawesi is particularly prone to landslides because of its rugged terrain, heavy rainfall, and continuous land-use changes. The frequent landslides in this region have caused damage to infrastructure, have displaced the residents, and have disrupted the economic activities. Previous research indicates that heavy rainfall and human activities, like deforestation and improper land use, are the main triggers of landslides in the region [7]. Ratte Village, located in Polewali Mandar Regency, is a designated transmigration settlement area, where the government has allocated large areas of land for residential and livelihood purposes. However, its susceptibility to landslides poses a serious threat to the safety and sustainability of these settlements. It has been shown that many transmigration settlements in Indonesia are constructed without proper geotechnical assessments beforehand, which increases the risk of disasters [8, 9].

Spatial analysis techniques, particularly Geographic Information Systems (GIS), are widely used for landslide susceptibility mapping, providing essential tools for disaster risk assessment and land-use planning. Methods, like the Analytic Hierarchy Process (AHP) and the Frequency Ratio (FR), have been effectively applied to combine multiple landslide-triggering factors [10, 11]. Despite these advances, research that integrates landslide risk assessments with settlement feasibility analysis remains limited, especially in transmigration areas. Internationally, GIS-based models have been successfully used for landslide hazard assessments. For example, authors in [12] created a landslide susceptibility map with machine learning algorithms, showing high accuracy in hazard prediction. Likewise, authors in [13] emphasized the importance of incorporating socio-economic factors into disaster risk assessments [13]. However, many existing studies focus only on hazard assessment without considering settlement planning, thus leaving a significant research gap [14, 15].

This study bridges this gap by combining landslide risk assessment with settlement feasibility analysis, offering a risk-informed framework for sustainable settlement development in transmigration areas. It advances previous research, which mainly focuses on landslide hazard mapping, by incorporating

land suitability evaluation and mitigation strategies to enhance the disaster resilience. Using GIS-based spatial analysis along with scoring and weighting techniques, the study provides a comprehensive decision-making framework for policymakers in disaster-prone regions. The primary objective of this study is to develop a risk-informed settlement planning framework for transmigration areas that are vulnerable to landslides. The study specifically aims to: (a) identify the landslide-prone areas in Ratte Village using geological, topographical, and land-use criteria; (b) evaluate the suitability of the existing and potential settlement sites in these regions; and (c) provide strategic recommendations to reduce the landslide risks and promote sustainable land management in the transmigration zones. The novelty of this research lies in that it combines risk assessment with settlement planning, enabling a proactive disaster mitigation strategy to guide future development in transmigration zones. By integrating hazard analysis with land-use planning, this study offers key insights for local and national policymakers, facilitating the development of more resilient and adaptable settlements in Indonesia's high-risk areas.

II. MATERIALS AND METHODS

A. Research Location

This study was conducted in Dusun Ratte Barat, Ratte Village, Tubbi Taramanu District, Polewali Mandar Regency, West Sulawesi, Indonesia. The area was selected because of its high risk of landslides, caused by the hilly terrain and ongoing land-use changes. The study site, identified through spatial analysis and field surveys, is situated between $118^{\circ} 57' 45''$ E and $118^{\circ} 59' 30''$ E, and between $03^{\circ} 11' 35''$ S and $03^{\circ} 14' 29''$ S. Its UTM coordinates range from $X = 718100$ to 721100 , and $Y = 9642100$ to 9646500 . The elevation ranges from 450 to 600 m above the sea level (m asl).

B. Research Approach

This study employs a spatial approach to assess the landslide risk distribution in transmigration areas by combining map interpretation, field surveys, and secondary data analysis. Satellite imagery and thematic maps were employed for the initial assessments and were later validated through field observations. Additionally, secondary data, such as rainfall records, geological maps, and land-use data supported the analysis further. To accurately classify the landslide susceptibility, a scoring and weighting method was applied to key factors, like the slope, soil type, land use, and rainfall, following established criteria. This integrated approach offers a comprehensive framework for risk-informed settlement planning in landslide-prone transmigration zones [16].

C. Research Method

This study employs GIS-based spatial analysis to assess the suitability of the settlements in the transmigration zones, focusing on seven key variables: slope, drainage, erosion, land use, road access, access to essential facilities, and landslide risk. Thematic maps and spatial overlays are used to classify the settlement suitability, incorporating data from official land surveys, the Land Office, the Ministry of Public Works and Public Housing (PUPR), Landforms of Indonesia topographic

maps (RBI), field surveys, and Regional Disaster Management Agency landslide hazard maps (BPBD). A scoring and weighting system, adapted from [17, 18], assigns scores (high, moderate, unsuitable) and weights (strong, moderate, low influence) to each variable, ensuring the accurate classification of the settlement feasibility (Table I). The priority development areas are identified by overlaying the settlement suitability maps with the existing settlements and spatial plans, such as the Ratte Village Spatial Plan (RTRW), in line with the regional development policies. The classification results in three categories: highly suitable areas (low hazard), moderately suitable areas (manageable risk), and unsuitable areas (high hazard or policy restrictions).

TABLE I. CLASSIFICATION CRITERIA WEIGHT AND SCORE VARIABLES

Variable	Weight	Classification	Criteria	Score
Slope	3	2-15%	High conformity	3
		15-40%	Medium conformity	2
		>40%	Low conformity	1
Drainage	1	Never flooded	High conformity	3
		Flooded periodic	Medium conformity	2
		Continuously flooded	Low conformity	1
Erosion	1	No erosion	High conformity	3
		Erosion medium	Medium conformity	2
		High erosion	Low conformity	1
Land use	3	Field, garden	High priority	3
		Settlement	Medium priority	2
		Rice fields /reservoirs/forests	No priority	1
Road accessibility	3	0-100 m	High potential	3
		100-200 m	Medium potential	2
		>200 m	Less potential	1
Accessibility	2	0-750 m	High conformity	3
		750-1500 m	Medium conformity	2
		>1500 m	Less suitable	1
Landslide vulnerability	3	Low vulnerability	High conformity	3
		Moderate vulnerability	Medium conformity	2
		High vulnerability	Low conformity	1

This approach provides a risk-informed framework for secure and sustainable settlement planning in landslide-prone transmigration regions.

$$\text{Total dignity} = V_1 \times b_1 + V_2 \times b_2 + \dots + V_n \times b_n \quad (1)$$

Description: V_1 represents the score of the first variable, V_2 represents the score of the second variable, and V_n is the score of the n-th variable. b_1 indicates the weight of the first variable, b_2 indicates the weight of the second variable, and b_n indicates the weight of the n-th variable. The residential suitability is crucial for safe and sustainable spatial planning, especially in areas with significant environmental constraints and opportunities for improvement. Based on the frameworks developed by [19, 20], with necessary adjustments for local conditions, this study classifies the settlement suitability into three levels, as shown in Table II. The classification intervals for each suitability level are determined using:

$$\text{Class interval} = \frac{\text{Max.account of dignity} - \text{Min.account of dignity}}{\text{Number of classes created}} \quad (2)$$

According to the total score calculation outlined in (2), the suitability of the settlement in landslide-prone transmigration areas is categorized into three levels: Class I (suitable, score range 38–48), Class II (conditionally suitable, score range 27–37), and Class III (not suitable, score range 16–26). The settlement development priorities are determined by evaluating the land availability through the overlay of the suitability maps, existing settlements, and zoning regulations from the RTRW 2012–2032. The land availability is classified into three categories: Available I, Available II, and Not Available. Priority is given to the areas designated as Available I, which have the largest land area. This classification system ensures that the risk-informed settlement development aligns with the regional planning frameworks and disaster mitigation strategies. The specific criteria for determining the settlement location availability are detailed in Table III.

TABLE II. LOCATION SUITABILITY CLASS FOR SETTLEMENT

Class	Levels
I	Suitable for residential area development
II	Conditionally appropriate for residential area development
III	Not suitable for residential area development

TABLE III. CRITERIA FOR CLASS AVAILABILITY OF LOCATIONS FOR RESIDENTIAL AREAS

Availability class	Criteria		
	Location suitability	Existing conditions of use	Spatial pattern allocation
Available I	In accordance	Residential and non-residential	Residential area
Available II	Conditionally appropriate		
Not available	Compliant, conditionally compliant, and non-compliant		Protected areas and non-residential cultivation areas

D. Landslide Mitigation Framework Method

This study employs a Landslide Mitigation Framework (LMF) that combines spatial analysis, hazard assessment, and settlement suitability evaluation. The specific approach involves overlaying thematic maps of the slope, geology, land use, rainfall, drainage, and erosion using a GIS-based method, with each factor scored and weighted according to its contribution to the slope instability. Field surveys were carried out to verify the spatial analysis, ensuring an accurate identification of the risk-prone areas and the development of a comprehensive landslide hazard map that guides sustainable land-use planning. To develop a risk-informed settlement strategy, the study combines hazard maps, infrastructure access, and zoning rules to evaluate the settlement viability. The settlement suitability is categorized into highly suitable, moderately suitable, and unsuitable zones based on regional development policies. The high-risk areas are proposed for relocation or structural mitigation, while the conditionally suitable zones require non-structural measures, such as improved drainage systems and adjustments to land use. This

integrated framework guarantees that the transmigration settlements in Polewali Mandar are planned proactively to reduce risks, striking a balance between disaster mitigation and sustainable land management.

III. RESULTS AND DISCUSSION

The settlement suitability in transmigration areas at risk of landslides is evaluated through a spatial decision-making process that considers seven key factors: slope, drainage, erosion, land use, road accessibility, access to key facilities, and landslide hazard. These factors are assessed based on their physical, environmental, and regulatory importance to ensure an accurate classification of the areas suitable for residential development. The classification process employs a structured spatial overlay method to thoroughly address both the landslide risk and settlement feasibility. This section presents the results and discussion, emphasizing how these factors influence the settlement suitability and help develop a framework that includes risk considerations. The main aim of these findings is to promote safe and sustainable settlement planning in the transmigration areas of Polewali Mandar.

A. Slope/Grid

The slope plays a vital role in determining the suitability of settlements in landslide-prone transmigration areas, as steeper slopes significantly increase the risk of land instability. For safety and stability, the residential development should primarily focus on areas with gentle slopes. In this study, the slope is classified into three categories based on topographic survey data: 2–15% (suitable), 15–40% (moderately suitable), and above 40% (unsuitable), as depicted in Table IV. These classifications help identify the safe zones for settlement and support the development of effective mitigation strategies in high-risk zones.

Table IV indicates that 71.58% (757.97 ha) of Ratte Village is on slopes of 15–40%, emphasizing the need for structural reinforcements to ensure safe development. Approximately 28.38% (300.51 ha) of the area has slopes between 2% and 15%, making it the most suitable zone for settlement. Only 0.04% (0.4 ha) of the area has slopes exceeding 40%, which are highly prone to landslides and are considered unsuitable for housing. Previous studies highlight that slopes below 15% offer a stable ground for construction, while slopes above 30% often require extensive mitigation measures. These findings emphasize the importance of prioritizing low-slope areas for residential development and applying strict regulations and engineering controls in medium-slope zones to reduce the landslide risks.

TABLE IV. SLOPE GRADIENT CRITERIA

Slope	Criteria	Wide (Ha)	%
2-15%	High conformity	300.51	28.38
15-40%	Medium conformity	757.97	71.58
>40%	Low conformity	0.4	0.04

B. Drainage

The study area has poor drainage, resulting in frequent waterlogging and flooding during heavy rainfall. This also accelerates the soil erosion, weakening the infrastructure

stability and increasing the risk of waterborne diseases. Improving the drainage system is crucial for enhancing the flood resilience and developing safer settlements in landslide-prone transmigration zones.

C. Land Use

Field observations reveal that the study area encompasses a mix of gardens, open land, dryland agriculture, settlements, and water bodies (Table V). Each land use type influences the residential suitability, with important implications for environmental sustainability and disaster resilience, especially in landslide-prone transmigration zones.

TABLE V. LAND USE CRITERIA

Land use	Criteria	Land use (Ha)	%
Mixed garden (cacao-pepper-banana-clove, candlenut, vegetables etc.), intercropping pattern	High priority	886.98	83.77
Open land	Medium priority	114.65	10.83
Dry agriculture land (field rice)	High priority	50.54	4.77
Settlement	Medium priority	5.33	0.50
Water bodies	High priority	1.38	0.13

The mixed gardens cover 83.77% of the study area and include crops, such as cocoa, pepper, and banana. The settlements account for only 0.50%, and the water bodies for just 0.13%, making them minor components. Previous studies indicate that these areas support the ecological sustainability, but often lack adequate infrastructure, which increases the erosion risks in open and dryland farming regions. Effective planning is essential for balancing the agricultural activities, safe settlement growth, and environmental protection in landslide-prone transmigration zones.

D. Road Accessibility and Accessibility of Important Places

Dusun Ratte Barat has limited access because of poor road conditions. The asphalt roads from Polewali to Luyo turn into gravel and dirt, making travel difficult, especially during heavy rain. The lack of bridges over the Mapi' and Mandar Rivers further isolates the area. Authors in [21] emphasize that poor infrastructure hampers the economic growth, emergency response, and quality of life. Improving roads and bridges is crucial for better connectivity and sustainable settlement development in landslide-prone regions.

E. Landslide Disaster Vulnerability

The settlement suitability is evaluated based on seven key factors: slope, drainage, erosion, land use, road access, facility access, and landslide risk. A GIS-based analysis combines these elements through maps, field surveys, and secondary data sources. Each factor is assigned a weight (3 for significant impact, 1 for minor impact) and rated on a scale from 1 to 3. The final classification, as presented in Table VI, categorizes the areas based on the total suitability scores, providing guidance for safe and sustainable settlement planning in landslide-prone transmigration zones.

TABLE VI. RESIDENTIAL LOCATION SUITABILITY CLASS

Suitability class	Criteria	Land use (Ha)	%
Class I	Highly suitable	306.83	28.99
Class II	Conditionally suitable	411.16	38.83
Class III	Not suitable	340.74	32.18

In Ratte Village, the settlement suitability is categorized into three classes: Class I (highly suitable), at 28.99%; Class II (conditionally suitable), at 38.83%; and Class III (not suitable), at 32.18%. Class I areas are ideal for building settlements, whereas Class II areas require improvements, such as drainage or erosion control. Class III areas are unsuitable due to factors, such as steep slopes, poor drainage, or other disaster-related risks. Previous research highlights the importance of GIS-based analysis in evaluating the settlement suitability, which supports the findings of this study. Improving Class II areas can boost the settlement potential, and Class III areas should be preserved for environmental protection.

F. Availability of Locations for Settlement

Evaluating the land for settlements in Ratte Village involves overlaying land suitability, existing settlements, and the RTRW spatial plan (2012–2032) for Polewali Mandar Regency. This analysis categorizes the land into three categories: Available I, Available II, and Not Available (Table VII). Although the area is large, steep slopes and conservation zones restrict the settlement expansion, mirroring the situation in nearby villages. It is essential to carefully select sites to minimize risks. Previous research emphasizes that mapping the settlement potential is vital for disaster mitigation and for encouraging sustainable land use.

G. Landslide Mitigation Framework

The analysis reveals that Ratte Village is highly vulnerable to landslides due to its hilly terrain, heavy rainfall, and ongoing land-use changes. The GIS-based spatial analysis categorized the study area into three susceptibility levels: high (42.6%), moderate (35.8%), and low (21.6%). High-risk areas primarily occur on steep slopes with a gradient of over 40%, where the settlements and agricultural expansion have disrupted the natural stability. These findings highlight the urgent need for both structural and non-structural mitigation strategies to ensure a safe and sustainable development in the transmigration area.

TABLE VII. AVAILABILITY OF RESIDENTIAL LOCATIONS

Suitability class	Land use (Ha)	%
Available I	862.56	81.46
Available II	60.57	5.72
Not available	135.75	12.82

Using a Multi-Criteria Evaluation (MCE) approach, the suitability of the settlements was assessed based on seven key variables: slope gradient, drainage, erosion, land use, road accessibility, facility accessibility, and landslide vulnerability. The overlay analysis categorized the region into three classes: Class I (highly suitable – 28.99%), Class II (conditionally suitable – 38.83%), and Class III (not suitable – 32.18%). The most suitable areas are primarily located in lower-slope regions with better infrastructure, while the conditionally suitable zones

require interventions, such as improved drainage and erosion control measures. The unsuitable zones align with high-risk landslide areas and conservation regions, underscoring the importance of avoiding settlements in these locations.

This research integrates settlement feasibility analysis with landslide risk mitigation, unlike previous studies that focus only on hazard mapping, creating a comprehensive decision-making framework and that future residential development aligns with disaster resilience principles. This methodology combines geospatial analysis and practical land-use planning, allowing policymakers to prioritize safe locations and implement mitigation strategies in medium-risk areas. The strategic recommendations for sustainable development included:

1. Relocation of high-risk settlements: Transmigration settlements in high-susceptibility zones should be relocated to safer, low-slope areas designated as Class I.
2. Reinforcement in medium-risk areas: Structural interventions, including retaining walls, terracing, and adequate drainage systems, are essential in Class II areas to mitigate the landslide risk.
3. Sustainable land-use planning: The study emphasizes the preservation of steep slopes and conservation zones to reduce the human-induced destabilization.
4. Improving infrastructure and accessibility: Enhancing road networks, bridges, and drainage systems will foster safe and sustainable community development.

The findings provide valuable guidance for local authorities and policymakers seeking to incorporate landslide risk reduction methods into spatial planning and migration initiatives. By emphasizing the development in low-risk areas and applying specific mitigation strategies in regions classified as medium-risk, this study boosts the long-term resilience of transmigrant populations in Polewali Mandar.

IV. CONCLUSION

This study evaluates the suitability of settlements and landslide risks in the transmigration areas of Polewali Mandar, aiming to support sustainable land use and reduce the disaster risks. The designated settlement is situated in the Other Land Use Area (OLUA) with community approval. The spatial analysis and interviews carried out highlight three key factors: habitability, economic viability, and development potential. The area has access to clean water, supports agriculture, and aligns with the regional planning goals. This research integrates risk assessment with settlement planning, promoting proactive mitigation measures, such as slope stabilization and infrastructure improvements. It also emphasizes economic links that promote the regional development. The proposed Landslide Mitigation Framework (LMF) integrates geospatial analysis with effective relocation and risk reduction strategies, offering a replicable model for other landslide-prone transmigration areas in Indonesia and similar regions worldwide. For future follow-up, the current study proposes expanding the framework to include dynamic data inputs, such as rainfall forecasts and real-time landslide monitoring, as well

as integrating community-based risk perceptions and assessments of adaptive capacity to improve the long-term resilience and policy relevance.

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