ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol 56, No 3 (2024): 446-455
DOI: 10.22146/ijg.89918 website: https://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

RESEARCH ARTICLE

The Development of Disaster Risk Map for Semeru Volcano Eruption 2021-2022, East Java, Indonesia

Syamsul Bachri[1], Eli Hendrik Sanjaya[2], Siti Sendari[3], Rajendra Prasad Shrestha[4], Listyo Yudha Irawan[1], Egi Nursari Billah[1], Nanda Regita Cahyaning Putri[1], Mellinia Regina Heni Prastiwi[1], A.Riyan Rahman Hakiki[1], Tabita May Hidiyah[1]

[1]Department of Geography, State University of Malang, Indonesia
[2]Department of Chemistry, State University of Malang, Indonesia
[3]Department of Electrical Engineering and Informatics, State University of Malang, Indonesia
[4]Natural Resources Management, Asian Intitute Technology, Thailand

Received: 2023-10-18
Revised: 2024-08-26
Accepted: 2024-06- 27
Published: 2024-12-03

Key words: risk map; semeru volcano; rejali watershed; laharz

Correspondent email: syamsul.bachri.fis@um.ac.id

Abstract The Semeru Volcano eruption on December 4, 2021 caused damage to social, economic and environmental aspects. The Rejali Watershed (DAS) is one of the areas severely affected due to the eruption. The eruption resulted in 51 deaths, 10,565 displaced people, 1,027 houses damaged, two connecting routes and 43 public facilities damaged. This study mapped the disaster risk areas due to the eruption of Semeru Volcano. This research used Laharz to analyze the lava flow hazard map and weighting for social, economic, physical, environmental, and capacity vulnerability parameters. The results showed that the risk level of Semeru Volcano eruption is divided into three classes: high, medium, and low risk. The high-risk area is 8915.09 Ha (14 %), the medium-risk area is 2174.74 Ha (17 %), and the low-risk area is 1885.60 Ha (69%). The high and medium risks were located on the upper and middle slopes of the Rejali watershed because the upstream area experiences a narrowing of the river flow (bottleneck) due to direct borders with structural land. The Semeru Volcano disaster risk map results can be used as a reference in sustainable risk management efforts in the Rejali watershed to reduce the impact and damage caused by the eruption.

1. Introduction

Mount Semeru is an active volcano in Indonesia that rises to an altitude of 3,676m above sea level (Hakim and Hairunisa 2017; Syuhada et al. 2022). It has strombolian and explosive eruption volcanic-type characteristics, with eruptions occurring every five to 15 minutes (Purba et al. 2022; Safitri, Hayati, and Bioresita 2021). According to archival data obtained from the Global Volcanism Program (GVP) 2020, the volcano began erupting on 8th November 1818 from its central crater (Purba et al. 2022). Throughout 2021, eruptions were recorded from 1st January to 31st December 2021, with southeastward flows heading towards the upstream areas of Besuk Kembar, Besuk Bang and Besuk Kobokan (Purba et al. 2022).

The eruption on 4th December 2021 formed a new dome, and its lava tongue reached 2km (GVP, 2021). The eruption caused ballistic bomb ejections 11km high, ash rains for 30km, incandescent lava flows of five to 11.5km to the southeast of the crater (Azizah, Listyo, and Irawan 2023), and an estimated pyroclastic lava flows volume 8.3 million m^3 that reached Besuk Kobokan, which is 11 to 16km away (GVP, 2021). The lava dome collapsed between October 2022 to April 2023 due to significant rain during the monsoon season (Regional Disaster Management Agency Lumajang 2021). The eruption on 4th December 2021 also resulted in 51 deaths, displaced 10,565 people, and affected 1027 houses as well as two bridges and 43 public facilities (Centre for Volcanology & Geological Disaster Mitigation, 2021).

The following year, another eruption occurred on 4th December, which increased the volcano's alert level from III (alert) to IV (Caution) (Energy & Mineral Resources, 2022). There was a 12km-long pyroclastic flow, a pyroclastic earthquake, and 13 eruption earthquakes (Energy & Mineral Resources, 2022; GVP, 2021). Furthermore, incandescent material accumulated around the surface of the volcano's crater (Energy & Mineral Resources, 2022), affecting three sub-districts and six villages. Damage occurred due to primary and secondary hazards from the eruption. Primary hazards include pyroclastic flows, rock ejections (incandescent), heavy ash rains, lava flows, and toxic gases (Larasati, Hariyanto, and Kurniawan 2017; Purba et al. 2022). While secondary hazards include lava dome collapse or volcanic avalanches, lava floods, rain lava, and flooding (Larasati 2017).

As the volcano's activity and seismicity fluctuates and is unstable, there is a risk of future disasters. Therefore, hazards from the volcano's future eruptions should be anticipated to avert significant losses (Bachri et al. 2023). Volcano disasters occur when eruptions affect residential areas and land use (Purba et al. 2022). As the population and number of settlements around the volcano are growing, there is a

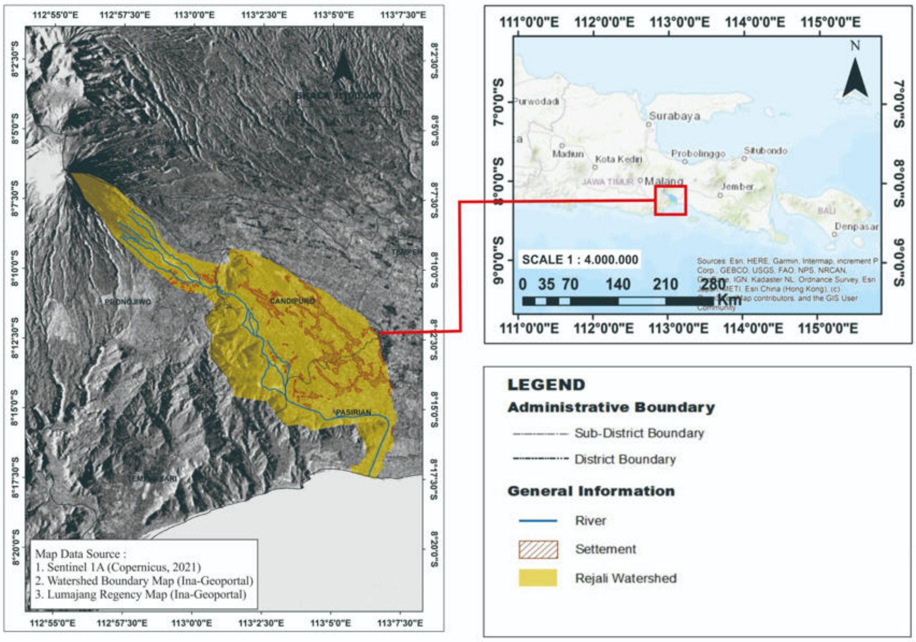

Figure 1. Research Location

Table 1. Research Data

Stages		Source	Processing Techniques
a. Hazard Mapping			
Lahars Modelling	Stream Threshold	National DEM 8,1 m resulution	Generate a flow direction, flow accumulation, and stream raster using Create Surface Hidrology Rasters on Laharz_py
	Lahar Volume (m^3)	PVMBG	Create areas of potential inundation using Lahar Distal Zones on Laharz_py
KRB Map		Geological Agency-ESDM	Overlay with lahars modelling
b. Vulnerability Parameters			
Social Vulnerability			
Population Density		Central Statistics Agency of Candipuro, Pasirian, Pronojiwo, and Tempursari Districts in Figures 2022	Analysis of social vulnerability factors using AHP (Analytical Hierarchy Process) with scoring or weighting techniques.
Sex Ratio			
Age Group Ratio			
Disability Population Ratio		One Data Lumajang Regency https://data.lumajangkab.go.id/main/lihat_file/aWptaw%3D%3D	
Physical Vulnerability			
Residential Area (Ha)		Researcher data analysis	Analysis of physical vulnerability factors using AHP (Analytical Hierarchy Process) with scoring or weighting techniques.
Public Facilities			
Health Facilities			
Environmental Vulnerability			
Protected Forests Area (Ha)		Sentinel 2A Imagery	Analysis of environmental vulnerability factors using AHP (Analytical Hierarchy Process) with scoring or weighting techniques.
Natural Forests Area (Ha)			
Mangrove Forests Area (Ha)			
Shrubs Area (Ha)			
Economic Vulnerability			
Produktive Land Area		Central Statistics Agency of Candipuro, Pasirian, Pronojiwo, and Tempursari Districts in Figures 2022	Analysis of economical vulnerability factors using AHP (Analytical Hierarchy Process) with scoring or weighting techniques.
Gross Regional Domestic Income (PDRB)(Million)			
c. Capacity Parameters			
Rules and institutions		Interviews with village authorities were conducted in accordance with the Head of the National Board for Disaster Management Regulation No. 2 of 2012.	Analysis of capacity parameters using AHP (Analytical Hierarchy Process) with scoring or weighting techniques.
Early Warning			
Disaster Education			
Reduction of Risk Factor			
Development of Preparedness at All Levels			

high risk of volcanic disasters. Furthermore, infrastructure development and economic growth in areas surrounding the volcano also increase their vulnerability to volcanic disasters. The areas surrounding a volcano should, ideally, be designated disaster-prone and left uninhabited. However, many factors, such as social, economic, political, cultural and individual conditions, cause people continue living in disaster-prone areas.

As such, it is necessary to map the disaster risk of the Mount Semeru Volcano to minimise damage and losses due to future eruptions. By mapping the volcano's disaster risk, the community may obtain information about areas at-risk of eruptions to help plan appropriate mitigation, response, and risk management efforts that are sustainable. After all, disaster risk mapping is not only needed on a local scale but also globally.

2. Methods

Research Location

The ecological boundary of the Rejali watershed, which is administratively located in the Candipuro and Pasirian sub-districts of the Lumajang Regency, is the research location. it was chosen for scrutiny as it is situated to the southeast of the volcano, through which lava flowed during the 2021 eruption. The Rejali watershed is 11,089.83Ha in size, with the Oro-Oro Ombo Village located upstream and the Supiturang and Bago Village located downstream (Figure 1).

Research Data

Both secondary and primary data were utilised. The primary data was gathered via field observation to obtain and plot data on village infrastructure facilities, disaster capacity, affected areas, and the volcano's lava flow characteristics. The secondary data included social, physical, economic, and environmental statistical information for hazard, vulnerability, and capacity analysis (Table 1).

The research methodology is illustrated in Figure 2, which outlines the sequence of steps undertaken, from problem identification to formulating research findings. This diagram serves as a visual guide to understanding the overall execution of the research.

Hazard Variables

The hazard parameters were analyzed by combining three methods, namely modelling, buffering, and overlaying with the disaster-prone zone map. Hazard modelling of the volcano was conducted using the Laharz_py programme integrated with ArcGIS. Laharz_py is designed for proximal hazard zone calculation and equation calculation that is integrated with GIS on topography to estimate the distal hazard zone. The primary data inputted into the model was the lava flow volume. The lava flow volume of the 2021 eruption was 10.5 million m^3. The Lava flow scenarios in the Laharz_py model aim to understand and predict the path and behavior of lava flows, thus improving our understanding of the hazard level an area may face. Furthermore, the classification of lava volume is based on the scenarios shown in Table 2.

The digital elevation model (DEM) was the primary data inputted into the Laharz_py model. The DEM data used was DEMNAS data at a spatial resolution of 0.27 arc seconds or 8.1m (Geospatial Information Agency, 2023). The DEM has pixel height values to form topographic conditions in certain areas (Schilling 2014).

The hazard index was determined using the overlay method, which used lahar flow data, lahar volume, and river body buffering, thus producing a lahar flow hazard map. Lahar flow is a significant hazard for communities living on the slopes of active volcanoes (Cole, 2011; Thouret et al. 1999).

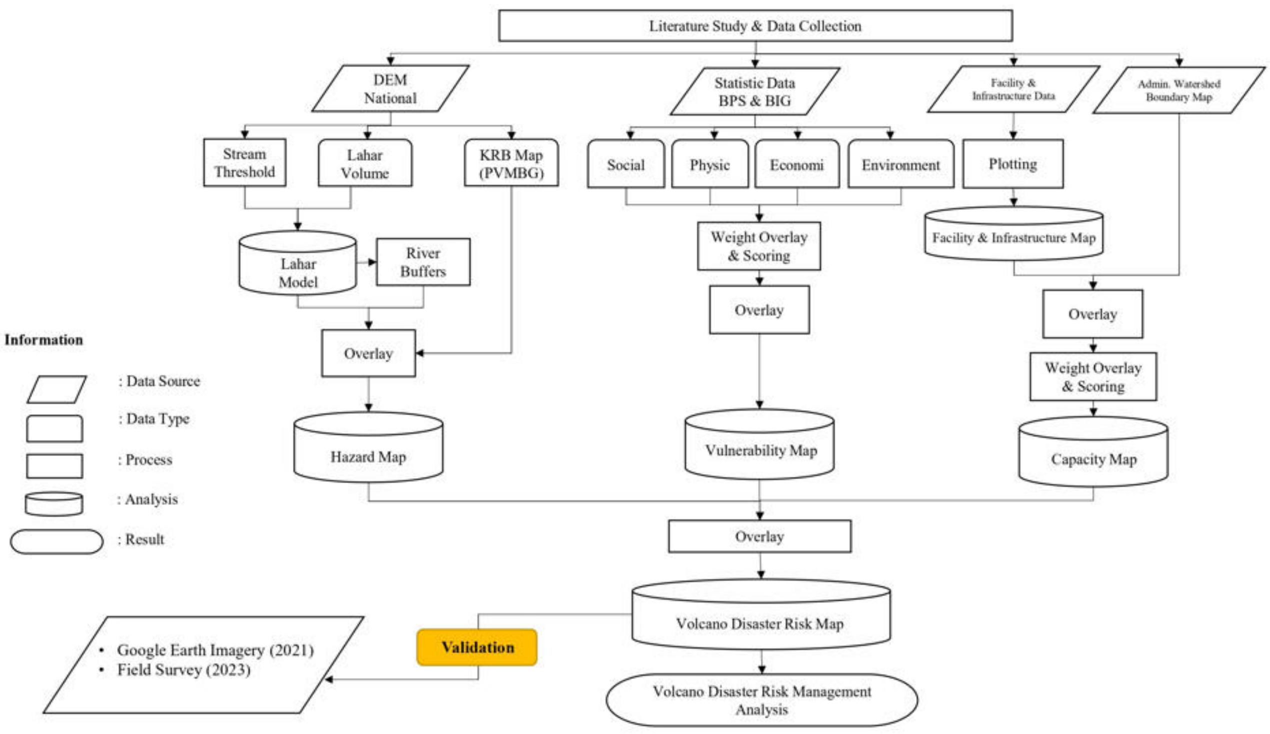

Figure 2. Research Methodology

Table 2. Laharz_py Model Scenario

Scenario	Lava Volume	Description
Model 1	1.500.000 m^3	Low
Model 2	3.000.000 m^3	Medium
Model 3	6.000.000 m^3	High
Total	10.500.000 m^3	Total eruption volume in 2021

Table 3. Hazard Zone Classification Buffer Method

Hazard Zone Classes	Description
High	0 – 200 m
Medium	200 – 400 m
Low	400 – 800 m

Table 4. Vulnerability Factor Statistics

	VULNERABILITY												
	Social Vulnerability				Physical Vulnerability			Environment Vulnerability				Economical Vulnerability	
Villages	Population Density (Jiwa/Km2)	Sex Ratio (%)	Age Group Ratio (%)	Disability Population Ratio (%)	Residential Area (ha)	Public Facilities	Health Facilities	Protected Forests Area (Ha)	Natural Forests Area (Ha)	Mangrove Forests Area (Ha)	Shrubs Area (Ha)	Productive Land Area (Ha)	Gross Regional Domestic Income (Million)
Jugosari	285	97.54	20.17	0.16	21	5	1	0	54.14	0	77.17	792	Rp 48,824,283.00
Jarit	806	98.05	19.44	0.33	105	0	0	0	0	0	0	939	Rp 105,096,096.00
Candipuro	630	101.28	19.68	0.44	68	0	0	0	0	0	0	618	Rp 105,009,867.00
Sumberrejo	516	104.39	18.56	0.45	45	0	0	0	0	0	19.80	573	Rp 63,256,111.00
Sumberwuluh	617	104.21	17.63	0.31	57	4	0	0	379.20	0	689.93	2821	Rp 52,396,388.00
Gondoruso	138	101.24	20.01	0.49	42	7	0	0	599.40	0	0	1492	Rp 49,399,039.00
Kalibendo	1140	100.19	19.06	0.39	88	5	0	0	0	0	0	690	Rp 105,866,268.00
Bades	264	100.77	20.88	0.56	105	3	0	0	225.99	0	16.65	1197	Rp 35,207,231.00
Bago	469	95.28	19.66	0.34	24	0	0	0	0	0	0	287	Rp 64,526,550.00
Pasirian	3534	97.31	21.10	0.47	23	0	0	0	0	0	0	188	Rp 12,585,852.00
Sumberurip	606	100.77	18.51	0.05	0	0	0	9.61	0	0	1.21	66	Rp 35,806,149.00
Oro-Oro Ombo	1044	101.77	17.68	0.12	0	0	0	587.37	292.93	0	307.09	75	Rp 110,393,258.00
Supiturang	953	102.22	19.56	0.17	14	1	0	690.81	251.39	0	466.80	1364	Rp 4,700,510.00
Kaliuling	380	100.44	19.39	0.08	0	0	0	0	51.36	0	0	50	Rp 79,957,206.00

Hazard mapping involves utilizing data to create river buffer areas to produce hazard zones as the potential cold lava areas are located around the river flowing along its pathway (Rani & Khotimah 2021). Table 3 shows the hazard zone classes.

Buffering refers to determining the specific distance from a river or water body that may affect the potential for lahar flooding. In the present study, this distance was the distance of the river to human settlements (Utama and Naumar 2015). The buffer class assessment were given based on the proximity of human settlements to the river or water body; the closer to the river, the higher the risk of inundation or lava flooding when the river overflowed.

Vulnerability Variables

The analysis of the volcano's disaster vulnerability was conducted using statistical data on environmental, social, and economic factors (Weis et al., 2016). The vulnerability data was obtained from the Central Statistic Agency of Lumajang Regency and plotted based on field conditions. Each data value was subsequently processed in ArcGIS using the weighting method for each variable based on the Head of National Board for Disaster Management Regulation 02/2012 concerning the General Guidelines for Disaster Risk Assessment. The statistical data for each vulnerability factor is depicted in Table 4.

Capacity Variables

The assessment of the disaster capacity level of the volcano was conducted based on the government's guidelines via the Head of the National Board for Disaster Management Regulation 2/2012. The capacity calculation was structured upon five capacity parameters, with data obtained from interviews and the plotting of infrastructure facilities. Infrastructure data were used to depict the capacity of a spesific area (Mutiarni, Nakamura, & Bhattacharya 2022). The eight infrastructure facilities in the Rejali watershed area included educational facilities (elementary, junior, senior high school/equivalent), government, healthcare facilities, financial, security services, places of worship, markets, and open spaces. The availability of educational facilities (schools) may encourage students to learn about disaster mitigation (Indriasari & Kusuma, 2020), thus increasing an area's disaster capacity. Government facilities indicate the presence of an administrative body that plays a crucial role in building disaster capacity (Heryati, 2020). Lastly, the availability of health facilities, such as hospitals and health centres, is also essential to minimise the impact of disasters (Mahfud & Rossa 2017). Table 5 presents the capacity calculations.

Data Analysis

Each parameters of the volcanic eruption risk indicators was subsequently analysed using the disaster risk assesment from the Head of the National Board for Disaster Management Regulation 02/2012 The assessment was based on three main assessment indicators, namely, hazard, vulnerability, and capacity level (Adiwijoyo & Danoedoro, 2014).

A weighting or scoring analysis technique was used to map vulnerability and capacity. Each vulnerability parameter was calculated according to the formula outlined by the Head of the National Board for Disaster Management Regulation 02/2012 (Figure 3).

Subsequently, the parameters for hazards, vulnerability, and capacity were computed to produce a disaster risk map using GIS. Disaster risk data processing uses the following equation:

$$R = H \times V / C$$

where, R = risk, H = hazard, V = vulnerability, and C = capacity, The results of the H, V, and C were then overlaid using the scoring method to map the volcano's disaster risk, classified into low-, medium-, and high-risk levels based on the risk interval values.

3. Result and Discussion

Hazard Level of the Mount Semeru Volcano

The results of Laharz_py and river buffers examinations were then overlaid with the vulnerability map to produce a hazard map (Figure 4).

As seen in Figure 4, Supiturang and Sumberwuluh Villages are areas with high hazard potential and are included in the area III classification, which are areas that may be affected by pyroclastic flows, lahars, and incandescent lava. Based on field observations, the settlements and agricultural land in these areas are at high risk of being affected. During an eruption, the lava flows to the southeast and passes through several villages in the Candipuro sub-district. The area upstream of the Rejali watershed is considered a high-risk area as it is a massive deposition, erosion, and sedimentation zone. Furthermore, the sand mining activities around the watershed area only increase the potential for lava to flow in this area.

Table 5. Capacity Calculations

Parameters	Weight (%)	Classification Low	Classification Medium	Classification High	Score
Rules and institutions Early Warning Disaster Education Reduction of Risk Factor Development of Preparedness at All Levels	100	<0.33	0.33 - 0.66	>0.66	Class/Max Clas Value
Capacity Index = 10 x Capacity Skor					

$$\begin{aligned} \textit{Volcanic Vulnerability} &= (0.4\ x\ \textit{social vulnerability score}) + (0.25\ x\ \textit{economic vulnerability score}) \\ &+ (0.25\ x\ \textit{physical vulnerability score}) + (\ 0.1\ x\ \textit{environmental vulnerability score}) \end{aligned}$$

Figure 3. Vulnerability Calculation

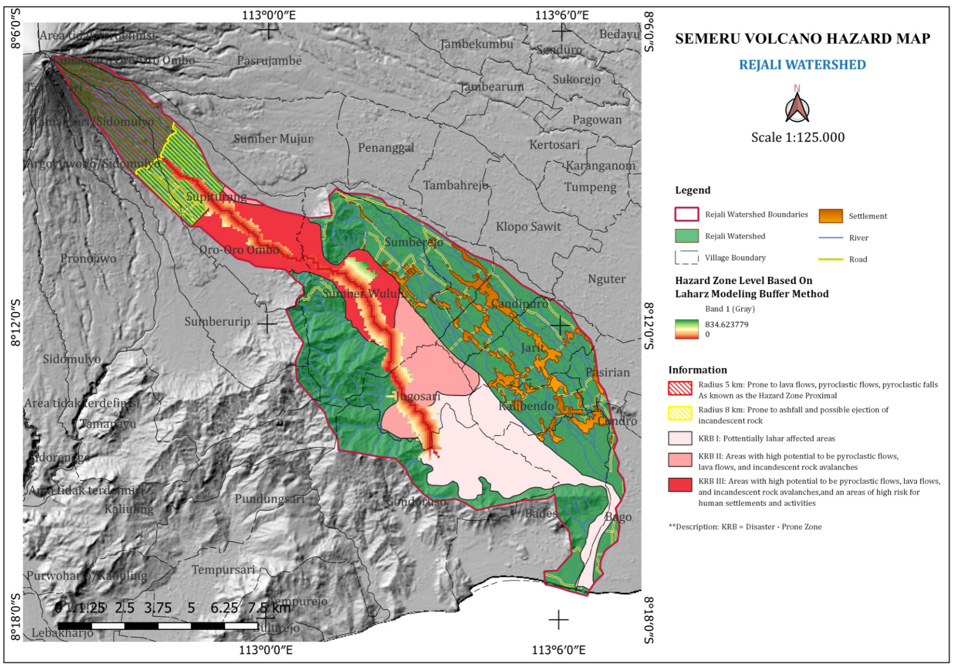

Figure 4. Semeru Volcano Hazard Map

There are 2212.11Ha (17%) of high-hazard areas in the Rejali watershed, 3349.96Ha of medium-hazard areas, and 7422.66Ha of low-hazard areas (Table 6).

The area's morphological conditions influence the high disaster risk level of Supiturang and Sumberwuluh Villages. The Rejali Watershed area is characterized by a hilly upstream area that increases along the slope. The Supiturang Village upstream area is a lahar production site, where erosion and lahar sedimentation occur. The appearance of a bottleneck with a steep slope characterises the middle area of the watershed in Sumberwuluh Village. This may cause lahars passing through the river to spread and fill the floodplain (Bachri et al., 2023). Therefore, the Supiturang and Sumberwuluh Villages are considered high-hazard areas, especially the river basin.

Vulnerability of the Mount Semeru Volcano

The Mount Semeru Volcano disaster vulnerability map results were divided into low-, medium-, and high-vulnerability levels. The low-vulnerability villages are Oro-Oro Ombo, Jugosari, Kaliuling, Sumberurip, and Sumberejo. The medium-vulnerability villages are Candipuro, Gondoruso, and Jarit, while the high-vulnerability villages are Supiturang, Sumberwuluh, Pasirian, Kalibendo, Bades, and Bago.

High-risk areas have a high hazard level and population vulnerability as population is a determining factor in an area's risk level. The high vulnerability level was evident during the field observations, as a reasonably high-impact area, which contributes to social activities in the community, such as settlements and agriculture. Figure 5 shows the vulnerability map.

Capacity of Semeru Volcano

The disaster capacity map of the Mount Semeru Volcano was categorized into low (1-1.4), medium (1.6-2.1), and high (2.2-2.7) capacities (Table 7).

Based on the capacity map result (figure 6), the villages of Oro-Oro Ombo, Sumberwuluh, Sumberejo, Sumberurip, Kaliuling, Jugosari, and Gondoruso had low-capacity levels as more facilities and infrastructure are needed in these villages. Meanwhile, the Jarit, Candipuro, and Supiturang villages were medium-capacity levels. The Jarit and Candipuro Villages were deemed to have medium-capacity levels as almost all the

Table 6. Hazard Level Areas

Hazard Level	Areas (Ha)
Low	7422, 56
Medium	3349, 96
High	2212,11

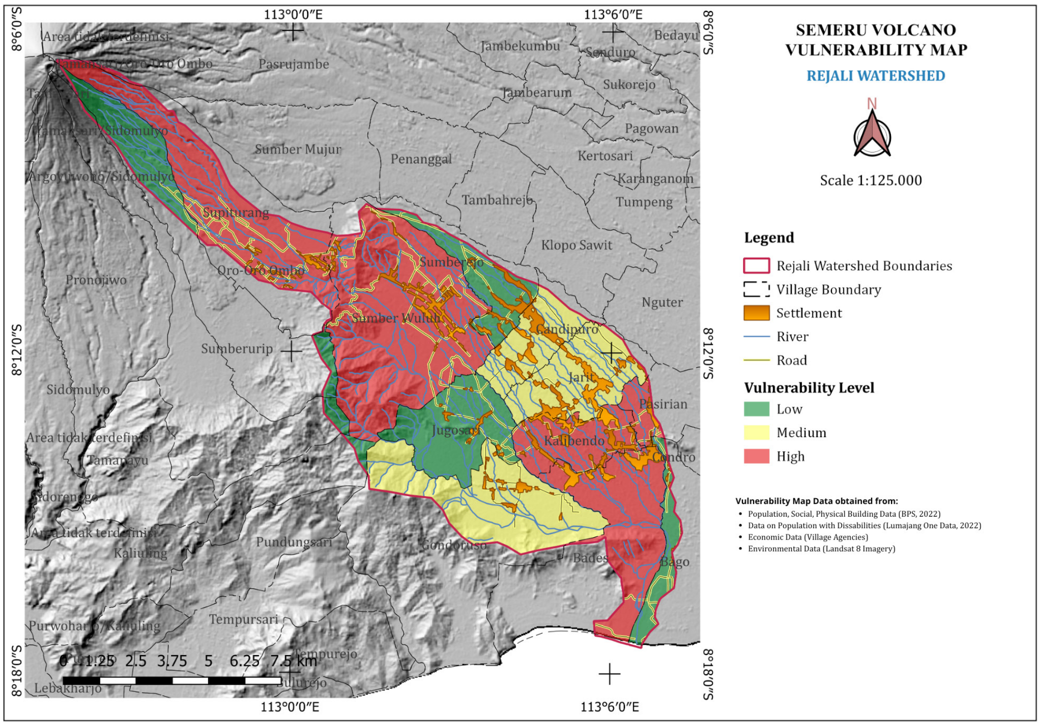

Figure 5. Semeru Volcano Vulnerability Map

Table 7. Capacity Level Area

Capacity Level	Area (Ha)
Low	7422, 56
Medium	3349, 96
High	2212,11

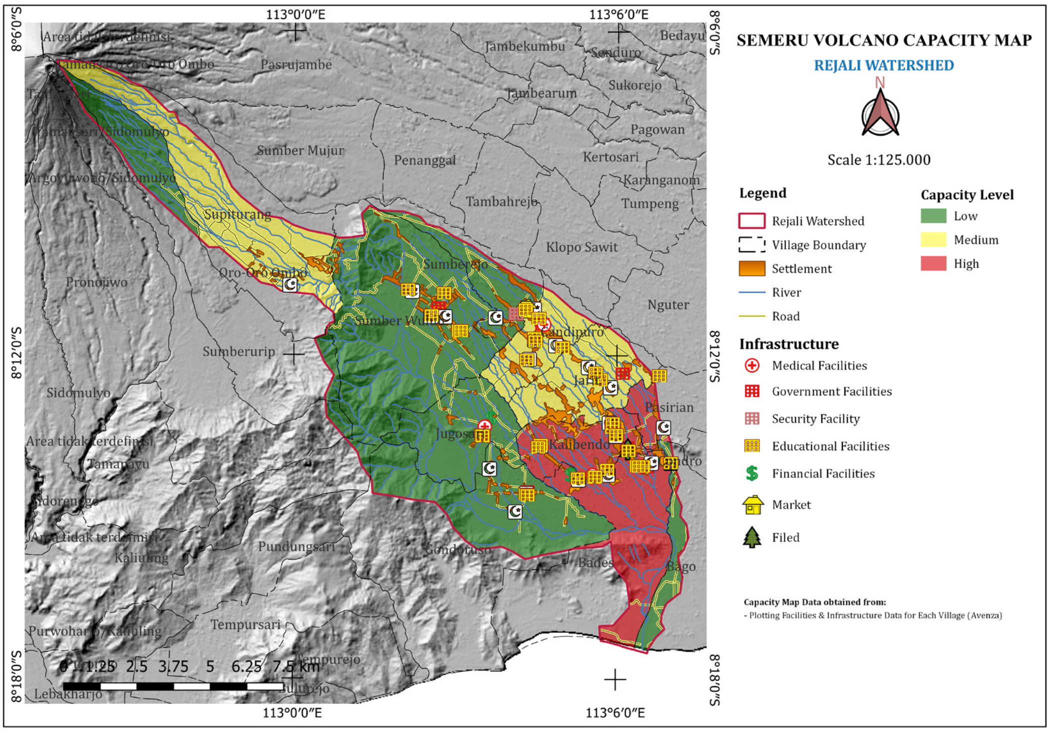

Figure 6. Disaster Capacity Map of Semeru Volcano

Table 8. The history of Semeru Volcano Eruption

Year	Causes of Disaster	Casualties	Affected Area
April 1885	Crater rim avalanche	70	South Slope (Besuk Kembar, Besuk Bang and Sarat)
1909	Galodo/Flash Flood	220	Avalanche on Eastern Slope
1968	Lahar Flows	5	Southeast Slope (Besuk Kobokan and Liprak River)
13 November 1976	Lahar Flows	119	Southeast Slope (Besuk Kobokan and Liprak River)
14 May 1981	Galodo/Flash Flood	265	Avalanche on East Slope (Besuk Sat into Mujur River)
3 February 1994	Pyroclastic Flows	8	Southeast Slope (Upper Besuk Kobokan and Liprak River)
December 2020	Pyroclastic Flows and Lahar Flood	3	Lahar leads to Rejali River
4 December 2021	Pyroclastic Flows and Lahar Flood	56	Lahar leads to Rejali River and damage Gladak Perak Bridge

facilities' infrastructure was available, ranging from security facilities to places of worship; however, only fields were unavailable.

The villages of Bades, Bago, Kalibendo, and Pasirian were had high-capacity levels due to the availability of complete facilities and infrastructure. The difference between the capacity levels of the Jarit and Candipuro Villages, which both had complete facilities infrastructure, lies in their health facilities. The villages of Jarit and Candipuro only have a community health centre. Meanwhile, the villages of Bades, Bago, Kalibendo and Pasirian have regional general hospitals at the sub-district level. In general, health facilities are more comprehensive than community health centres.

Disaster Risk of the Mount Semeru Volcano

The Mount Semeru Volcano's eruptions result in disruption to society, economy, and infrastructure. During the eruptions, the lahar flows down the sloping valleys, from the crater's opening, at high speed. The area affected by the lahar flow was in the volcano's Lahar Fan Deposits 2 formation (Bachri et al., 2023), demonstrating that the 2021 eruption was the path of the lahar flow. The history of the volcano's eruptions is shown in Table 8.

Based on field observations, the Candipuro sub-district is the most severely affected area, especially in the central region of the Rejali watershed (Figure 7). The types of land use affected are densely populated settlements and agriculture. Meanwhile, the downstream area of the watershed is unaffected by the volcano's lahar flow.

The Mount Semeru Volcano disaster risk map includes low-, medium-, and high-risk levels (figure 8). Low-risk areas of 8915.09Ha included Oro-Oro Ombo, Sumberurip, Kaliuling, Jugosari, parts of Gondoruso, Sumberejo, Candipuro, Jarit, Kalibendo, Pasirian, Bades, and Bago villages. The medium-risk areas measure 2174.74Ha and encompass parts of Gondoruso, Supiturang, and Sumberwuluh villages. The High-risk area of 1885.60Ha mostly encompasses Sumberwuluh Village, which has a high level of hazard, but low disaster capacity, resulting in severe damage. The Mount Semeru Volcano disaster risk map is displayed in Figure 9.

Figure 7. Lahar Flow Affected of Semeru Volcano

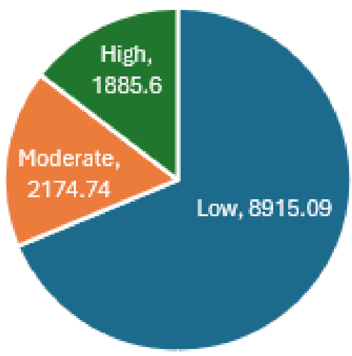

Figure 8. Risk Level Area

The morphological conditions of the Rejali watershed area affected by lava flow ranges from plains to undulating hills. The upstream area, with a steep slope, is a flow path, but the upstream area in Supiturang Village is classified as a steep area at high risk of volcanic disasters. This is due to the river's condition in the upstream area, which narrows due to its direct border with structural land. The Rejali River is an area that is prone to pyroclastic flows, lava flows, and toxic gases, especially in upstream, which is mostly caused by the erosion and lava sedimentation in the lava floodplain in the upstream area.

The middle slope of the Rejali watershed is the deposition area for lahar flow material from past eruptions. This is due to the construction of buildings that function as lahar control, resulting in reduced lahar flow energy and material deposition. The plain area is the worst affected because the lahar flow expand to inundate it. The volcano's eruptions caused changes in morphological conditions and landforms in the Rejali watershed area. Morphological changes due to the eruption cover residential areas, agriculture and forests, covering a vast expanse of the area with eruption material. Changes in the upstream area are dominated by erosion activities that contribute to the erosion of riverbanks by lahar flows.

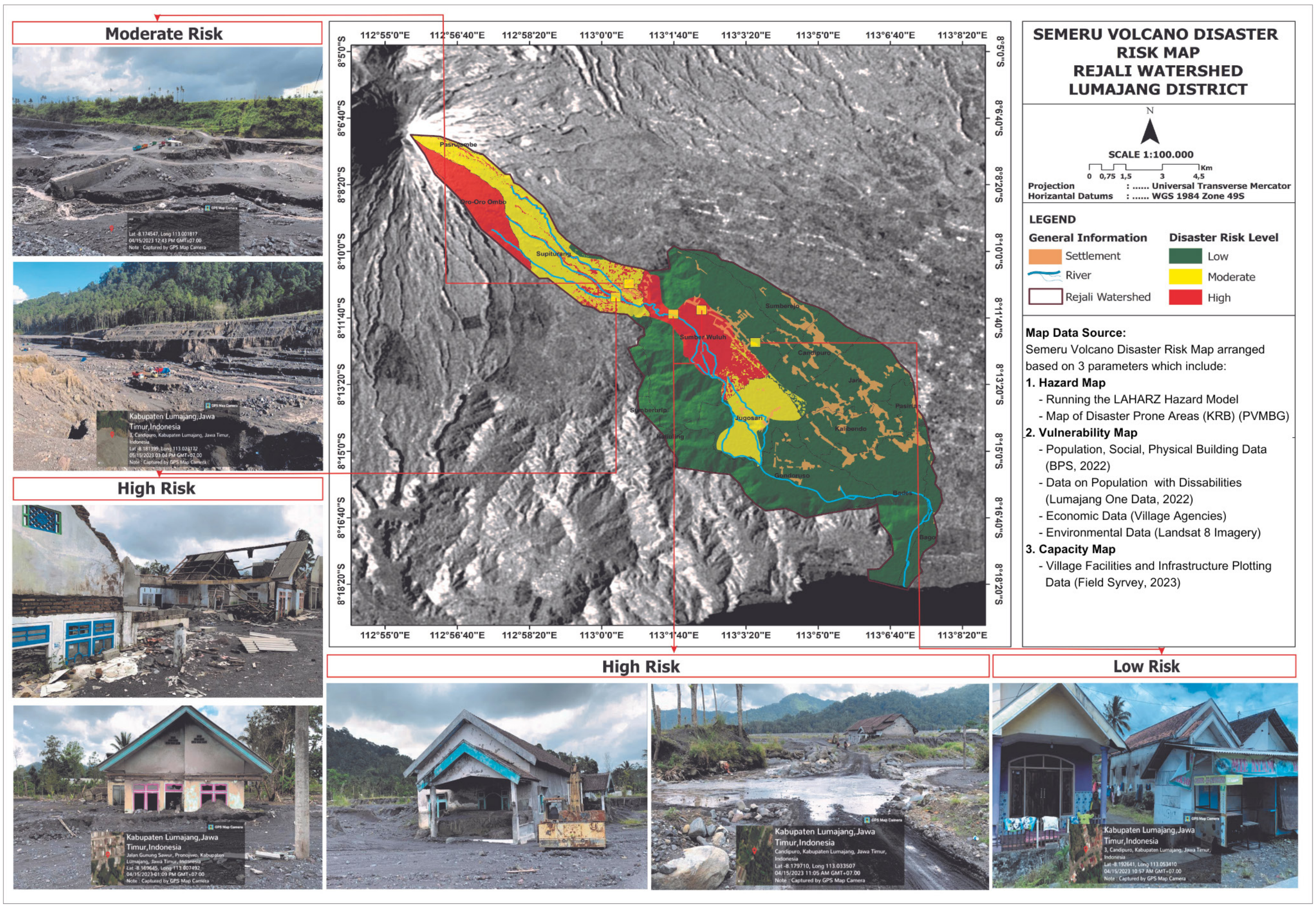

Figure 9. Semeru Volcano Disaster Risk Map

The validity of the field observation results illustrated that high-risk areas experienced damage to residential and agriculture land due new lahar flows. Areas within a 5km radius of the volcano's crater were severely impacted. Hence, the community's social activities must be relocated to temporary shelters in the future as residential areas have been destroyed and inundated by volcanic materials when the volcano erupts. This is consistent with Bachri et al. (2023) and Larasati (2019), who highlighted that high-risk areas, such as Supiturang and Sumberwuluh Villages are particularly susceptible to disaster due to their hilly terrain and steep slopes, disposing them to lahar sedimentation and pyroclastic flows.

This present study classified areas within the Rejali watershed as being at high-, medium-, and low-risk due eruptions. These findings could serve as a basis for decision-making by local governments and other authorities related to regional development to mitigate disaster risks. However, several limitations must be considered.

One primary limitation is the resolution of the DEM used in the Laharz_py modelling, which significantly affects the detail of the topographic features represented. A low-resolution DEM might fail to capture minute but critical topographic features, such as narrow valleys or sharp gradient changes, which are vital in determining the path of lahar flows.

To overcome this limitation, future research should incorporate higher-resolution DEM data, such as those derived from light detection and ranging (LiDAR), to produce more accurate topographical representations. High-resolution DEMs would allow for more precise identification of critical features, enhancing prediction of lahar flow paths and contributing to more effective disaster mitigation efforts. Moreover, future research should integrate field validation more extensively to verify the accuracy of hazard zones, ensuring a comprehensive understanding of volcanic risks in regions like the Rejali watershed.

4. Conclusion

The 2021 and 2022 eruptions of the Mount Semeru Volcano were severe threats as the lava flows caused various damages and losses, including deaths, destruction to buildings, disruption of transportation access, displacement of residential areas, and interruptions of community economic activities. This study of GIS-based Laharz_py mapping of the Mount Semeru Volcano disaster risk area showed three risk areas: a high-risk area of 1885.60Ha, and a medium-risk area of 2174.74Ha. The high- and medium-risk areas are on the upper and middle slopes of the Rejali watershed in steep morphological conditions. Meanwhile, the low-risk area of 8915.09Ha is in the downstream area, with plain morphological conditions. The results of the Mount Semeru Volcano disaster risk map can be used as a reference in sustainable risk management efforts in the Rejali watershed to develop action plans that effectively minimise the impact and damage caused by eruptions.

Acknowledgement

The authors are grateful to the State University of Malang for providing support through the study center scheme research grant agreement No 5.4.396/UN32.20.1/LT/2023 until the completion of this research. Thanks are also to the Lumajang Regency Government, including Candipuro and Pasirian Sub-districts, which have given permission to conduct the research. In addition, thanks to the entire team and institution involved in the research.

References

Adiwijoyo, Adiwijoyo, and Projo Danoedoro. 2014. "Perbandingan Teknik Resampling Pada Citra Hasil Pan-Sharpening Untuk Pemetaan Penutup Lahan Dengan Menggunakan Klasifikasi Terselia Maximum Likelihood." *Jurnal Bumi Indonesia* 3(4).

Azizah, Vischawafiq, Dan Listyo, and Yudha Irawan. 2023. "Deteksi Perubahan Jalur Lahar Di Curah Lengkong Pasca Erupsi Gunungapi Semeru 2021 Menggunakan Google Earth Engine." 7(1):70–93.

Bachri, S., M. N. Fathoni, H. Masruroh, N. A. Wibowo, N. Khusna, E. N. Billah, and L. Yudha. 2023. "Geomorphological Mapping and Landform Characterization of Semeru Volcano after the Eruption in 2021." P. 12004 in *IOP Conference Series: Earth and Environmental Science*. Vol. 1180. IOP Publishing.

Badan Informasi Geospasial. 2023. "Seamless Digital Elevation Model (DEM) Dan Batimetri Nasional." *Tanahair.Indonesia.Go.Id*. Retrieved October 12, 2023 (https://tanahair.indonesia.go.id/demnas/#/).

BPBD Lumajang. 2021. "UPDATE SITUASI PENANGANAN BENCANA ERUPSI GUNUNG SEMERU." *Https://Bpbd.Lumajangkab.Go.Id/?P=1096*.

Cole, Elizabeth, S. 2011. "Geophysical Investigation into the Internal Dynamics of Moving Lahars." 216.

ESDM. 2022. "Press Release KENAIKAN STATUS G. SEMERU DARI LEVEL III (SIAGA) KE LEVEL IV (AWAS)." *Https://Magma.Esdm.Go.Id/v1/Press-Release/222/Press-Release-Kenaikan-Status-g-Semeru-Dari-Level-Iii-Siaga-Ke-Level-Iv-Awas*.

Hakim, Arif Rahman, and Hairunisa Hairunisa. 2017. "Analisis Energi Gempa Letusan Gunung Semeru 09 Oktober 2009." *Jurnal Pendidikan MIPA* 7(1):30–35.

Heryati, Sri. 2020. "Peran Pemerintah Daerah Dalam Penanggulangan Bencana." *Jurnal Pemerintahan Dan Keamanan Publik (JP Dan KP)* 139–46.

Indriasari, Fika Nur, and Prima Daniyati Kusuma. 2020. "Peran Komunitas Sekolah Terhadap Pengurangan Risiko Bencana Di Yogyakarta." *Jurnal Perawat Indonesia* 4(2):395–401.

LARASATI, ZAHRA RAHMA. 2017. "Pemetaan Daerah Risiko Banjir Lahar Berbasis Sistem Informasi Geografis Untuk Menunjang Kegiatan Mitigasi Bencana (Studi Kasus: Gunung Semeru, Kabupaten Lumajang)." *Tugas Akhir* 4.

Larasati, Zahra Rahma, Teguh Hariyanto, and Akbar Kurniawan. 2017. "Pemetaan Daerah Risiko Banjir Lahar Berbasis SIG Untuk Menunjang Kegiatan Mitigasi Bencana (Studi Kasus: Gunung Semeru, Kab. Lumajang)." *Jurnal Teknik ITS* 6(2). doi: 10.12962/j23373539.v6i2.23899.

Mahfud, Wowo Masthuro, and Elsye Maria Rossa. 2017. "Analisis Kapasitas Fungsional Rumah Sakit Umum Prambanan Dalam Menghadapi Bencana Berdasarkan Hospital Safety Index." *Universitas Muhammadiyah Yogyakarta* 1(1):210–23.

Mutiarni, Yosi S., Hitoshi Nakamura, and Yasmin Bhattacharya. 2022. "The Resilience Community: Strengthening People-Centered Disaster Risk Reduction in the Merapi Volcano Community, Java, Indonesia." *Sustainability (Switzerland)* 14(4). doi: 10.3390/su14042215.

Network, Global Volcanism. 2021. "Most Recent Weekly Report: 16 August-22 August 2023." *Https://Volcano.Si.Edu/Volcano.Cfm?Vn=263300*.

Purba, Anggiat, Siswo Hadi Sumantri, Anwar Kurnadi, Dimas Raka, and Kezia Aprillia Ango. 2022. "The Capacity of Affected Communities to Manage Disasters in the Eruption of Mount Semeru." *International Journal of Arts and Social Science* 5(6):161–71.

PVMBG. 2021. "Aktivitas Vulkanik Gunung Semeru, Jawa Timur 4 Desember 2021." *Https://Www.Esdm.Go.Id/Id/Media-Center/Arsip-Berita/Aktivitas-Vulkanik-Gunung-Semeru-Jawa-Timur-4-Desember-2021*.

Rani, M., and N. Khotimah. 2021. "Disaster Risk Analysis of Merapi Volcano Eruption in Cangkringan District Sleman Regency." in *IOP Conference Series: Earth and Environmental Science*. Vol. 884.

Safitri, Eka Diah Nur, Noorlaila Hayati, and Filsa Bioresita. 2021. "Analisis Deformasi Akibat Aktivitas Vulkanik Menggunakan Data Citra Sentinel-1A Dan Metode DInSAR Three-Pass Interferometry (Studi Kasus: Gunung Semeru, Jawa Timur)." *Jurnal Teknik ITS* 10(2):A399–405.

Schilling, Steve P. 2014. *Laharz_py: GIS Tools for Automated Mapping of Lahar Inundation Hazard Zones*. US Department of the Interior, US Geological Survey.

Syuhada, Muhammad Farrel, Sandri Erfani, Ilham Dani, Okta Mulya Sari, and Rahmat Catur Wibowo. 2022. "Analisis Kerentanan Bencana Berbasis SIG (Sistem Informasi Geografis) Menggunakan Metode Weighted Overlay Dengan Scoring Di Kecamatan Sekitar Gunung Api Semeru." *Jurnal Teknologi Dan Inovasi Industri* 03(02):13–17.

Thouret, Jean Claude, Jaime Suni, Jean Philippe Eissen, and Pedro Navarro. 1999. "Assessment of Volcanic Hazards in the Area of Arequipa City, Based on the Eruptive History of the Misti Volcano, Southern Peru." *Zeitschrift Fur Geomorphologie, Supplementband* 114:89–112.

Utama, Lusi, and Afrizal Naumar. 2015. "Kajian Kerentanan Kawasan Berpotensi Banjir Bandang Dan Mitigasi Bencana Pada Daerah Aliran Sungai (DAS) Batang Kuranji Kota Padang." *Jurnal Rekayasa Sipil* 9(1):21–28.

Weis, Shawn W. Margle., Vera N. Agostini, Lynnette M. Roth, Ben Gilmer, Steven R. Schill, John English Knowles, and Ruth Blyther. 2016. "Assessing Vulnerability: An Integrated Approach for Mapping Adaptive Capacity, Sensitivity, and Exposure." *Climatic Change* 136(3–4). doi: 10.1007/s10584-016-1642-0.