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Mitigating the impact of the Mount Semeru eruption in Lumajang regency using a geographic information system approach

Ilham Dani[1,*], Syamsurijal Rasimeng[1], Firda Amalia[1]

[1]Department of Geophysical Engineering, Faculty of Engineering, Lampung University, Bandar lampung, Indonesia

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Corresponding Author:
Ilham Dani
Ilham.dani0917@eng.unila.ac.id

Abstract
Indonesia is a country with high volcanic activity, with more than 130 active volcanoes. Mount Semeru is the highest volcano on the island of Java, which is located between Malang Regency and Lumajang Regency. Mount Semeru's volcanic activity can cause disasters such as lava flows, poisonous gas, volcanic ash ejections and rock avalanches. Mitigation of volcanic eruption disasters in Lumajang Regency is carried out by mapping areas that are potentially affected. This research aims to examine the use of Geographic Information Systems (GIS) in mapping areas affected by the eruption of Mount Semeru. The method used is GIS-based spatial analysis to identify areas prone to volcanic eruptions, which are divided into three zones based on their level of vulnerability. The mapping results show that Pronojiwo and Pasrujambe District has the highest level of vulnerability, followed by Candipuro and Senduro Districts.

Introduction

Indonesia is recognized as one of the most tectonically and volcanically active countries in the world. Its geological complexity arises from its location at the convergence of three major tectonic plates: the Indo-Australian Plate, the Pacific Plate, and the Eurasian Plate. This setting places Indonesia within the Pacific Ring of Fire, a horseshoe-shaped area known for intense seismic and volcanic activity (Hidayat et al., 2020; Peterman & Cordes, 2021). The subduction and interaction of these plates result in frequent earthquakes and volcanic eruptions, making Indonesia home to more than 130 active volcanoes.

One of the most prominent and active volcanoes in Indonesia is Mount Semeru, also known as Mahameru, the highest peak on the island of Java at 3,676 meters above sea level. It straddles the administrative boundaries of Malang and Lumajang Regencies and is a part of the Bromo Tengger Semeru National Park. Semeru is classified as a stratovolcano, characterized by its steep conical shape and layered structure, which is built from repeated eruptions of lava, ash, and pyroclastic material. Its formation is associated with the subduction of the Indo-Australian Plate beneath the Eurasian Plate (Suhendro & Haryono, 2023).

Mount Semeru exhibits persistent volcanic activity and is considered one of the most active volcanoes in Indonesia. Historical records indicate that since 1818, Semeru has undergone frequent eruptions, with eruption intervals ranging from 5 to 15 minutes during periods of high activity (Rawa et al., 2019). The main eruptive vent is located at Jonggring Seloko Crater, positioned on the southern side of the summit. This crater produces strombolian and vulcanian-type eruptions, often releasing lava flows, glowing rocks, volcanic ash, and pyroclastic density currents that flow rapidly down the mountain slopes.

One significant eruption occurred on December 4, 2021, which resulted in severe destruction. Hot clouds and lava avalanches devastated nearby villages, causing substantial damage to infrastructure and homes. The disaster led to 51 fatalities, 169 injuries, and numerous cases of burns and displacement (Huda et al., 2024). The direction of eruptive material tends to follow the topographic channels to the southeast and east, making Lumajang Regency—particularly the districts of Pronojiwo, Pasrujambe, Candipuro, and Senduro—particularly vulnerable to volcanic hazards.

In volcanic regions such as around Semeru, disaster vulnerability is influenced by both physical and socio-economic factors. These include the proximity of residential settlements to the eruption center, the presence of rivers that serve as paths for lahars (cold lava flows), land use such as agricultural fields, population density, and the quality of infrastructure. Among the districts in Lumajang Regency, Pronojiwo and Pasrujambe are noted for having medium to high vulnerability. Pronojiwo, for example, lies directly south of the crater and is affected by the Lengkong River, which channels lava and debris flows during eruptions. Meanwhile, Pasrujambe, although slightly further from the crater, has large areas of farmland interspersed with settlements, making it economically and physically susceptible to damage.

In response to these hazards, Indonesia has implemented a Volcano Disaster Prone Area (KRB) classification system to map volcanic risk zones. These maps divide areas into three levels of danger (Astari et al., 2022):

- KRB III indicates the highest hazard level, including zones directly impacted by lava, pyroclastic flows, and incandescent rock ejections.
- KRB II includes areas that are likely to be affected by hot clouds, ash rain, and lava flows.
- KRB I represents areas with a lower probability of being affected but still at risk from lahars and ash fall.

An effective method for enhancing disaster preparedness and risk mitigation is the use of Geographic Information Systems (GIS). GIS is a computer-based system used for collecting, managing, analyzing, and displaying spatial data. In volcanic disaster management, GIS enables the integration of hazard maps, land use data, demographic information, and topographical features to identify vulnerable areas and prioritize mitigation efforts. For Mount Semeru, GIS has been employed to overlay hazard data with social, economic, and environmental vulnerability factors to produce comprehensive disaster vulnerability maps.

These maps serve as crucial tools for decision-makers, enabling the identification of high-risk zones and supporting the development of evacuation routes, logistics centers, and disaster response strategies. The maps also help local authorities and the Regional Disaster Management Agency (BPBD) to conduct community outreach, simulations, and early warning dissemination, particularly in vulnerable districts such as Pronojiwo and Candipuro.

Moreover, regular monitoring by the Center for Volcanology and Geological Hazard Mitigation (PVMBG) has shown that Mount Semeru remains active. In the period between January and June 2024 alone, 343 eruptions were recorded (Fahmi, 2024). This data highlights the importance of continuous surveillance and the timely updating of hazard and vulnerability maps using real-time data and GIS tools.

Eventually, the active status of Mount Semeru and its recurrent eruptions present ongoing threats to surrounding communities. The integration of GIS-based mapping, KRB zoning, and continuous volcanic monitoring is vital for minimizing risks, enhancing community resilience, and ensuring effective disaster preparedness and response in Lumajang Regency and beyond.

Methods

This study was conducted in June 2024 using data from satellite imagery. This research uses a geographic information system approach to analyze areas prone to Mount Semeru eruption disasters. Geographic information systems (GIS) are used to collect, store, analyze and display spatial data (data related to location) and attribute data (information about spatial data). Spatial data is collected through geographic information systems such as topographic maps, geological data, volcano locations and eruption history data, as well as integrating and analyzing this data to identify areas potentially affected by eruptions.

The tools used in this processing are a laptop for processing data and writing research, ArcGis 10.8 software for creating eruption hazard maps, Goggle Earth software and Microsoft Word software. And the materials used in this research are Google Earth images of the Mount Semeru area, the Indonesian Topographical Map (RBI) of Mount Semeru, Mount Semeru eruption data. Flowchart to produce vulnerability map in research area as shown in Figure 1.

The vulnerability index used in this study was obtained from data issued by the Central Statistics Agency of Lumajang Regency (BPS, 2023). Social vulnerability index (*SVI*) is based on population density, number of disabled people, poor people and vulnerable ages which places Pasrujambe District at a high level of vulnerability, Pronojiwo and Sendiro at a medium level and Candipuro at a low level. Physical vulnerability index (*PVI*) is based on the number of residential areas and public facilities available, showing Parsujambe, Pronojiwo and Sendiro at a high level of vulnerability and Candipuro at a low level. Meanwhile, economic vulnerability index (*EVI*) is based on data on agricultural products produced in a year, placing Pasrujambe, Pronojiwo and Candipuro at a high level of vulnerability, while Sendiro is at a low level. Furthermore, the environmental vulnerability index (*EnVI*) refers to the land use map (Figure 2), where the vulnerability scores from high to low are settlements, forests, agriculture, rivers and vacant land.

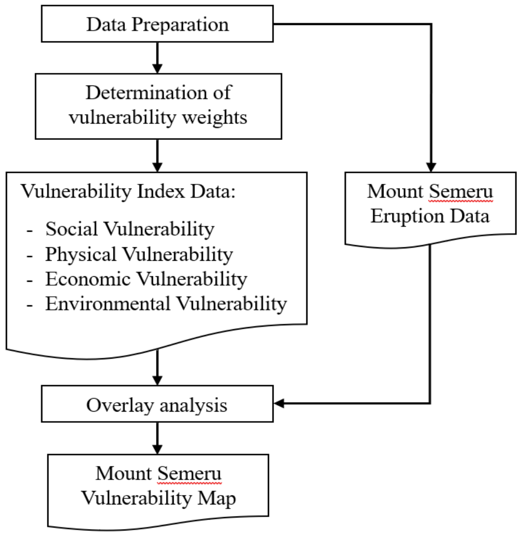

Figure 1. Data analysis flowchart.

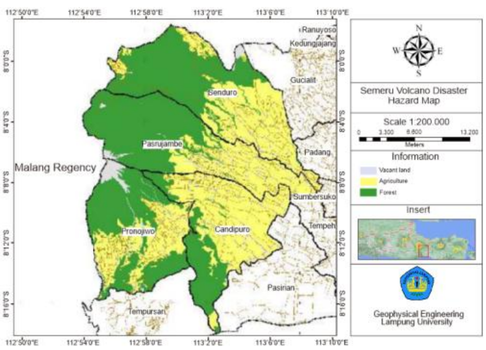

Figure 2. Land use map of the research area.

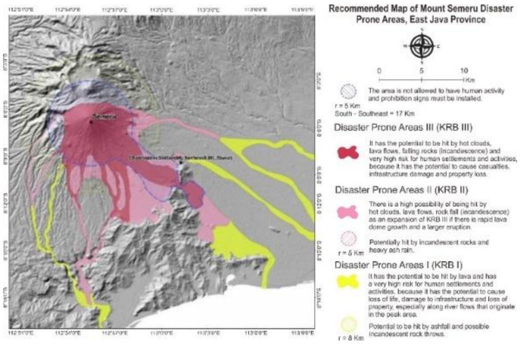

Figure 3. Map of the Semeru Volcano disaster-prone area (modified from KESDM, 2024).

In this study, GIS is used to analyze, observe, and map areas prone to volcanic disasters. The data used are Mount Semeru eruption data published by PVMBG (2024) (Figure 3), literature studies and qualitative analysis of secondary data containing the required vulnerability index. Furthermore, the vulnerability information obtained is combined using GIS software to obtain a volcanic vulnerability index (*VVI*) with a weighting formula:

$$VVI = SVI\ x\ 20\% + PVI\ x\ 20\% + EVI\ x\ 20\% + EnVI\ x\ 10\% + Volcanic\ x\ 30\% \quad (1)$$

The literature study was carried out through the process of collecting data, understanding and evaluating relevant information regarding the activities of Mount Semeru. Furthermore, the information obtained is used as a guide in analyzing and studying the activities of Mount Semeru to provide an overview in designing research designs, formulating problems and developing theories. Meanwhile, qualitative analysis was carried out to determine aspects of Mount Semeru such as geographical characteristics, volcanic activity, impacts and risks, social aspects as well as management and conservation.

Results and Discussion

Mount Semeru is included in the highest mountain range in Indonesia. Mount Semeru has complex topography with a height of around 3,676 meters above sea level, which is the highest mountain on the island of Java. This mountain has the morphology of a Stratovulvano volcanic type, with steep slopes and a lava dome at the top. The symmetrical and conical shape of the mountain is the result of the accumulation of eruptive material over thousands of years (Valentine et al., 2006). Mount Semeru is composed of volcanic rocks produced from eruptions that have occurred such as andesite, basalt and pyroclastic material. The geological structure in the Mount Semeru area is influenced by the activity of regional faults that form grabens and horsts as well as igneous rock intrusions that form bodies mountains (Harijoko et al., 2023).

The average return period for Mount Semeru's eruption is around 30 years (Thouret et. al., 2014). The eruption pattern is generally dominated by phreatic and phreatomagmatic eruptions with explosive eruption types. The eruption of Mount Semeru usually lasts for several days to weeks, with the height of the eruption column reaching 3-5 km. Based on the disaster-prone area map created by KESDM (2024), the research area has the potential to be hit by hot clouds, lava flows and rock falls, especially in the Northwest and North.

The area around the administration of Mount Semeru has a high level of vulnerability to the dangers of volcanic eruptions (Permadi, 2018). Residential settlements such as villages located on the slopes and foothills of mountains have a higher potential for impacts from eruptions, especially the occurrence of hot clouds, lava and pyroclastic flows. Hot clouds spread at high speed and can threaten residential areas, other dangers such as lava flows and pyroclastic flows which are a mixture of solid material and hot gas that travel at high speeds of up to hundreds of kilometers per hour can destroy any object in their path (Laksono, 2019). Pyroclastic flows on Semeru can be observed from the characteristics of their materials such as incandescent material, sulfur odor, and the presence of larger boulders. These flows flow down the slopes of the volcano, often following existing paths and can be simulated numerically (Shimomura, et al., 2019). A part from the areas on the slopes of the mountain, the area around Mount Semeru is also undeniably affected by volcanic eruptions. Areas around volcanoes have a high risk of eruptions such as falls and poroclastic eruptions consisting of volcanic ash and incandescent rock which can be thrown tens of kilometers away and lava flows several kilometers away.

The GIS map of the distribution of Mount Semeru's eruption (Figure 4) shows the areas that have a hazard index level due to the eruption of Mount Semeru. Areas with a green index are included in the low level of vulnerability category because they are located far from the top of the mountain so the potential for being affected by an eruption is low. Areas marked in yellow are categorized as areas with a medium danger index. Meanwhile, areas marked in red are categorized as areas with a high danger index due to their location close to the peak of Mount Semeru and river basins that flow near Mount Semeru. So it has a high potential danger from the eruption of Mount Semeru because it has the potential to be directly affected by the ejection of poroclastic material and incandescent rock, and also potentially affected by lava flows due to the eruption of Mount Semeru.

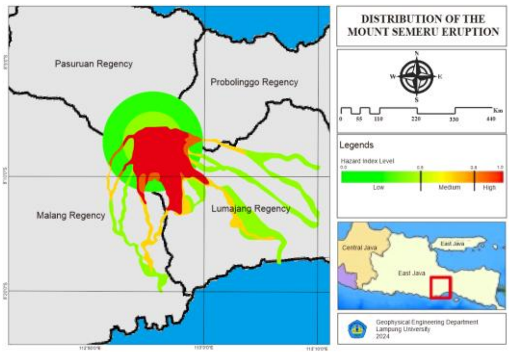

Figure 4. Map of the distribution of Mount Semeru's eruption.

The map of the distribution of Mount Semeru's eruption (Figure 4) indicates that volcanic eruptions tend to be directed towards the East-South, which is Lumajang Regency. Therefore, further analysis of this study is focused on disaster vulnerability in Lumajang Regency which is close to the peak of Mount Semeru, namely Senduro, Pasrujambe, Candipuro and Pronojiwo Districts. The factors used include social, physical, economic and environmental vulnerability. These four factors were then combined with a map of the distribution of Mount Semeru's eruption using GIS software to obtain a disaster vulnerability map (Figure 5).

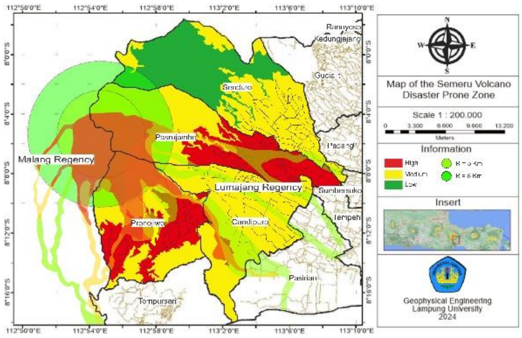

Figure 5. Mount Semeru eruption vulnerability map in Lumajang Regency overlayed with eruption data.

From the vulnerability map produced from this study, Pronojiwo and Pasrujambe Districts are two districts that have medium-high vulnerability. High vulnerability in Pronojiwo District is caused by the geological and morphological conditions of Mount Semeru which is located in the north of the area. The edge of the crater of Mount Semeru which tends to be lower in the south makes Pronojiwo District the main destination for eruption flows. The presence of the Lengkong River in the area also contributes to increasing vulnerability because it is a path for cold lava flows. Meanwhile, in Pasrujambe District, although not the main destination of the eruption flow, 75% of the area of this district is a rice field and fields between settlements, making Pasrujambe economically and physically vulnerable if Mount Semeru erupts.

Economic and physical vulnerability in Candipuro District is classified as moderate, but the west bordering Pronojiwo may still have high vulnerability to the possibility of cold lava flowing through large rivers in the area, including the Regoyo, Rejali and Mujur rivers. On the other hand, Senduro District is an area with relatively low vulnerability compared to the other four districts. A comparison of the level of vulnerability to the eruption of Mount Semeru in the four sub-districts can also be seen from the table of the area of vulnerability in each area (Table 1).

Table 1. The area vulnerable to eruption of Mount Semeru.

Subdistrict	High (Km^2)	Moderate (Km^2)	Low (Km^2)
Pronojiwo	84.89	56.59	0
Pasrujambe	51.56	45.73	0
Candipuro	15.94	128.99	0
Senduro	0	116.62	112.0

In addition to mapping the areas vulnerable to volcanic eruptions of Mount Semeru, volcanic disaster mitigation in Lumajang Regency also needs to pay attention to tectonic earthquake activity. Mount Semeru's activity from January 1 to June 1 2024 has experienced 343 eruptions recorded at the Mount Semeru observation post (Figure 6). From this data, it is known that Mount Semeru's activity experienced a decline but has again experienced an increase in its eruptive activity. This can be an early warning of volcanic disaster preparedness.

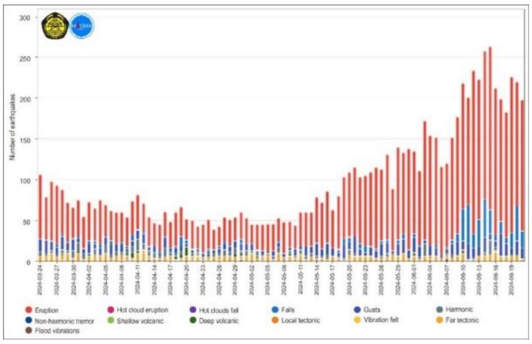

Figure 6. Daily monitoring of Mount Semeru activity (KESDM, 2024)

PVMBG (Center for Volcanology and Geological Disaster Mitigation) carries out intensive and regular observations to develop an early warning system (Yulianto, 2018) to anticipate eruptions and warn the surrounding community regarding the potential dangers of volcanic eruptions. The regional government's efforts together with the Regional Disaster Management Agency (BPBD) are making comprehensive efforts to increase the preparedness of communities around Mount Semeru in facing the dangers of volcanic eruptions. Disaster outreach, training and simulation activities are routinely carried out to ensure the public understands the risks, knows evacuation procedures and is trained in dealing with emergency situations. Apart from that, developing disaster management infrastructure is also a priority, including the construction of evacuation routes, logistics warehouses and evacuation centers. It is hoped that this effort can support emergency response and recovery efforts during the eruption of Mount Semeru, so that communities around the mountain can be better prepared and able to overcome the impact of the disaster.

Conclusions

Mount Semeru, the highest peak on Java Island, has complex volcanic morphology and poses significant eruption hazards. Characterized as a stratovolcano with steep slopes and a lava dome, it experiences regular explosive eruptions approximately every 30 years, predominantly affecting areas to the East-South, especially Lumajang Regency. The eruptions produce pyroclastic flows, lava, and volcanic ash that threaten nearby settlements, particularly in Pronojiwo and Pasrujambe Districts, which exhibit medium to high vulnerability due to their topographic and economic conditions. GIS-based hazard and vulnerability mapping highlights Pronojiwo as most at risk due to its proximity to the crater and river paths facilitating lava flow. Although Senduro District shows low vulnerability, neighboring districts like Candipuro and

Pasrujambe still face significant threats. Regular monitoring by PVMBG and mitigation efforts from local authorities and BPBD, including public education, infrastructure development, and early warning systems, are crucial in reducing disaster impacts. These comprehensive measures aim to enhance community resilience and preparedness in the face of Mount Semeru's volcanic activity.

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