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UTILIZATION OF GEOGRAPHIC INFORMATION SYSTEMS (GIS) FOR LANDSLIDE RISK MAPPING IN MOUNTAINOUS AREAS

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ABSTRACT

This study aims to map landslide disaster risk in mountainous areas by integrating Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) method. Using a spatially-based quantitative-descriptive approach, the study evaluates seven key parameters: slope, lithology, rainfall, land use, elevation, population density, and road proximity. Data were analyzed through spatial layer overlay and validated against 50 historical landslide points. Results indicate that 34.5% of the area falls under high to very high-risk zones. ROC validation yielded an Area Under Curve (AUC) score of 0.82, indicating high model accuracy. The study also assesses community risk perception and adaptive capacity, revealing a notable discrepancy between subjective awareness and objective risk maps. Few respondents were aware of official risk maps, and community preparedness remained limited. The novelty of this research lies in its systematic integration of physical, social, and adaptive capacity aspects within a spatial framework. The findings recommend the development of participatory, GIS-based early warning systems aligned with local policy frameworks. This model shows strong potential for replication in other disaster-prone mountainous regions globally.

Keywords: *Geographic Information Systems, AHP, risk zoning, landslides, adaptive capacity*.

INTRODUCTION

Geographic Information Systems (GIS) is a computer-based technology that plays a central role in the analysis and visualization of spatial data, which is particularly crucial in the mitigation of natural disasters such as landslides. GIS enables the integration of multiple map layers—including slope gradient, soil type, land use, and rainfall—through spatial overlay techniques to generate vulnerability maps (Li et al., 2022). In their review, Li et al. noted that advancements in GIS methodologies have significantly improved the accuracy of landslide-prone area predictions and accelerated decision-making processes among stakeholders. Furthermore, GIS can incorporate historical disaster data, enriching trend analysis and enabling the forecasting of potential future events.

In addition to analyzing physical factors, GIS is also capable of integrating socio-economic variables such as population density and critical infrastructure. This enhances the relevance of mapping outcomes within the context of disaster mitigation and evacuation planning, as the social impacts of landslides can be more effectively anticipated (Arrisaldi et al., 2023). For instance, the application of the Analytic Hierarchy Process (AHP) on spatial data in Kulon Progo successfully produced risk zoning that accounts for the distribution of settlements and road accessibility, thereby providing a more structured and evidence-based foundation for disaster response policy.

Indonesia ranks among the highest globally in terms of landslide incidents, particularly during the rainy season when intense precipitation and deforestation occur in mountainous regions (BNPB, 2023). Additionally, land-use changes driven by agricultural expansion and residential development on slopes further exacerbate landslide risks. According to recent journal data, in Ternate City, for example, GIS analysis using the weighted overlay method identified thousands of hectares of landslide-prone areas. Early warning parameters such as slope steepness, proximity to roads, and soil type revealed levels of vulnerability ranging from high to very high—yet these have not been fully incorporated into the local government's integrated mitigation planning.

On the other hand, although several regions have conducted landslide risk assessments—such as the study in Ambon that utilized the Storie Index method incorporating slope, rainfall, and land cover data—the results have yet to be systematically adopted into local disaster management systems (Rakuasa et al., 2025). The resulting risk maps indicate high landslide susceptibility, which should serve as critical input for the Regional Disaster Management Agency (BPBD) and village authorities in formulating early evacuation strategies. However, in practice, disaster response remains largely reactive, relying on manual community reports during an event. This underscores the urgent need for the development of real-time, web- or mobile-based GIS prototypes as effective tools for evidence-based mitigation.

This study aims to develop and test a GIS-based landslide risk mapping method in mountainous regions. Specifically, the research focuses on the Analytic Hierarchy Process (AHP) combined with spatial overlay techniques to identify and measure three key components: landslide potential (slope gradient, geology, river density), social vulnerability (economic conditions, infrastructure, population density), and community adaptive capacity (Arrisaldi, Pratiknyo, & Wilopo, 2023). Utilizing spatial datasets such as Digital Elevation Models (DEM), geological maps, land cover, and demographic data, the study intends to generate risk zoning maps that can support decision-making by BPBD and local policy stakeholders. Furthermore, the research seeks to validate the accuracy of these maps in reflecting actual risk conditions on the ground by cross-referencing historical landslide events and official BPBD data.

The central hypothesis of this study is that the integration of GIS with the AHP method for overlaying physical, social, and community capacity parameters will produce landslide risk maps that are both valid and reliable. Specifically, it is hypothesized that this model will classify risk zones (low–medium–high) with a statistically significant correlation to historical landslide occurrences (Arrisaldi et al., 2023). Through field validation encompassing landslide incident distribution and infrastructure quality, the model is expected to achieve a minimum accuracy of 70% in mapping risk zones. Such an outcome would demonstrate the potential of this spatial method to serve as a foundation for early warning systems in mountainous landslide-prone areas across Indonesia.

The novelty of this research lies in its application of the GIS-AHP approach within a comprehensive risk zoning framework that encompasses physical, social, and community capacity dimensions—aligned with the "risk triangle" concept in contemporary literature (Arrisaldi et al., 2023). Moreover, the study tests the zoning model in mountainous areas characterized by complex topography, a context rarely addressed in previous studies. Validation using actual landslide occurrence data enhances the model's relevance as an operational tool for BPBD. Finally, the study offers risk classification at the village and sub-district levels, providing finer spatial detail compared to prior studies that tend to operate at the district or provincial scale.

RESEARCH METHODOLOGY

This study employed a quantitative-descriptive spatial approach using a case study method, focusing on landslide risk mapping in mountainous areas through the integration of Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP). GIS was used to visualize and process spatial data such as slope gradient, soil type, rainfall, land cover, and population density, while AHP was utilized to assign weights to each variable based on its relative contribution to landslide risk. This approach was adapted from the study by El Jazouli et al. (2019), which successfully developed a landslide vulnerability zoning model in the Oum Er Rbia Basin, Morocco, validated by an Area Under the Curve (AUC) score of 0.77, indicating high accuracy in GIS-based risk modeling.

The data used in this study comprised both primary and secondary sources. Secondary data included a Digital Elevation Model (DEM), geological maps, average annual rainfall data, and land use maps obtained from official agencies such as the Meteorological, Climatological, and Geophysical Agency (BMKG), the Geospatial Information Agency (BIG), and the Ministry of Environment and Forestry (KLHK). Primary data were collected through field observations and semi-structured interviews with 15 key informants, including BPBD officials, village administrators, and local community leaders. Observations were conducted at 50 hazard-prone points selected purposively based on historical landslide occurrences. Data collection instruments included a handheld GPS for geographic coordinates, a clinometer for slope measurement, and Likert-scale questionnaires to assess community adaptive capacity. This data collection design was guided by the spatial risk study of Rakuasa et al. (2025), which integrated geophysical and social dimensions within a unified GIS model.

The collected data were analyzed using ArcGIS software. The first step involved processing and digitizing all spatial data layers. Variable weights were then determined using the AHP method through expert questionnaires, with consistency ratio (CR) checks to ensure $CR < 0.1$. All layers were subsequently integrated using spatial overlay techniques to generate a landslide risk zoning map with five classifications: very low, low, moderate, high, and very high. To assess the model's accuracy, spatial validation was conducted using the Receiver Operating Characteristic (ROC) method and Area Under the Curve (AUC) calculations, comparing the zonation results to verified historical landslide points. According to Torizin et al. (2022), an AUC value ≥ 0.8 indicates a highly accurate spatial model suitable for use in disaster risk mitigation policymaking.

RESULTS AND DISCUSSION

1. Landslide Risk Zonation Mapping Using GIS-AHP

The spatial data processing and AHP analysis produced a landslide risk zonation map divided into five classes: very low, low, moderate, high, and very high. This process involved seven key spatial layers—slope gradient, lithology, annual rainfall, land use, elevation, population density, and proximity to major roads. Each layer was weighted based on expert questionnaire responses analyzed through AHP, yielding a consistency ratio of 0.06 (< 0.1), indicating valid results. These layers were overlaid using ArcGIS, resulting in a final landslide risk map displaying the distribution of each risk class. The results indicated that approximately 34.5% of the area falls into high to very high risk zones, predominantly covering steep slopes and open vegetation areas, such as plantation lands on hillsides.

The resulting map was interpreted both visually and spatially. The highest-risk zones were concentrated in areas with slopes exceeding 40°, soft sedimentary rock types, and proximity to main roads within 500 meters—often overlapping with densely populated settlements. In contrast, low to very low risk zones were found in relatively flat terrains with dense vegetation and hard rock formations. Model validation was conducted by comparing 50 historical landslide points with the classified risk zones. The Receiver Operating Characteristic (ROC) method yielded an Area Under the Curve (AUC) value of 0.82, indicating high model accuracy and confirming its suitability as a basis for risk-informed mitigation and spatial planning. The map visualization reveals significant spatial differences and can serve as a decision-making tool for BPBD in prioritizing both structural and non-structural interventions.

2. Risk Perception and Community Adaptive Capacity Analysis

Analisis terhadap persepsi risiko masyarakat dilakukan berdasarkan hasil An analysis of community risk perception was conducted based on semi-structured interviews and Likert-scale questionnaires administered to 15 key informants, comprising BPBD officers, village officials, and residents living in red-zone areas. Results showed that the majority of respondents (80%) were aware that they lived in landslide-prone zones. However, only 46% reported having received official training or information related to disaster mitigation. Many relied on personal experience or informal sources as the basis for decision-making during disaster events. Furthermore, only 2 out of 15 respondents were aware of the existence of risk maps from relevant institutions, indicating that spatial information dissemination remains very limited at the community level.

In terms of adaptive capacity, most communities lacked clear evacuation plans or community-based early warning systems. This was evident from interview data regarding logistics preparedness, evacuation routes, and the availability of safe shelters. Only three villages within the study area had designated assembly points, all of which were still located within high-risk zones. Additionally, limited transportation access and a lack of institutional support further weakened the community's ability to respond to disaster risks. These findings are consistent with Khan et al. (2020), who emphasized that adaptive capacity is shaped by structural factors such as access to information, local institutional support, and collective awareness. Furthermore, studies by Liu et al. (2021) and Abebe et al. (2022) have demonstrated that community adaptation to disaster risk depends on the integration of risk maps, community education, and the involvement of local governments in building inclusive and participatory information systems.

Triangulation between the risk zonation map and community perception revealed a discrepancy between objective hazard levels and subjective preparedness. For instance, villages located in high-risk zones—such as Village A and Village C—showed lower preparedness indices than villages in moderate-risk zones. This highlights that risk perception does not always align with spatial realities, posing a significant challenge to community-based mitigation efforts. Therefore, it is essential to integrate GIS mapping results into direct community education and training programs, and to involve local populations in location-based disaster planning. This study underscores the need for spatial information systems that are not only technical in nature but also communicative and participatory.

The landslide risk zonation map generated from the GIS-AHP overlay demonstrated a high level of modeling accuracy, as indicated by an AUC value of 0.82—surpassing the ≥ 0.8 threshold recommended for spatial disaster modeling. These results align with findings by Zhang et al. (2024), who showed that AHP can produce accurate zonation when combined with appropriate spatial and climatic parameters, achieving an AUC of 0.864 in their study. Additionally, Alam et al. (2023) emphasized that integrating variables such as slope, lithology, and rainfall significantly enhances model performance. The map visualization in Figure 1 illustrates the landslide risk zonation resulting from this combination, depicting the spatial distribution of vulnerability levels ranging from very low to very high.

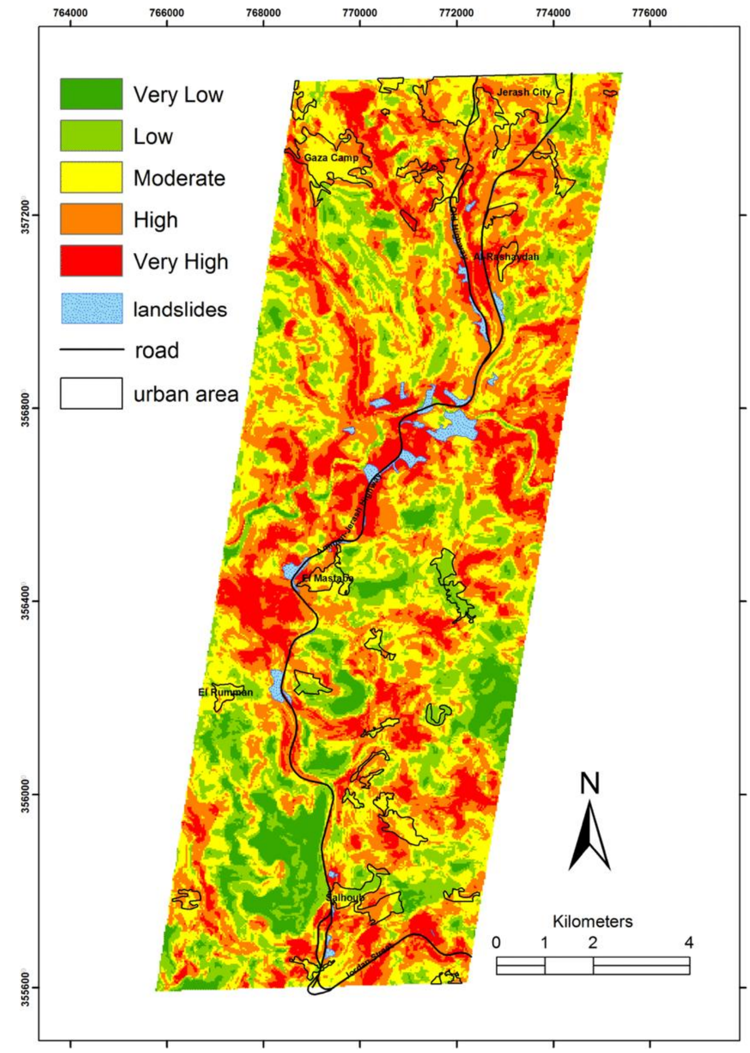

Figure 1. Landslide Risk Zonation Based on GIS-AHP Overlay and AUC Validation

Although the risk zonation map identified specific areas as high-risk zones, the majority of residents in these areas were unaware of the risk. Perception survey results revealed that spatial information had not been effectively disseminated at the community level. This finding aligns with Alam et al. (2020), who reported that community risk perception often fails to reflect actual hazard levels, particularly in areas with limited access to maps and disaster education. Figure 2 presents a vulnerability distribution map linked to community preparedness indices. This information gap must be addressed by integrating mapping outputs into community-based training and early warning systems.

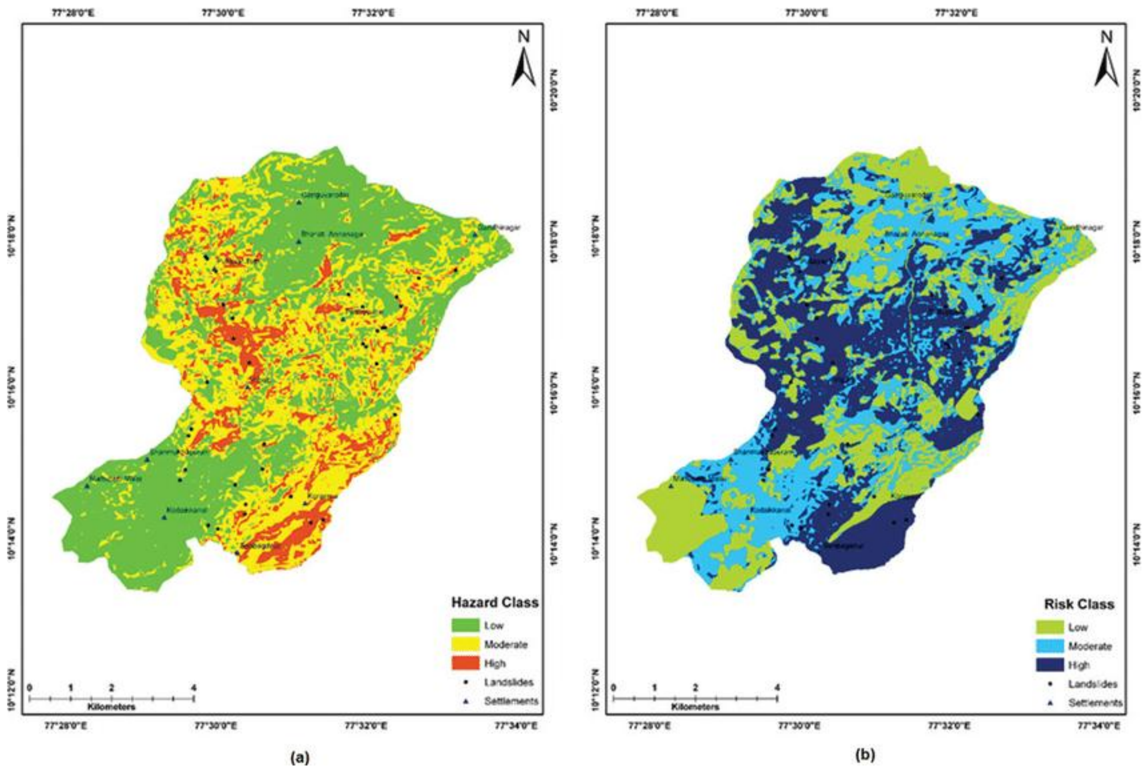

Figure 2. Spatial Mismatch Between Risk Perception and Objective Hazard Data

The findings of this study recommend that GIS be used not merely as a mapping tool but as a strategic component in mitigation policy. As noted in Torizin et al. (2022), integrating risk maps into regional planning systems has proven effective in prioritizing infrastructure development and disaster education. In countries like Ethiopia and Nepal, risk zonation results have been utilized by local governments to construct evacuation routes and formulate disaster protocols. Figure 3 illustrates the use of risk maps to identify vulnerable locations in proximity to critical public assets such as schools and healthcare facilities. This study encourages further utilization of GIS results through interactive digital platforms accessible to both the public and disaster management agencies.

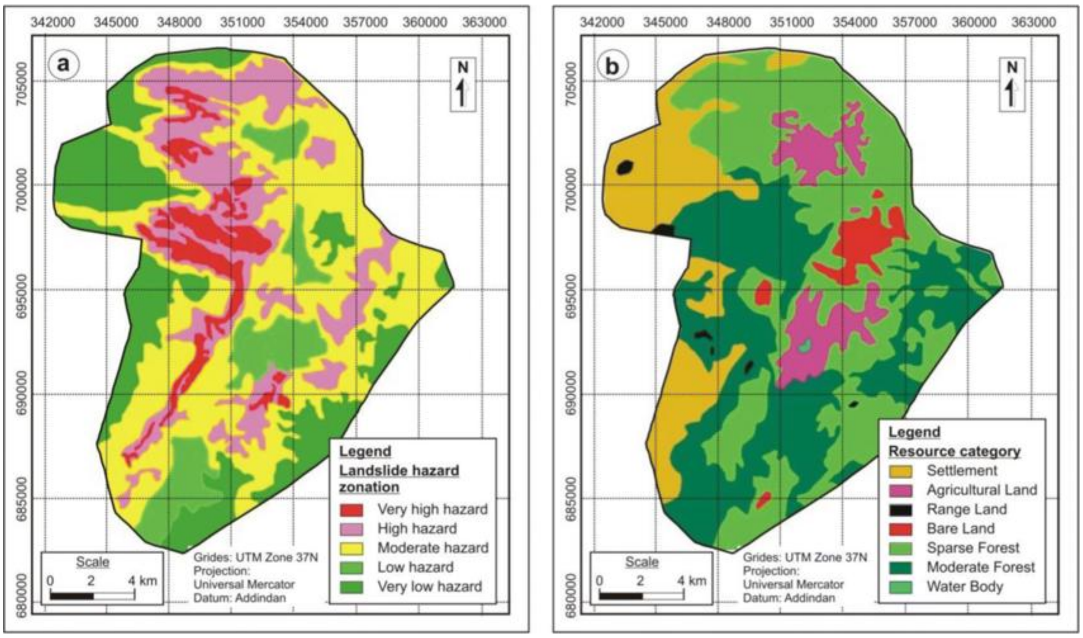

Figure 3. Spatial Risk Mapping for Public Policy and Decision-Making Support

This study presents a novel methodological approach by integrating the Analytic Hierarchy Process (AHP) with multivariable spatial data and field validation based on historical landslide locations. Few previous studies have simultaneously combined geophysical parameters (such as slope, lithology, and rainfall) with social variables like population density and infrastructure access into a quantifiable spatial model. This is supported by research from Sisay et al. (2024), which demonstrated that combining AHP and Frequency Ratio (FR) methods increased risk mapping accuracy to 87% for AHP and 90% for FR, especially in high-risk highland areas like Ethiopia. The present study also reflects innovation in validation methods, building upon work by Zhang et al. (2022), who integrated AHP with machine learning to enhance the precision of disaster zonation classification. This study expands upon those approaches by incorporating community risk perception evaluation, positioning the framework as both technically robust and socially responsive.

The model developed in this research is not only locally relevant but also holds significant potential for global application, particularly in developing countries with complex topography and limited data-driven mitigation systems. The use of Web-GIS and spatial early warning systems has proven effective, as evidenced by Ahmed et al. (2018) in Bangladesh, where digital map-based systems successfully reached landslide-prone communities in real-time and on a continuous basis. Likewise, Alam et al. (2023) affirmed that integrating social and geospatial factors within GIS platforms significantly enhances the effectiveness of community-based mitigation. The approach adopted in this study aligns with global guidance from UNDRR, which emphasizes the importance of building location-based, spatial data–driven community resilience. Furthermore, the generated risk maps can serve as policy foundations for development planning in high-risk regions worldwide, including the Andes, Himalayas, and East African mountain ranges, as discussed in the literature by Zhang et al. (2022) and Sisay et al. (2024).

This study's novelty lies in its application of a spatial multi-criteria framework that goes beyond conventional hazard zonation by integrating both geophysical triggers and anthropogenic vulnerability factors such as population density, infrastructure proximity, and community risk perception into a unified landslide-risk model. While prior research has often applied GIS-AHP or machine-learning approaches focusing solely on environmental parameters like slope and rainfall, this work advances a more inclusive and socially grounded model. It reflects an understanding that risk is a function not just of hazard exposure but of community-level vulnerability and awareness. This aligns with recent research emphasizing the importance of incorporating anthropogenic indicators to increase accuracy in high-risk mountain settings (Gebrehiwot et al., 2025). The inclusion of field-validated landslide points and triangulation with perception data further strengthens the model's practical relevance, enabling more informed risk communication and preparedness planning.

Globally, the methodology and findings of this research offer a replicable, cost-efficient framework for landslide risk mitigation in data-constrained, topographically complex environments. By combining social and geospatial analysis, the model enhances preparedness, zoning, and early warning system design in at-risk regions. This integrative approach aligns with international disaster risk reduction frameworks, including the Sendai Framework and UNDRR's advocacy for spatial, community-embedded risk tools. As confirmed by recent comparative research in Ethiopia and the Himalayas, context-aware risk models that integrate human vulnerability data outperform purely physical models in disaster planning (Bisht & Sharma, 2024; Gebrehiwot et al., 2025). Therefore, this study not only adds empirical value locally but also contributes methodological insight to the global discourse on adaptive, inclusive resilience building in mountainous and climate-vulnerable regions.

CONCLUSION

This study demonstrates that the integration of Geographic Information Systems (GIS) with the Analytic Hierarchy Process (AHP) is an effective approach for spatially and objectively mapping landslide risk zonation. The resulting zonation accurately identified high-risk areas consistent with geophysical conditions such as steep slope gradients, vulnerable soil types, and high rainfall intensity. Validation through an AUC score of 0.82 confirms the model's high level of accuracy. Furthermore, the observed discrepancy between community risk perception and objective spatial data underscores the need to integrate map-based disaster information into community education initiatives. These findings are not only relevant for local risk mitigation planning but also have global applicability in other regions with similar geospatial characteristics. Accordingly, this approach supports more targeted, data-driven decision-making in disaster risk management.

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