https://jurnal.unimed.ac.id/2012/index.php/geo/article/view/60443
https://doi.org/10.24114/jg.v17i2.60443 - (Vol 17, No 2 – 2025)
available at http://jurnal.unimed.ac.id/2012/index.php/geo
e-issn (2549-7057) & p-issn (2085-8167)

Utilizing Spatial Multi-Criteria Evaluation for Analyzing Physical and Social Vulnerability at Merapi Volcano

Hannan Revi Hermawan*, Dyah Rahmawati Hizbaron
Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Indonesia

ARTICLE INFO
Article History:
Received: June 26, 2024
Revision: July 17, 2025
Accepted: July 20, 2025

Keywords:
Merapi Volcano
Physical Vulnerability
SMCE
Social Vulnerability
Vulnerability

Corresponding Author
E-mail:
hannan.revi.hermawan@mail.ugm.ac.id

ABSTRACT
Merapi Volcano is one of the most active volcanoes in Indonesia, which poses a primary eruption hazard in the form of pyroclastic flows. Pakem District is one of the areas affected by the eruption. Vulnerability is the situation where a community experiences a decrease in resilience due to a threatening event that jeopardizes their survival and livelihood. Vulnerability analysis aims to reduce disaster risk. The purpose of this research is to map and analyze the social, physical, and total vulnerability resulting from the eruption of Merapi Volcano in Pakem District using the SMCE method. This research employs the Spatial Multi Criteria Evaluation (SMCE) method to create scenarios based on specific criteria. The results indicate that each village has various classifications of social and physical vulnerability classes. Population density is the most significant variable affecting social vulnerability, whereas the estimated losses from housing damage are the most significant variable influencing physical vulnerability. The results of total vulnerability scenarios, including social, physical, and equal, show the same and consistent class classifications. Candibinangun Village, Harjobinangun Village, and Pakembinangun Village are classified as low total vulnerability. Meanwhile, Hargobinangun Village is classified as low and medium total vulnerability, while Purwobinangun Village is classified as low, medium, and high total vulnerability.

INTRODUCTION

Indonesia has 129 volcanoes, offering benefits and potential volcanic hazards, such as eruptions (Rijanta et al., 2018). Mount Merapi is one of the most active volcanoes in Indonesia, as evidenced by its high frequency of eruptions. One of the most significant eruptions occurred in 2010, with a Volcanic Explosivity Index (VEI) of 4 out of 8 (Voight et al., 2000). This disaster caused substantial damage, disrupting residents' daily activities, paralysing the economic sector, and potentially hindering national development efforts (Mahli et al., 2024).

Mount Merapi exhibits three types of eruption-related hazards: primary, secondary, and tertiary (BPBD Jateng, 2019). According to Rizal and Hizbaron (2015), a large-scaleMount Merapi eruption can result in primary and secondary disasters in the surrounding areas. One of the primary hazards is pyroclastic flow, which is used as a representative parameter of Merapi's volcanic hazards in this study. Pyroclastic flow is a hazardous phenomenon produced by volcanic eruptions, consisting of volcanic ash, toxic gases, and rock fragments (Voight et al., 2000; Marfai et al., 2012). The pyroclastic flow of Mount Merapi has a unique type, known as the "Merapi-type," which is formed due to the collapse of the lava dome and flows through crater openings or summit fissures, following river channels on the slopes (Bronto et al., 1997). The materials from the summit to the lower slopes threaten the surrounding communities.

Pakem District is one of the areas in Sleman Regency that was impacted by the

2010 eruption. Located approximately 5 to 6 kilometres south of Mount Merapi, Pakem District suffered damage to residential buildings and public infrastructure due to the eruption. The 2010 eruption resulted in 381 fatalities in Sleman Regency and displaced 15,366 people (BNPB, 2011). These losses highlight existing vulnerabilities, emphasising the need for a risk assessment that includes vulnerability analysis. Such assessments cannot rely solely on technology and resources, but also require collective awareness, continuous education, and strong coordination among stakeholders (Sembiring et al., 2025).

Vulnerability refers to the condition in which a community experiences reduced resilience due to hazardous events threatening their survival and livelihood, including livelihoods, economic productivity, infrastructure, welfare, and natural resources (Prayogi & Asyiawati, 2021). Vulnerability information is crucial for disaster risk reduction, as disasters only occur when existing hazards intersect with vulnerable conditions (Nurjanah et al., 2013). Accordingly, vulnerability assessment should consider physical, environmental, social, and economic aspects (ISDR, 2004).

This study uses the Spatial Multi-Criteria Evaluation (SMCE) method to analyse social and physical vulnerability. Social vulnerability represents an estimated level of risk to human life and health in the event of a hazard (Habibi & Buchori, 2013), while physical vulnerability refers to the potential for damage, loss, or destruction of physical elements such as buildings, constructions, or other infrastructure when a hazard occurs (Fitria et al., 2019).

This research aims to map and analyse social, physical, and overall vulnerability resulting from the eruption of Mount Merapi in Pakem District using the SMCE method. Using SMCE allows for developing multiple scenarios to identify areas with consistent vulnerability levels. One of the strengths of the SMCE method is its ability to integrate spatial data and apply decision-making results in spatial data outputs (Wibowo et al., 2015). Numerous studies on disaster-related vulnerability have been conducted in Indonesia (Armaya & Hizbaron, 2015; Choirunisa & Giyarsih, 2016; Rahmanu et al., 2021; Aristo, 2022; Wibowo et al., 2025). However, this study is distinct in its application of the SMCE method in Pakem District, Sleman, a context that previous researchers have not widely explored.

RESEARCH METHODS

The research focuses on Pakem District as the study area, utilising administrative units such as villages or districts, considering data availability. The research employs the spatial multi-criteria evaluation (SMCE). Spatial Multi Criteria Evaluation (SMCE) is a decision-making approach utilising simulation models that assess multiple criteria in a spatial context (Kurnia et al., 2022). The SMCE method utilises ILWIS (Integrated Land and Water Information System) software. SMCE methodology offers the advantage of scenario creation based on diverse criteria. The vulnerability assessment in this research focuses on two types: physical and social vulnerability. The results of these vulnerability assessments are combined to create a total vulnerability assessment using scenarios derived from the SMCE method.

Total vulnerability is an overlay of social vulnerability, physical vulnerability, and the hazard map of pyroclastic flows from Merapi Volcano. The hazard map of pyroclastic flows from Merapi Volcano is derived from data from the Geological Disaster Research and Development Centre (BPPTKG) covering eruptions from 1911 to 2010. The data were then overlaid and classified into low (0–0.333), medium (0.334–0.666), and high (0.667–1).

Total vulnerability with the SMCE method is categorised into social, physical, and equal scenarios. The social scenario emphasises a higher weighting on social vulnerability, whereas the physical scenario emphasises a weighting on physical vulnerability. Meanwhile, the equal scenario assigns equal weighting to each variable, balancing physical and social vulnerability variables equally.

The SMCE method proceeds through four stages: problem tree classification, standardisation, weighting, and scenario analysis. The problem tree classification stage identifies variables to be used in assessing both social and physical vulnerability. The subsequent stage involves standardisation to address differences in data types among variables to enable uniform measurement and comparison. In this study, variables are approached using the benefit method, where higher indicator values correspond to higher vulnerability levels.

The following process is weighting, employing the Analytical Hierarchy Process (AHP). AHP's pairwise comparison method utilises expert judgments from four experts to determine the weights of each social and physical vulnerability variable. These experts include two from the Faculty of Geography, Universitas Gadjah Mada, and two representatives from national institutions, namely BPPTKG and the Sleman Regency BPBD.

Secondary data sources obtained from institutional surveys and literature studies are employed. The research variables and data types refer to Regulation of the Head of BPBD No. 2 of 2012 on General Guidelines for Disaster Risk Assessment, adding variables. The total vulnerability was determined using social and physical components. For social vulnerability, the variables used were population density, sex percentage, elderly population percentage, infant population percentage, pregnant women population percentage, poor population percentage, and disabled population percentage. The data for these variables were sourced from secondary data provided by the Department of Population and Civil Registration of Sleman Regency. The physical vulnerability was assessed from the land value of settlements, public facilities (schools and worship facilities), critical facilities (hospitals, community health centres, and government offices), and the distance between assembly points and safe points. The data for these variables were obtained using Hot Export Tools from OpenStreetMap. Below is Table 1 for classifications for each social and physical vulnerability variable.

Table 1. Classifications of each variable of social and physical vulnerability following Regulation of the Head of BNPB No. 2 of 2012 (with modifications)

Variable	Classification and Criteria		
	Low	Medium	High
	Social		
Population density (people/km^2)	< 500	500-1,000	> 1,000
Sex percentage	>40%	20%-40%	<20%
Elderly population percentage	<10%	10%-20%	>20%
Infant population percentage	<5%	5%-10%	>10%
Pregnant women population percentage	<5%	5%-10%	>10%
Poor population percentage	<20%	20%-40%	>40%
Disabled population percentage	<20%	20%-40%	>40%
	Physical		
Settlements (IDR)	<807.28 billion	807.28 billion – 1.05 trillion	> 1.05 trillion
Public facilities (universities, middle and high schools and worship facility) (IDR billion)	< 72.64	72.64 – 105.29	> 105.29
Critical facilities (hospitals, community health centers, government offices) (IDR billion)	< 85.53	85.53 – 168.6	> 168.6

Distance between assembly points and safe points (km)	< 2.67	2.67-4.13	>4.13

The classification results of each social and physical vulnerability variable are then assigned weights derived from expert judgment using the pairwise comparison method of AHP to produce maps of social vulnerability and physical vulnerability. These weights reflect the influence of each variable on vulnerability. The resulting vulnerability values were classified into low (0–0.333), medium (0.334–0.666), and high (0.667–1). Three scenarios are created using the SMCE method for total vulnerability: social, physical, and environmental. Each scenario highlights variables that have the most significant influence on total vulnerability. Below is the table of weights for the total vulnerability scenarios.

Table 2. Variable weighting with three different scenarios from the SMCE Method

Variable	Equal Scenario	Physical Scenario	Social Scenario
Vulnerability		0.5	
Social Vulnerability	0.5	0.25	0.75
Population density	0.143	0.20	0.20
Sex percentage	0.143	0.05	0.05
Elderly population percentage	0.143	0.16	0.16
Infant population percentage	0.143	0.11	0.11
Pregnant women population percentage	0.143	0.19	0.19
Poor population percentage	0.143	0.13	0.13
Disabled population percentage	0.143	0.16	0.16
Physical	0.5	0.75	0.25
Settlements	0.25	0.42	0.42
Public facilities	0.25	0.16	0.16
Critical facilities	0.25	0.35	0.35
Distance between assembly points and safe points	0.25	0.07	0.07
Hazard Map		0.5	

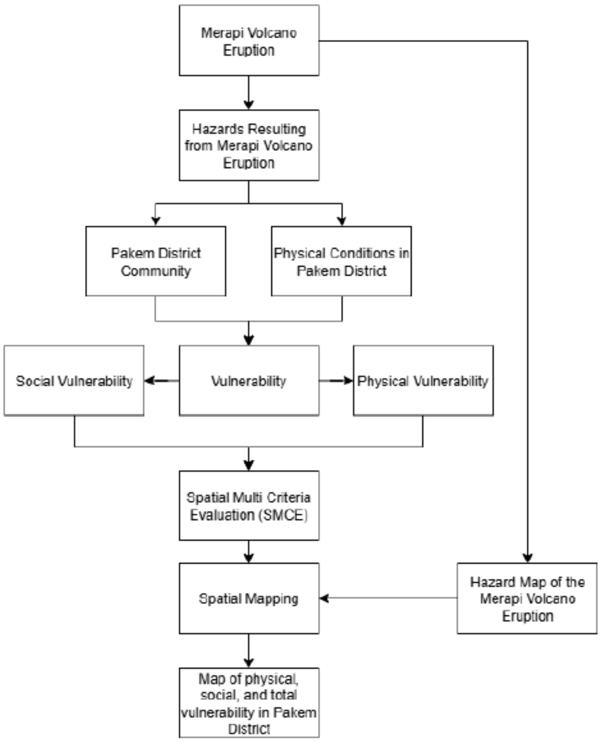


Figure 1. Framework Research (Source: Data Processing, 2024)

RESULTS AND DISCUSSION

Social Vulnerability

Social vulnerability focuses on demographic and socio-economic factors influencing a community's ability to cope with disasters (Maharani et al., 2020). Social vulnerability describes the likelihood of losses to specific risk elements associated with individual conditions, including age, gender, education level, economic status, or other factors that may make them more susceptible to disaster impacts (Birkmann & Wisner, 2006; Ebert et al., 2007, cited in Hizbaron et al., 2010). Social vulnerability in this study comprises seven variables: population density, percentage of toddlers, percentage of elderly population, percentage of disabled population, percentage of pregnant women, percentage of impoverished population, and gender percentage. Population density holds the highest weight of 0.20 among the variables, indicating it has the most significant influence on social vulnerability compared to others. Conversely, gender percentage has the most negligible influence, at 0.05, on social vulnerability due to its lower weight.

Classifying six out of seven variables produced consistent results across the five villages in Pakem District. The percentages of elderly and infant populations fall into the low category; the populations of persons with disabilities, the poor, and pregnant women are categorised as moderate; while the gender ratio is classified as high. A higher proportion of the female population than males contributes to increased social vulnerability. Women generally face limited access to resources, such as early warning systems, policy and decision-making processes in disaster risk reduction and management, knowledge and information, and disaster assistance (Aryanti & Muhlis, 2020).

Meanwhile, population density in Purwobinangun and Hargobinangun villages is moderate, while Candibinangun, Pakembinangun, and Harjobinangun villages are high. High population density may hinder evacuation efforts and indicate a greater potential for casualties during disaster events (Akbar, 2018). Areas with high population density tend to exhibit higher levels of social vulnerability.

Each village has different social vulnerability classifications. Purwobinangun village has classifications ranging from low to moderate to high due to its varying levels of exposure to high, moderate, and low pyroclastic flow hazards. Similarly, Hargobinangun village is classified as mild and low because parts of its area face moderate and high pyroclastic flow hazards.

Candibinangun, Pakembinangun, and Harjobinangun villages exhibit low social vulnerability. Despite their high population density, these villages are far from Merapi Volcano, leading many residents to settle there. Since pyroclastic flows do not directly affect these areas, their social vulnerability is low.

Table 3. Social Vulnerability Score and Classification

Subdistrict	Social Vulnerability Score	Low Hazard	Medium Hazard	High Hazard	Total Score	Classification
Purwobinangun	0.525	-	-	0.25 km²	0.763	High
		-	1.91 km²	-	0.596	Medium
		3.66 km²	-	-	0.429	Medium
		-	-	-	0.263	Low
Hargobinangun	0.525	-	0.05 km²	-	0.596	Medium
		3.87 km²	-	-	0.429	Medium
		-	-	-	0.263	Low
Candibinangun	0.593	-	-	-	0.297	Low
Pakembinangun	0.593	-	-	-	0.297	Low
Harjobinangun	0.593	-	-	-	0.297	Low

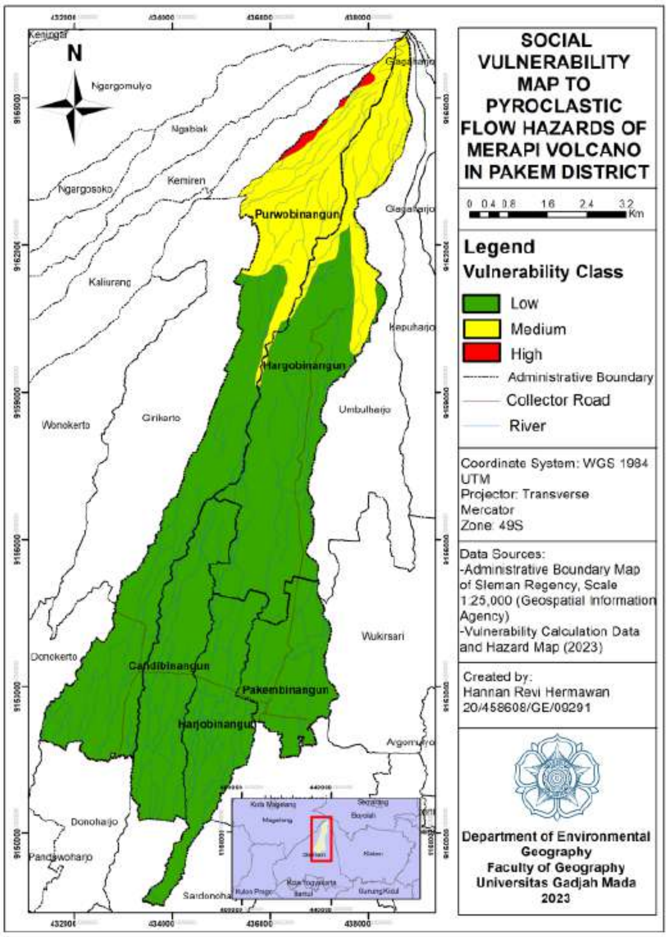


Figure 2. Social Vulnerability Map to Pyroclastic Flow Hazards of Merapi Volcano in Pakem District

Physical Vulnerability

Physical vulnerability describes the capacity of the built physical environment within hazard zones to withstand the impacts of disasters (Woodruff et al., 2018). Physical vulnerability in this study encompasses four variables: estimated damage to houses, estimated damage to public facilities, estimated damage to critical facilities, and distance between gathering points and safe points. The calculation of damage estimates is based on the area of a building multiplied by the estimated damage price. Weighting using the AHP method reveals that estimated damage to houses is the most influential variable, with the highest weight score of 0.42. Conversely, the distance between gathering and safe points is the least influential variable, with a weight of 0.07. Gathering points in this context refer to village halls, while safe points denote district offices.

Purwobinangun Village exhibits a range of physical vulnerability classifications across its territory, spanning from low to moderate to high categories. This variation is attributed to the village's inclusion within the pyroclastic flow hazard zone. Specifically, Purwobinangun Village is classified as mild regarding estimated damage to residential buildings and public facilities, and low for estimated damage to critical facilities. The high estimated damage to residential buildings indicates a high level of vulnerability, resulting in the loss of housing for affected communities. Immediate restoration of damaged residential infrastructure is essential, as the burden of displacement poses a significant challenge for the affected population (Juliani et al., 2011).

Candibinangun and Harjobinangun villages are classified as having low physical vulnerability. This classification is due to the low estimated damage to houses and critical facilities in both towns. This condition is supported by the fact that the entire territories of these villages are not within the pyroclastic flow hazard zone. Pakembinangun village, although entirely outside the pyroclastic flow hazard zone, exhibits moderate physical vulnerability. This is attributed to high estimated damage to public and critical facilities, influenced by its status as the district's centre, which results in relatively comprehensive public and vital facilities compared to other villages.

Table 4. Physical Vulnerability Score and Classification

Subdistrict	Physical Vulnerability Score	Low Hazard	Medium Hazard	High Hazard	Total Score	Classification
Purwobinangun	0.572	-	-	0.25 km^2	0.786	High
		-	1.91 km^2	-	0.619	Medium
		3.66 km^2	-	-	0.452	Medium
		-	-	-	0.286	Low
Hargobinangun	0.692	-	0.05 km^2	-	0.679	Medium
		3.87 km^2	-	-	0.512	Medium
		-	-	-	0.346	Low
Candibinangun	0.355	-	-	-	0.193	Low
Pakembinangun	0.673	-	-	-	0.337	Medium
Harjobinangun	0.387	-	-	-	0.177	Low

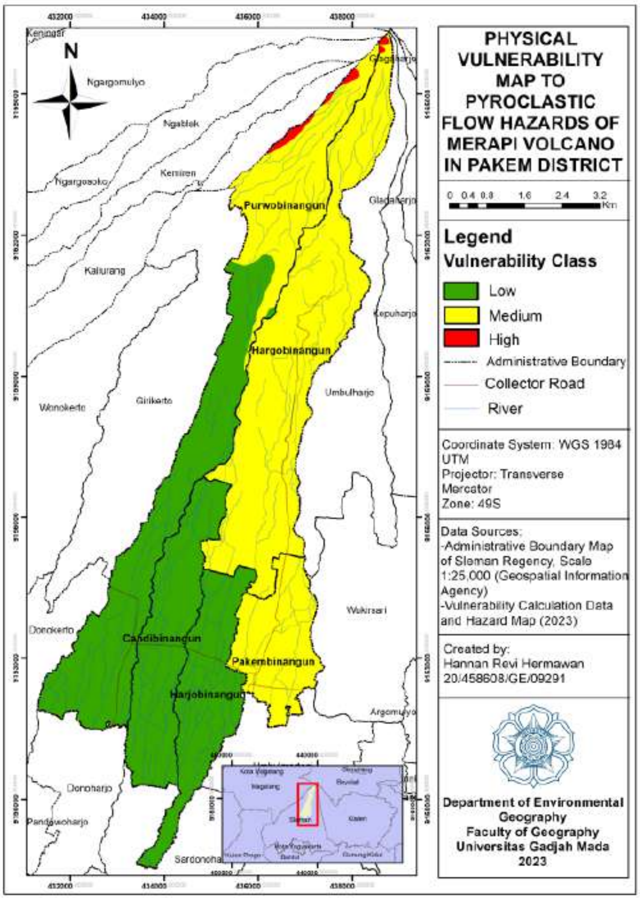


Figure 3. Physical Vulnerability Map to Pyroclastic Flow Hazards of Merapi Volcano in Pakem District

Total Vulnerability

The classification of total vulnerability to pyroclastic flow hazards from Merapi Volcano in Pakem District employs three scenarios: social, physical, and equal to the SMCE method. The results of total vulnerability classification in the social scenario are consistent with those of the physical and equal scenarios. This classification indicates that Purwobinangun and Hargobinangun villages exhibit diverse vulnerability classes due to their inclusion in the pyroclastic flow hazard zone. Areas within these villages categorised as low and moderate pyroclastic flow hazards are classified as mild in total vulnerability. In contrast, areas in Purwobinangun village classified as high pyroclastic flow hazard are classified as high in total vulnerability. Additionally, areas in Purwobinangun and Hargobinangun villages outside the pyroclastic flow hazard zone are classified as low total vulnerability. Similarly, outside the pyroclastic flow hazard zone, Candibinangun, Harjobinangun, and Pakembinangun villages are classified as having low total vulnerability.

The similarity in total vulnerability classification results among the physical, social, and equal scenarios is attributable to the inherent vulnerability values. However, differences in vulnerability scores exist between physical and social scenarios for each village due to varying influences of the most significant variables. The total vulnerability results in the social scenario are more influenced by population density levels, followed by the percentage of pregnant women and other variables with lesser percentages. In contrast, the physical scenario is more influenced by levels of vulnerability in estimated damage to houses, followed by damage to critical facilities and other variables with lower percentages. The equal scenario equalises the impact of each variable to eliminate discrepancies in vulnerability influence. This contrasts with the other two scenarios, prioritising greater influence on one type of vulnerability. The consistent results among the social, physical, and equal scenarios indicate reliability in vulnerability assessment across different scenario applications. Below is the table (table 5, table 6, and table 7) and map illustrating the levels of total vulnerability in the equal scenario concerning pyroclastic flow hazards from Merapi Volcano in Pakem District.

Table 5. Total Vulnerability Score and Classification in Social Scenario

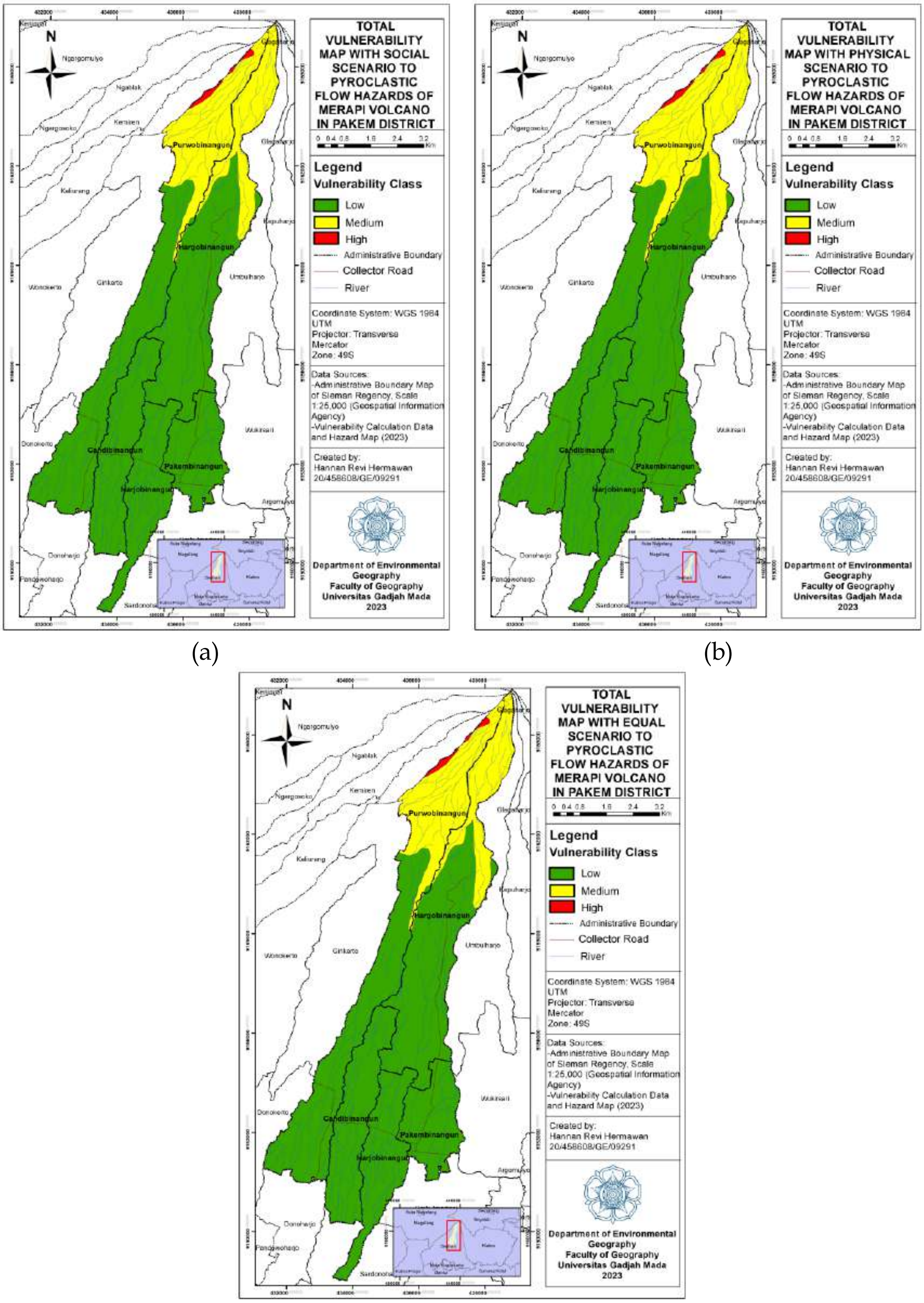
Subdistrict	Total Vulnerability Score in Social Scenarios	Low Hazard	Medium Hazard	High Hazard	Total Score	Classification
Purwobinangun	0.538	-	-	0.25 km²	0.769	High
		-	1.91 km²	-	0.602	Medium
		3.66 km²	-	-	0.435	Medium
		-	-	-	0.269	Low
Hargobinangun	0.568	-	0.05 km²	-	0.617	Medium
		3.87 km²	-	-	0.450	Medium
		-	-	-	0.284	Low
Candibinangun	0.534	-	-	-	0.267	Low
Pakembinangun	0.613	-	-	-	0.307	Low
Harjobinangun	0.542	-	-	-	0.271	Low

Table 6. Total Vulnerability Score and Classification in Physical Scenario

Subdistrict	Total Vulnerability Score in Physical Scenarios	Low Hazard	Medium Hazard	High Hazard	Total Score	Classification
Purwobinangun	0.561	-	-	0.25 km²	0.780	High
		-	1.91 km²	-	0.613	Medium
		3.66 km²	-	-	0.447	Medium
		-	-	-	0.280	Low
Hargobinangun	0.650	-	0.05 km²	-	0.658	Medium
		3.87 km²	-	-	0.492	Medium
		-	-	-	0.325	Low
Candibinangun	0.414	-	-	-	0.207	Low
Pakembinangun	0.653	-	-	-	0.327	Low
Harjobinangun	0.439	-	-	-	0.219	Low

Table 7. Total Vulnerability Score and Classification in Equal Scenario

Subdistrict	Total Vulnerability Score in Equal Scenarios	Low Hazard	Medium Hazard	High Hazard	Total Score	Classification
Purwobinangun	0.574	-	-	0.25 km²	0.741	High
		-	1.91 km²	-	0.574	Medium
		3.66 km²	-	-	0.407	Medium
		-	-	-	0.287	Low
Hargobinangun	0.574	-	0.05 km²	-	0.574	Medium
		3.87 km²	-	-	0.407	Medium
		-	-	-	0.287	Low
Candibinangun	0.473	-	-	-	0.236	Low
Pakembinangun	0.598	-	-	-	0.299	Low
Harjobinangun	0.472	-	-	-	0.236	Low



(a) (b)

(c)

Figure 4. (a) Total Vulnerability Map With Social Scenario to Pyroclastic Flow Hazards of Merapi Volcano in Pakem District; (b) Total Vulnerability Map With Physical Scenario to Pyroclastic Flow Hazards of Merapi Volcano in Pakem District; (c) Total Vulnerability Map With Equal Scenario to Pyroclastic Flow Hazards of Merapi Volcano in Pakem District

CONCLUSION

Population density is the most influential variable on social vulnerability. The classification of social vulnerability levels reveals that Purwobinangun Village and Hargobinangun Village exhibit diverse classes, whereas Harjobinangun Village, Pakembinangun Village, and Candibinangun Village fall into the low vulnerability classification. The variable estimating housing damage is the most influential in physical vulnerability. The classification indicates that Harjobinangun Village and Candibinangun Village have low physical vulnerability, while Pakembinangun Village has a medium physical vulnerability classification. Hargobinangun Village exhibits medium to high physical vulnerability, whereas Purwobinangun Village shows a range of low, medium, and high physical vulnerability. The total vulnerability classification remains consistent when combining physical, social, and equal-weight scenarios using the SMCE method. Candibinangun Village, Harjobinangun Village, and Pakembinangun Village consistently exhibit low total vulnerability. In contrast, Purwobinangun Village demonstrates a range of low, medium, and high total vulnerability, and Hargobinangun Village shows low to medium total vulnerability.

ACKNOWLEDGMENT

The author thanks the Faculty of Geography at Gadjah Mada University (UGM) for funding this research through the Independent Grant Program for Lecturers, Faculty of Geography, UGM, 2024.

REFERENCE LIST

Akbar, S. (2018). Analisis Kerentanan Banjir di Kecamatan Baleendah Kabupaten Bandung. Thesis. Bogor: Institut Pertanian Bogor.

Aristo, M. R. (2022). Analisis Kerentanan Fisik Dan Sosial Bencana Erupsi Gunungapi Merapi Di Kecamatan Turi. Thesis Yogyakarta: Fakultas Geografi, Universitas Gadjah Mada.

Armaya, D. A. B., & Hizbaron, D. R. (2015). Penaksiran tingkat kerentanan sosial terhadap bahaya banjir lahar pasca erupsi gunungapi merapi (Studi Kasus: Kec. Cangkringan, Kec. Ngemplak dan Kec. Kalasan, Kab. Sleman, Prov. DIY). Jurnal Bumi Indonesia, 4(4).

Aryanti, T., & Muhlis, A. (2020). Disaster, Gender, and Space: Spatial Vulnerability in Post-disaster Shelters. IOP Conference Series: Earth and Environmental Science, 447(1). https://doi.org/10.1088/1755-1315/447/1/012012

Badan Nasional Penanggulangan Bencana. (2011). Rencana Aksi Rehabilitasi dan Rekonstruksi Wilayah Pascabencana Erupsi Gunung Merapi di Provinsi D.I. Yogyakarta dan Jawa Tengah Tahun 2011-2013. Jakarta: Badan Nasional Penanggulangan Bencana.

Badan Penanggulangan Bencana Daerah Jawa Tengah. (2019). Dokumen Rencana Kontingensi Erupsi Gunung Merapi. Semarang: Badan Penanggulangan Bencana Daerah Jawa Tengah.

Bronto, S., Hartono, G., Sampara, D. T., & Soehardija, D. (1997). Bunker Sebagai Penanggulangan Darurat Awan Panas Gunung Merapi di Daerah Yogyakarta-Jawa Tengah. Prosiding Ikatan Ahli Geologi Indonesia Pertemuan Ilmiah Tahunan ke XXVI. Jakarta: Ikatan Ahli Geologi Indonesia.

Choirunisa, A. K., & Giyarsih, S. R. (2016). Kajian kerentanan fisik, sosial, dan ekonomi pesisir samas Kabupaten Bantul terhadap erosi pantai. Jurnal Bumi Indonesia, 5(4).

Fitria, L. M., Ni'mah, N. M., & Danu, L. K. (2019). Kerentanan Fisik Terhadap Bencana Banjir di Kawasan Perkotaan Yogyakarta. Reka Ruang, 2(1), 1-9. https://doi.org/10.33579/rkr.v2i1.1048

Habibi, M., & Buchori, I. (2013). Model Spasial Kerentanan Sosial Ekonomi dan KelembagaanTerhadap Bencana Gunung Merapi. Jurnal Teknik PWK

2(1): 1-10. https://doi.org/10.14710/tpwk.2013.1402

Hizbaron, D. R., Hadmoko, D. S., Samodra, G., Dalimunthe, S. A., & Sartohadi, J. (2010). Tinjauan Kerentanan, Risiko dan Zonasi Rawan Bahaya Rockfall di Kulonprogo, Yogyakarta. Forum Geografi, 24(2): 119-136. https://doi.org/10.23917/forgeo.v24i2.5021

ISDR. (2004). Living with Risk: A Global Review of Disaster Reduction Initiatives. Geneva: UNISDR.

Juliani, A., Brontowiyono, W., Ribut, L., Hamidin, H., & Evi, O. (2011). Rapid Assessment Terhadap Kerusakan Bangunan Akibat Erupsi Merapi Tahun 2010. Jurnal Sains & Teknologi Lingkungan, 3(2), 115-124. https://doi.org/10.20885/jstl.vol3.iss2.art5

Kurnia, G. R., Nugraha, A. L., & Sukmono, A. (2022). Analisis Spasial Tingkat Risiko Akibat Pandemi Coronavirus Disease 2019 (Covid–19)(Studi Kasus: Kabupaten Indragiri Hulu, Provinsi Riau). Jurnal Geodesi Undip, 11(1): 1-10. https://doi.org/10.14710/jgundip.2022.31815

Maharani, Y. N., Nugroho, A. R. B., Adiba, D. F., & Sulistiyowati, I. (2020). Pengaruh Kerentanan Sosial Terhadap Ketangguhan Masyarakat dalam Menghadapi Bencana Erupsi Gunungapi Merapi di Kabupaten Sleman. Jurnal Dialog Penanggulangan Bencana, 11(1). p-ISSN: 2087-636X

Mahli, R. A. K., Maharani, M., & Erfani, S. (2024). Studi Interdisipliner Risiko Bencana Erupsi Gunung Berbasis SIG (Sistem Informasi Geografis) Menggunakan Metode Overlay Pada Daerah Sekitar Kawasan Gunung Marapi. Jurnal Teknologi dan Inovasi Industri (JTII), 5(1). https://doi.org/10.23960/jtii.v5i1.86

Marfai, M. A., Cahyadi, A., Hadmoko, D. S., & Sekaranom, A. B. (2012). Sejarah Letusan Gunung Merapi berdasarkan Fasies Gunungapi di Daerah Aliran Sungai Bedog, Daerah Istimewa Yogyakarta. Riset Geologi dan Pertambangan-Geology and Mining Research, 22(2),:73-80. http://dx.doi.org/10.14203/risetgeotam2012.v22.59

Nurjanah., Sugiharto, R., Kuswanda, D., Siswanto, B. P., & Adikoesoemo. 2013. Manajemen Bencana. Bandung: Alfabeta.

Prayogi, W. A., & Asyiawati, Y. (2021). Kajian kerentanan pantai terhadap pengembangan wilayah Pesisir Pangandaran. Jurnal Riset Perencanaan Wilayah Dan Kota, 89-98. https://doi.org/10.29313/jrpwk.v1i2.370

Rahmanu, Y., Hadmoko, D., & Marwasta, D. (2021). Tingkat Kerentanan Fisik Bangunan terhadap Potensi Erupsi Gunungapi Kelud. Jurnal Dialog Penanggulangan Bencana, 12(1), 33-45. p-ISSN: 2087-636X

Rijanta, R., Hizbaron, D. R., & Baiquni, M. (2018). Modal Sosial dalam Manajemen Bencana. Yogyakarta: UGM PRESS.

Rizal, M. A., & Hizbaron, D. R. (2015). Analisis Kerentanan Fisik Bahaya Banjir Lahar Di Desa Sekitar Kali Putih Kabupaten Magelang. Jurnal Bumi Indonesia, 4(1): 175-184.

Sembiring, Z., Ahmad, C. M., Harahap, F., Nabila, W. A., Dhari, W., & Amalia, Z. T. (2025). Kesiapan dalam Menghadapi Bencana Alam Gunung Meletus. Indonesian Research Journal on Education, 5(3), 511–518. https://doi.org/10.31004/irje.v5i3.2682

Voight, B., Constantine, E. K., Siswowidjoyo, S., & Torley, R. (2000). Historical Eruptions of Merapi volcano, Central Java, Indonesia, 1768–1998. Journal of Volcanology and Geothermal Research, 100(1-4): 69–138. https://doi.org/10.1016/S0377-0273(00)00134-7

Wibowo, D. A., Raharjo, P. D., Puswanto, E., Handoko, U., Afif, M. A., & Setiawan, M. A. (2024). Assessment of Physical, Social, and Economic Vulnerability to Landslide Disasters in the Karangsambung Karangbolong National Geopark, Indonesia. In IOP Conference Series: Earth and Environmental Science, IOP Publishing. https://doi.org/0.1088/1755-1315/1378/1/012003

Wibowo, T. W., Putri, E. A. W., & Loekman, H. Y. (2015). Evaluasi Multi-kriteria Keruangan untuk Pemetaan Kerentanan Terhadap Bahaya Tsunami di Pesisir Kabupaten Bantul. Prosiding Seminar Nasional Geografi UMS. Surakarta : Universitas Muhammadiyah Surakarta. https://doi.org/10.13140/RG.2.1.5152.2723

Woodruff, S., Vitro, K. A., & Bendor, T. K. (2018). GIS and Coastal Vulnerability to Climate Change. Comprehensive Geographic Information Systems, 236–257. https://doi.org/10.1016/B978-0-12-409548-9.09655-X