Formulation of an Eruption Mitigation Plan for Mount Merapi Based on Settlement Land Suitability in Umbulharjo, Yogyakarta

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Received: 2026-01-08 Received in revised from 2026-01-20 Accepted: 2026-01-22

Abstract

Umbulharjo sub-district, Kapanewon Cangkringan has experienced an increase in population every year, thereby intensifying the demand for residential land. In the meantime, the area of Umbulharjo sub-district is located within the Mount Merapi Disaster-Prone Area (DPA). Land suitability is an important instrument in mitigation efforts, as it provides an overview of the physical characteristics of the area that influence the level of disaster risk. This study aims to formulate an eruption mitigation plan for Mount Merapi from technical and social perspectives. Residential land suitability analysis was conducted using a quantitative method, namely an overlay technique employing ArcGIS software. The results show that 78.24% of the land is marginally suitable, 21.04% is unsuitable, and less than 1% is suitable for residential use. Relocation emerges as one of the main mitigation strategies to eliminate risk, especially for communities living within disaster-prone zones. However, relocation presents its own implementation challenges, as residents in the study area are unwilling to be relocated, despite the existence of local government policies regulating relocation. Therefore, in addition to focusing on spatial planning, the mitigation plan is also formulated from technical and social aspects, such as enhancing building resilience to earthquakes and volcanic ash, planning evacuation routes, and providing community education, particularly regarding disaster preparedness.

Keywords: land suitability; mitigation; volcanic eruption

1. Introduction

The growth and development of the population in Umbulharjo sub-district has led to an increasing demand for residential land. This condition has driven construction activities in locations that are in fact unsuitable for residential purposes, thereby increasing the risk of natural disasters [1]. Umbulharjo sub-district is located within the Mount Merapi Disaster-Prone Area (DPA). The eruption of Mount Merapi on 26 October 2010 triggered a series of natural phenomena, such as pyroclastic flows, lava flows, and ashfall, which had severe impacts on the community and the surrounding environment. Mount Merapi is still classified as an active volcano to this day. Therefore, efforts to manage volcanic eruption disasters are required.

As is known, Umbulharjo sub-district is located on the slopes of Mount Merapi, making it at risk of eruption disaster threats [3]. The Disaster-Prone Area (DPA) is divided into three levels, namely DPA III, DPA II, and DPA I. DPA III is the zone with the highest level of hazard, which is potentially affected by pyroclastic flows, lava flows, ejection or collapse of incandescent rocks, as well as toxic gases. DPA III lies within a range of two kilometres from peak of Mount Merapi. Meanwhile, DPA II covers areas with potential exposure to lava flows, ejected incandescent rocks, phreatic eruptions, heavy ashfall, toxic gases, pyroclastic flows, and landslides of volcanic material. DPA II is located within a radius of five kilometres from peak of Mount Merapi. The level of hazard in DPA II is classified as moderate to high. DPA I, on the other hand, is a zone with a lower level of hazard, which is at risk of being affected by lava flows, ashfall, and ejected incandescent material within a radius of eight kilometres from peak of Mount Merapi [4].

According to Sleman Regency Regulation Number 20 of 2011 concerning the Mount Merapi Disaster-Prone Area, the development of new settlements and commercial as well as service activities is prohibited within Disaster-Prone Area Zone III. Nevertheless, activities such as conservation, research, and forestry remain highly feasible, even though settlement activities are restricted. Therefore, this study is needed to analyze residential land suitability based on physical conditions and disaster risk, as a reference for developing eruption mitigation strategies for Mount Merapi in both technical and social aspects. Actions taken to address or reduce disaster risk are known as disaster mitigation [2].

According to Law of the Republic of Indonesia Number 24 of 2007 on Disaster Management, mitigation is defined as measures undertaken to reduce disaster risk. This effort can be implemented through physical development, awareness raising, and strengthening community capacity. The formulation of a disaster mitigation action plan plays an important role in supporting disaster preparedness processes. Disaster mitigation can be carried out through the development of infrastructure and regulations, as well as through education and the enhancement of public awareness [5].

Relevant studies indicate that the effects of volcanic eruptions and other disasters have been widely investigated, as illustrated by the following research. A study has been conducted to model land use change in the Rejali watershed, located around Mount Semeru, for the period from 2022 to 2032. The research employed Land Change Modeler, a logistic regression method with a Markov chain algorithm, and built-up land scenarios, based on historical land use data from 2002 to 2022. Primary data consisted of field survey results, conversion elasticity, and conversion probabilities, while secondary data included Landsat imagery, physical factors (slope and elevation), and socio-economic factors (distance to main roads, rivers, government centers, economic activity centers, and population density). The findings show a decrease in the surface area of water bodies by 5.31% and forest area by 23.80%, alongside an increase in built-up land by 3.15%, open land by 0.48%, agricultural land by 23.71%, and undeveloped land by 0.01% over the 2002–2022 period. The expansion of built-up land around Mount Semeru is expected to increase eruption risk in the future [6].

The earthquake in Yogyakarta and Central Java on 27 May 2006 was one of the largest earthquakes in Indonesia. In response to this event, a study was conducted to classify and map Bantul into residential and non-residential areas, based on earthquake management considerations using remote sensing and Geographic Information System (GIS) methods. The mapping process applied several parameters with assigned scores. Landsat 7 ETM+ imagery from 2007 and secondary data from previous studies were utilized in the mapping process. The study's results recommend a spatial design framework to guide future regional planning [7].

Earthquake disaster mitigation in Bolu Province, Turkey was formulated based on a GIS model. The GIS model criteria used included distance from the main fault, ground motion acceleration, bedrock type, and slope gradient. Based on these criteria, a residential suitability map was generated. The provincial road network map was then superimposed onto the residential suitability map so that the government could provide 200 m evacuation zones along the roads. The residential suitability map served as a reference for formulating plans to strengthen existing settlements and designate new areas for urbanization and industrialization [8].

The subsequent research consists of a study aimed at assessing and mapping landslide susceptibility in the Wolaita Zone, Ethiopia. An integrated geospatial and Multi-Criteria Decision-Making (MCDM) approach was employed. The datasets were obtained from USGS Earth Explorer, NASA POWER, and the World Geologic Maps, and the data analysis was carried out using ArcGIS 10.8.2 software. Fourteen causative factors were selected and grouped into five domains, namely topographic, hydrologic, geologic, anthropogenic, and environmental. Each factor was standardized and weighted using the Analytical Hierarchy Process (AHP). The findings indicate that areas with steep slopes, high rainfall, sparse vegetation, proximity to river channels, and specific lithological formations are more susceptible to landslides [9].

The subsequent study employs spatial autocorrelation statistics to investigate the spatial and temporal dynamics associated with compound disasters resulting from global climate change. The Soil and Water Assessment Tool is employed to calculate runoff volume and sediment discharge. Through this method, land use locations that trigger disasters can be identified. The modelling results indicate the presence of various spatial and temporal clusters among compound disasters. In certain areas, similar disasters occur regularly, whereas other locations may act as sources of those recurrent disaster events [10].

2. Method

The analysis of residential land suitability was conducted using a quantitative method based on numerical data. Data collection was carried out through field surveys and mapping. Field surveys involved direct observation and measurement of soil type, slope gradient, and rock type parameters. Mapping was conducted to obtain data on residential radius from the Merapi summit and disaster-prone areas. These data were then integrated with secondary data on flood events, rainfall, and groundwater. The integration of these datasets was intended to obtain a comprehensive overview of land conditions in the study area.

Subsequently, the formulation of the disaster mitigation plan was based on the results of the residential land suitability analysis by applying a scoring method and overlay technique. In the weighting method, a scoring scale or system was established for risk categorization. Overlay or superimposition techniques were applied to integrate all data, enabling spatial visualization and analysis of the relationships between land physical conditions and disaster risks. The overlay was performed on the disaster-prone area map; the residential radius map from the Merapi summit; the land unit map derived from integrating slope, rock unit, and soil type maps; as well as the results of disaster event, rainfall, and groundwater analyses. With this approach, appropriate mitigation strategy recommendations to reduce adverse impacts on communities and the environment can be properly formulated.

3. Results and Discussion

The land suitability assessment in Umbulharjo sub-district, Cangkringan, employed eight parameters, namely rainfall, soil type, slope gradient, rock type, flood hazard, groundwater, Disaster-Prone Area (DPA) status, and the distance of settlements from peak of Mount Merapi. The rainfall analysis used data for a 10-year period. The average annual rainfall intensity over this period is 2,569 mm/year, which falls into the moderate category. The soil type in the study area is regosol. Regosol is highly susceptible to erosion, making it less suitable for residential use because it can cause the loss of fertile topsoil, increase the risk of flooding, and trigger landslides that may damage buildings and settlement infrastructure. The study area exhibits a variety of slope gradients, ranging from flat with a slope of 0–8%, gentle 8–15%, moderately steep 15–25%, to steep 25–45%. An illustration of the slope gradient is presented in Figure 1. The majority of settlements are located on flat and gently sloping terrain. The rock formations in Umbulharjo sub-district consist of young Mount Merapi volcanic rocks and older Mount Merapi deposits. The rock types in the study area are predominantly volcanic. The groundwater table depth in the study area is 13 meters. Most residents use mountain spring water for their daily needs. The water is stored in reservoirs, as shown in Figure 2. Another parameter in the residential land suitability analysis is flood hazard potential. Although the study area does not experience inundation flooding, there is a potential for cold lahar floods due to high rainfall that transports volcanic material from the summit of Mount Merapi. The study area includes three categories of Disaster-Prone Areas (DPA), as shown in Figure 3. Meanwhile, Figure 4 presents residential areas within a radius of five kilometres and 15 kilometres from the summit of Mount Merapi. These conditions indicate that the study area has a high level of disaster hazard.

Subsequently, the results of the analysis of the eight parameters were assigned weights using an overlay technique, as presented in Figure 5. The findings indicate that 78.24% of the land area, or 7,111,000 m², falls into the marginally suitable category for settlement. A total of 21.04% of the land area, or 1,912,000 m², is classified as unsuitable. The remaining area, accounting for less than 1% or 49,580 m², is categorized as suitable for residential development.

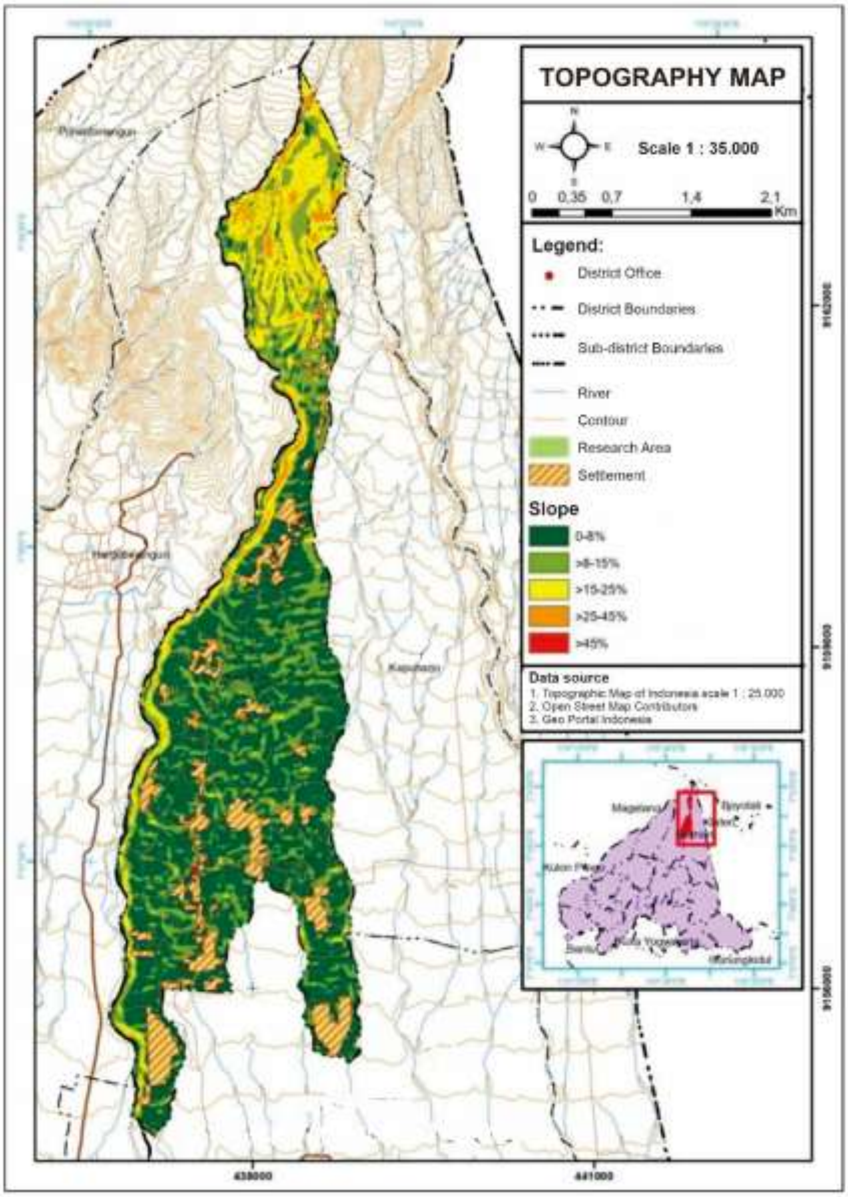

Figure 1. Topography Map

Figure 2. Water Storage Facilities in the Study Area

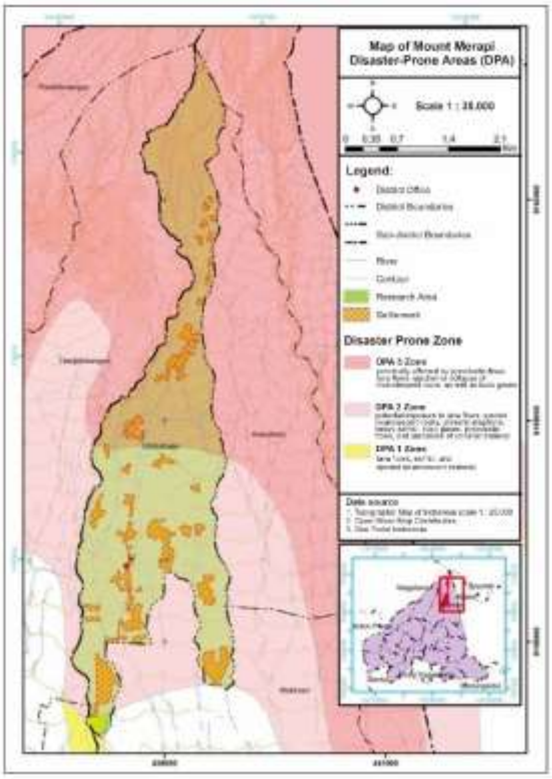

Figure 3. Map of Mount Merapi Disaster-Prone Areas (DPA)

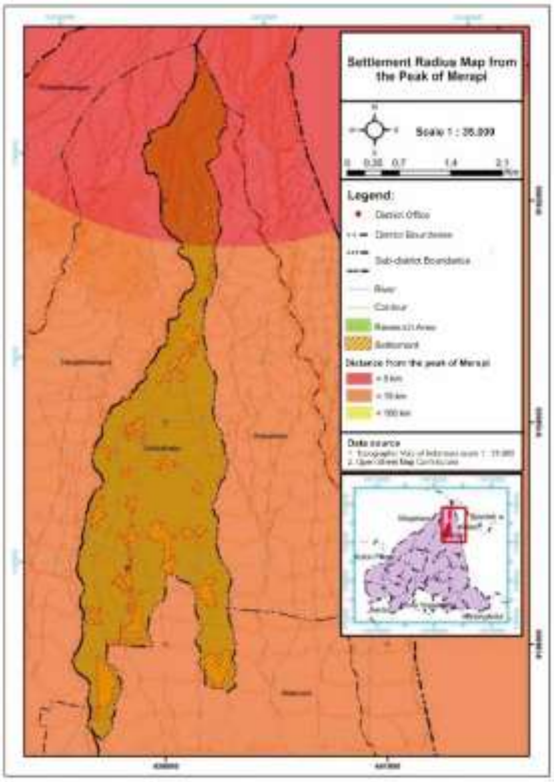

Figure 4. Settlement Radius Map from the Summit of Merapi

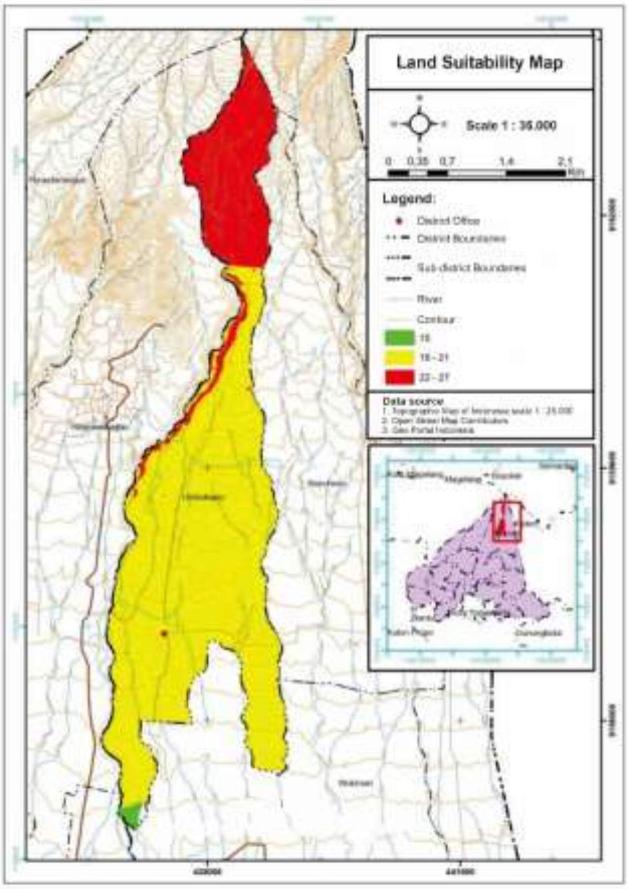

Figure 5. Land Suitability Map

The mitigation plan for Mount Merapi eruptions in Umbulharjo sub-district, based on the results of the residential land suitability analysis, is centred on relocation. The primary mitigation strategy, namely relocation, is intended to eliminate risk for communities residing within disaster-prone zones. However, in practice, residents have refused to be relocated [11]. The Sleman Regency Regulation Number 20 of 2011 concerning the Disaster-Prone Areas of Mount Merapi stipulates that two out of nine hamlets in Umbulharjo Village fall within the zone with the highest level of hazard, and therefore their areas are prohibited from being used as residential zones. Given the challenges encountered in implementing relocation, a mitigation plan has also been formulated from both technical and social perspectives. This includes enhancing the resilience of buildings to earthquake and volcanic ash hazards, planning evacuation routes, and providing community education on disaster response activities.

Volcanic eruptions are typically accompanied by the emission of volcanic ash, sand, rock material, and lava flows that cause damage to surrounding areas. The destructive impacts of volcanic activity can extend over a wide area. To reduce the associated risks, the government and relevant institutions continuously strive to raise public awareness of potential hazards through the implementation of disaster mitigation strategies. One such measure is the planning of emergency-responsive infrastructure designed to withstand earthquakes and volcanic ash [12]. The application of earthquake-resistant building concepts is carried out by ensuring that connections between structural elements are robust and strong, selecting appropriate materials, and implementing proper construction methods [13]. The use of lightweight building materials can improve structural performance in anticipating seismic forces, for example, through the use of light steel roof trusses, metal roof tiles, timber walls, and ceilings with hollow frames [14]. During an eruption, ashfall accumulates on rooftops and forms a mass that cannot be easily displaced. This condition increases the roof load and may cause structural damage [15]. Roof construction types capable of withstanding the impact of volcanic sand can be realised by using light steel structures made of durable metal that resists extreme weather conditions, with a recommended triangular roof truss design so that volcanic sand does not accumulate on its surface [16].

Mitigation of Mount Merapi eruptions also involves the recommendation to plan evacuation routes. The Regional Disaster Management Agency (BPBD) has designated evacuation routes for Umbulharjo Village, as shown in Figure 6. The evacuation routes are required to have a minimum width of three metres so that cars and motorcycles can pass simultaneously, enabling rapid evacuation. Another mitigation measure is providing community education on disaster response. The government or non-governmental organizations can conduct outreach to communities regarding potential natural hazards such as Mount Merapi eruptions and lava floods. These activities are intended to enhance public understanding of self-evacuation procedures during disasters. Social media plays an important role in emergency response management, particularly in disseminating up-to-date disaster information and increasing public awareness [17].

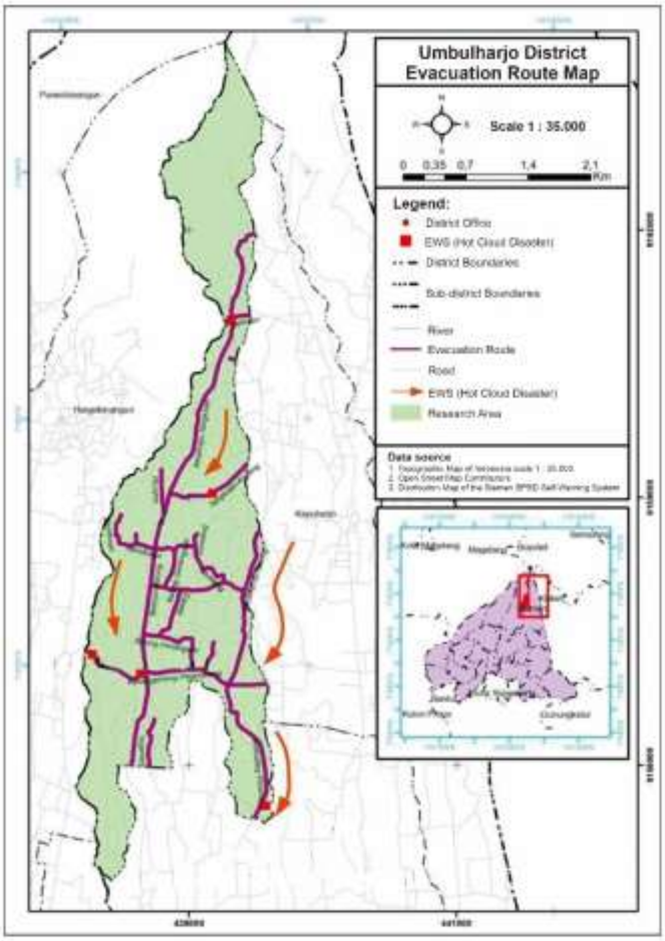

Figure 6. The Evacuation

4. Conclussion

The results of the study indicate that 78.24% of the study area is classified as marginally suitable for residential use, 21.04% as unsuitable, and only less than 1% as suitable for settlement. Relocation emerges as the primary strategy to eliminate risk, particularly for communities residing within disaster-prone zones. However, relocation poses specific implementation challenges, especially because residents in the study area are unwilling to be relocated despite the high eruption risk of Mount Merapi and the existence of local government relocation policies. The mitigation plan was also successfully formulated from technical and social perspectives, including enhancing the resilience of buildings to earthquakes and volcanic ash, planning evacuation routes, and providing community education on disaster preparedness.

Future research is recommended to utilize data with higher spatial and temporal resolutions to achieve greater analytical accuracy. Subsequent studies could incorporate analyses of social, economic, and community perception aspects regarding disaster risks. This would include exploring the impacts of climate change on rainfall intensity, eruption frequency, or cold lahar flow development, thereby providing a broader understanding of the long-term risks associated with Mount Merapi eruptions.

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