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ASSESSING COMMUNITY VULNERABILITY TO THE 2010 MERAPI ERUPTION: AN ANALYSIS OF EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY

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ABSTRACT: Mount Merapi is one of the most active volcanoes in Indonesia. In the past century, Merapi erupted several times and caused damage and loss of life to the surrounding communities, especially in Cangkringan Sub-district, Sleman. However, it does not stop the community from inhabiting the volcano's slopes. One of the main reasons is the communities rely on their livelihood on livestock and agriculture within those areas. This study assessed the vulnerability of the communities who live on the slopes of Merapi by identifying three key aspects: exposure, sensitivity, and adaptive capacity. This study employs a qualitative approach using secondary data from scientific literatures, hazard maps, government reports, and statistical records. Overall, the findings indicate that community vulnerability results from the intersection of persistent exposure, socioeconomic sensitivity, and uneven adaptive capacity. Strengthening disaster risk reduction in Merapi's hazard zones requires not only enhancing institutional preparedness but also addressing livelihood dependence and local cultural dimensions. The study underscores the importance of integrating social vulnerability assessment into volcanic disaster management and resilience planning.

Keywords: Merapi Volcano, Volcanic Eruption, Vulnerability, Assessment

1. INTRODUCTION

Volcanic eruptions are a natural phenomenon that commonly occurs in high seismic areas like Indonesia. Since it is located at the boundary of three major tectonic plates, the Indo-Australia plate, Eurasian plate, and Pacific plate, consequently Indonesia is categorized as a country with high seismic activity and has plenty of volcanoes. Some of the volcanoes are still active and some are not. Merapi is an active volcano in Indonesia which is located on the border between Yogyakarta and Central Java province. It is classified as one of the most hazardous volcanoes in Indonesia due to the high level of eruptive activity and densely populated surroundings [1].

The recent Merapi eruption occurred in 2010 and caused a lot of damages, loss of life, and loss of livelihoods. It was the largest eruption in the past 100 years [2]. Almost 400,000 people were internally displaced, around 2,200 houses were damaged, and at least 270 people passed away [3] [4]. In 2010, there were more than 1 million people reportedly living on the slopes of Merapi, within a radius of 20 km from the summit (BPS, as cited in Mei et. al. [4]). These communities are spread in four districts within Central Java and Yogyakarta Province namely, Klaten, Boyolali, Magelang, and Sleman. Sleman district suffered the most from the Merapi eruption in 2010. It is located in the southern part of Merapi. The 2010 eruption produced pyroclastic flows that headed to the south and swept the areas nearby.

In Indonesia, there are seven levels of government administrative namely national, province, district, sub-district, municipality, village, and sub-village. In order to manage the disaster caused by Merapi, the government already divided the areas surrounding the summit of Merapi into three different zones based on the potential to be affected by eruption called Hazard Zone (Kawasan Rawan Bencana, KRB) (Fig. 1). KRB III is the riskiest areas and often perished by pyroclastic flows, lava flows, rock avalanches, incandescent materials, and toxic gases. KRB II is potentially swept by pyroclastic flows, toxic gases, and rock avalanches, and lahar flows. KRB I is potentially swept by lahar/flood.

Based on the population distribution data 2010, there are three sub-districts in Sleman that have several villages located in KRB III and KRB II. They are Cangkringan, Pakem, and Turi sub-district. Cangkringan is the sub-district with the most villages located in risky hazard zone KRB III. These communities are particularly at risk of an eruption from Mount Merapi. In 2010, the eruption

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caused damages to 67.1% of the houses of the communities living in Cangkringan [3]. This article attempts to assess the vulnerability of the communities who live on the slopes of Merapi volcano based on the exposure, sensitivity, and adaptive capacity. Exposure and sensitivity are the aspects that if the values are high, they will contribute to vulnerability. Adaptive capacity is what the community has or what the government does to reduce vulnerability.

We must be wondering why these communities live in the risky areas since the hazard might come anytime and perish everything; or why they do not choose to live in safer areas; why the government does not evacuate them from these areas. These questions are asked by most people when they watch or read the news regarding the Merapi eruption. Answering these questions is not very easy. However, we should at least try to conceive their background, or we should feel the way they feel or we should put ourselves in their situation so that we can understand their position.

We will begin by observing the land on the slope of Merapi. The communities have been living in this prone are since hundreds of year ago [5]. Most of them are farmers and animal husbandries, but some of them are also carpenters, and sand miners [6]. The reason why they live here is, this land provides plenty of potential natural resources for agriculture, plantation, and livestock. The land on the slope of Merapi was formed by the eruption in the past. This land provides good nutrients which are greatly beneficial for agricultural purposes [7]. The community uses this nutrient-rich land for planting chilies, melons, garlic, shallots, cabbage, carrot, etc. Livestock is also a source of subsistence for community who lives on the slope of Merapi. They raise cattle, especially dairy cattle so that they can sell the dairy milk. However, livestock is usually only as an additional income. Livestock is also their bank account. It is a saving which can be exchanged for money anytime.

Communities living on the slopes of Mount Merapi are continuously exposed to volcanic hazards such as pyroclastic flows, lahar, and volcanic ash. Despite the recurring eruptions and high risk of destruction, many residents continue to inhabit these areas due to their strong dependence on the fertile volcanic soils for agriculture and livestock-based livelihoods. The 2010 eruption demonstrated the magnitude of potential losses thousands of houses were damaged, hundreds of people lost their lives, and many others suffered long-term livelihood disruptions.

Understanding the decision of the community to stay at risky area requires understanding beyond physical aspects. The approach should also address the other factors such as socioeconomic, cultural beliefs, and institutional capacity. This study aims to assess the vulnerability of the community who lives in the slopes of Mount Merapi by addressing three key dimensions: exposure, sensitivity, and adaptive capacity.

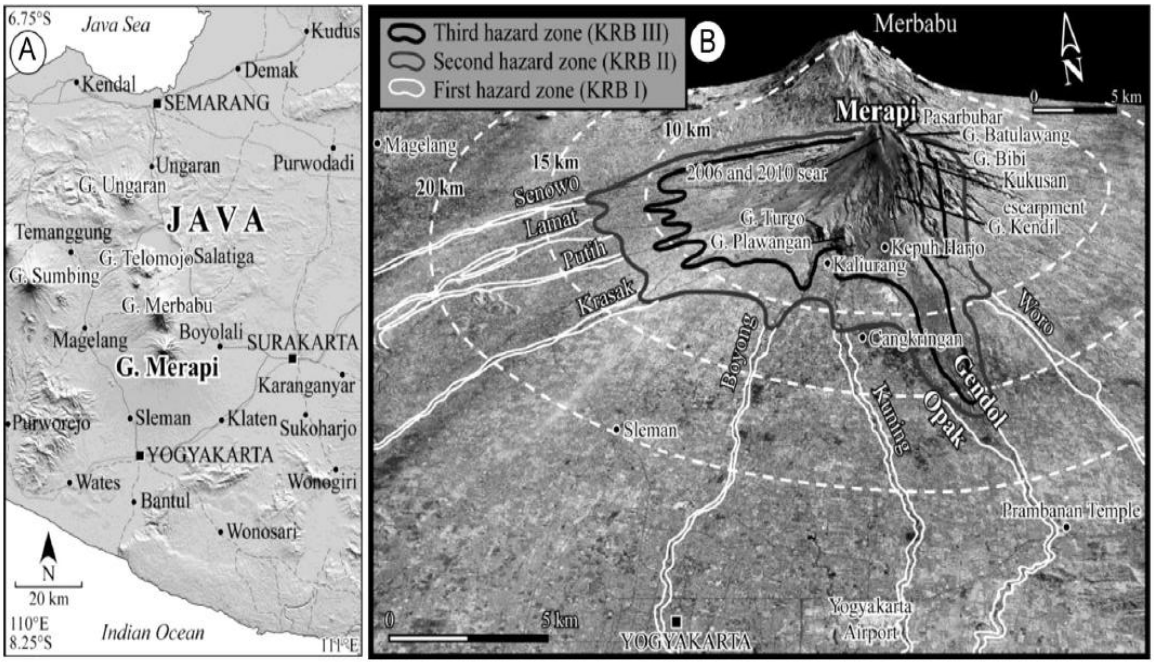

Figure 1. (a) Location of Merapi Volcano and surrounding cities; (b) The Hazard Zone (KRB) of Merapi Volcano **[8]**

2. METHODS

This study is qualitative research. This study is supported by secondary data analysis to assess the vulnerability of the community who lives on the slope of Merapi Volcano. The assessment is conducted by following the framework of UNDP-SCDRR concept [9]. UNDP-SCDRR defines vulnerability as a function of three key aspects: exposure, sensitivity, and adaptive capacity. The relationship between these variables can be express as :

$$V = E + S - AC$$

where E represents exposure, S represents sensitivity, and AC represents Adaptive Capacity [10]. Briefly, the influence of each variable in this equation is as follows: exposure and sensitivity increase vulnerability, while adaptive capacity reduces it [11].

The study assessed the vulnerability of the communities who live in the Cangkringan Sub-district of Sleman, Yogyakarta. This area is located at the southern part of Mount Merapi. Some villages of this sub-district is located in the Hazard Zone III (KRB III). These villages suffered the most impact subjected to the Merapi Eruption in 2010. The communities in this area are mostly relied on their lives in agriculture and dairy farming. This makes them stay in these villages because the soil is fertile due to volcanic ashes. However, they are exposed to volcanic hazards.

Data Collection

The analysis relies on secondary data obtained from various reputable sources, including:

1. Government documents and reports from BNPB, BPPTK, and Pemerintah Kabupaten Sleman concerning the 2010 eruption and disaster management activities.
2. Statistical data from Badan Pusat Statistik (BPS) on population distribution, occupation, and socioeconomic conditions.
3. Academic literature and peer-reviewed journal articles such as those by Mei et al. [4], Bakkour et al. [8], and others addressing Merapi's eruptions, evacuation, and community resilience.
4. Hazard zone maps and spatial data from Badan Informasi Geospasial (BIG) and PVMBG describing KRB I–III boundaries.

No primary data was collected; however, the analysis integrates multiple verified sources to ensure reliability and consistency.

Data Analysis

The assessment of vulnerability was conducted through three analytical components:

1. Exposure Analysis
   Exposure was evaluated based on the physical and environmental characteristics of the study area, including the proximity of settlements to the Merapi summit, population density within each hazard zone, and the types of volcanic hazards (pyroclastic flows, ash fall, and lahar). The information was synthesized from hazard maps, eruption records, and existing studies to identify the areas and communities most at risk.
2. Sensitivity Analysis
   Sensitivity refers to the degree to which a population is affected by hazards. Three main indicators were used:
   a. Cultural factors, including traditional beliefs that influence people's responses to evacuation orders.
   b. Economic conditions, particularly the dependence on agriculture and livestock as main sources of income.
   c. Demographic factors, such as the proportion of elderly, children, and low-education groups.

   These indicators were derived from existing literature, census data, and case studies.
3. Adaptive Capacity Analysis
   Adaptive capacity was examined by reviewing the ability of institutions and communities to prepare for, respond to, and recover from disasters. The analysis considered:
   a. Institutional mechanisms, including the role of BNPB, BPBD, and local governments in coordinating disaster management.
   b. Early warning systems (EWS) and communication networks established by PVMBG and BPPTK.
   c. Community initiatives, such as volunteer groups, evacuation drills, and local leadership figures that influence collective action.
   These aspects were evaluated qualitatively based on official reports and scholarly literature.

Validation

To ensure validity, data and findings were triangulated across multiple sources. Consistency between scientific publications, government reports, and statistical data was cross-checked. Interpretations were aligned with the broader theoretical framework of community resilience and adaptive governance in volcanic disaster contexts.

This methodological approach enables a holistic understanding of vulnerability as a dynamic interaction among physical exposure, social sensitivity, and institutional capacity. Although limited to secondary data, the framework provides

a comprehensive basis for future studies involving quantitative or field-based validation.

3. RESULTS AND DISCUSSION

3.1 Exposure

The collision between Indo-Australian plate and Eurasian plate has formed a number of volcanoes which are scattered in Java Island and Sumatera Island. These two major islands are the most populated island with the total population of 145 million and 55 million people respectively [12]. Moreover, approximately there are 5 million people are living/working near the volcanoes within the dangerous area which means they need to be evacuated immediately when the activity of the volcanoes are rising significantly [13].

Just like the other volcanoes in Java Island and Sumatera Island, Merapi has the similar characteristic in terms of eruption type. It begins with the formation of the lava dome. If the lava dome is not stable, it will avalanche and produce pyroclastic flows. The pyroclastic flow is the main hazard. It is a mixture of hot lava in various size including ash-sized to boulder-sized. The flows hurtle down in high speed up to 90 km/hour in a very hot temperature, about 600^{o}C (Fig. 2). If human beings are hit by this hazard, no one can survive.

Based on the Hazard zones map which was established by National Disaster Management Authority (BNPB), pyroclastic flows often sweep KRB III which located about 0 – 5 km from the summit of Merapi. When the volcano shows an increasing activity, the villages within this KRB III should be evacuated. This does not mean people who live in KRB II and I are simply safe from the eruption. They still have the potential to be affected by other hazards. KRB II which is located about 5-10 km from the summit is potentially swept by the same hazard as the KRB III but it less likely to happen. The third hazard zone, KRB I, encompasses the villages near the rivers that originate from mountains. These villages usually are affected by secondary lahars called cold lava. The eruption produces pyroclastic flows that end up as debris in the headwaters. During heavy rainfall, water can mobilize the debris including mud, rocks, woods, and other materials and sweep everything near the rivers. People who live in these areas should beware of this hazard.

Merapi volcano produces hazards which are able to directly hit the villages nearby right away after the eruption. Furthermore, it also produces indirect hazards which need to be triggered by the other aspect, for example, heavy rainfall. However, both of this hazards can cause primary impacts and also secondary impacts not only for the villages nearby but also the cities nearby. Primary impacts are physical, for example, damage to buildings, infrastructures, and properties. Secondary impacts are non-physical and usually triggered by the primary impacts such as economic disruption, health, and safety. See Table 1 below to get a detail explanation.

Figure.1 Pyroclastic Flows of Merapi [14]

Table 1 Direct and Indirect Merapi Eruption Hazards and Primary and Secondary Impacts

Direct Hazard		
Hazard	**Primary Impacts**	**Secondary Impacts**
Pyroclastic flow	• Loss of life • Loss of cattle • Damage to houses • Damage to cattle pens • Damage to plantation lands and farmlands	• Economic disruption to farmers, dairy cattle farmers, and plantation sector • Loss of subsistences • Due to tourism area nearby are shut down, hotels, motels, and inns incure losses
Volcanic Ash (This hazard not only affects people nearby but also it can affect people who live hundreds of kilometers away from the summit)	• Respiratory health problem • Skin irritation • Eyes irritation • Airport closed • Tourism palces closed • Economic activities disturbed	• Airport closing lead to decrease of tourists number • Ash covers the roads, makes it slippery and lead to incidents
Indirect Hazard		
Hazard	**Primary Impacts**	**Secondary Impacts**
Cold Lava	• Flooding • Damage to infrastructures such as bridges and roads • Damage to weirs • Damage to river embankment	• Economic disruption to settlement • Siltation of river which leads to decrease of river capacity, can cause the other floods in the future • To spread disease

3.2 Sensitivity

Sensitivity can be defined as "the degree to which different system and sectors of population are affected by hazard" [9]. Some group of people may be exposed to the same hazards, but they may have distinct impacts. In an extreme comparison, we can say some communities may survive and some may not survive. What makes them have different impact is the notion of sensitivity. For example, there are two adjacent households who live in Merapi slope area and both of them are exposed to pyroclastic flows from the eruption. These two households have different level of education that leads to different knowledge and awareness to eruption. The household that has better education level conceive very well what to prepare and what to do if the volcano is showing the preliminary signs of eruption. On the contrary, the household that does not have good education level does not know what to do and what to prepare. Eventually, the same hazard can cause a distinct impact on these two households.

In the case of Merapi volcano, beside education level, there are several indicators which are able to influence the sensitivity of the community. In this article, I identify three indicators of sensitivity. Each indicator is explained below,

1. Cultural factors
   Javanese are well-known as an ethnic group that still stick to traditional beliefs. Traditional beliefs moreover, have the propensity to mysticism beliefs. Even though in these modern era the traditional beliefs have faded due to more rational way of thinking but literally there are still some parts of them that still lingered on [15]. Particularly in terms of Merapi eruption 2006 and 2010, the cultural belief was one of the indicators that contribute to community sensitivity level. At Merapi volcano, there was a man called as Kuncen (volcano's gatekeeper), Mbah Maridjan. He was renowned as the man who was able to tame the volcano. During 2006 eruption he insisted to stay in his village despite Merapi's imminent eruption. During the 2010 eruption, Mbah Maridjan did the same thing as well as 2006 eruption and moreover, 34 people stayed with him, although the government repeatedly requested to follow the evacuation order [4]. Ultimately, all of them perished by the flows.
2. Economic status
   Poverty levels can contribute to sensitivity as well. Economically poorer people are more vulnerable to disturbances [16]. Due to disaster, households may lose their properties and jobs. Economically poorer people who lose properties will have a serious problem. It will be hard for them to get the new properties. As well as properties, losing jobs due to

disaster is also a serious problem. People become unemployed and are not able to provide enough income to fulfill their daily needs. It makes the situation aftermath of disaster even worse. At Merapi, most of the livelihoods of the community are farmer and dairy cattle farmer. The pyroclastic flows perished their houses, farmlands and their cattle sheds. Eventually, they become unemployed and do not have places to live. The attention by the government is crucial in this matter.

3. Age group
   Babies, toddlers, and elderly people are more vulnerable to disaster. They need more assistance and protection during a disaster. Babies and toddlers do not know about disaster and cannot protect themselves. Elderly people (over 60 years old) may know about disaster but usually, they have lost adaptability due to health issue such as illness and disability. That is why elderly groups become less capable of coping with disaster [17].

3.3 Adaptive Capacity

Adaptive capacity is what makes the community less vulnerable. It can be autonomous, collective, or institutional adaptive capacity [9]. Autonomous means the individual or household actions to protect themselves during the disaster. Collective adaptive capacity means the community actions, how they do coordination before, during, and after the disaster. Institutional adaptive capacity means the role of government in disaster events such as policies, regulations, and evacuation mechanism.

In the case of Merapi eruption 2010, institutional adaptive capacity was crucial. The President of Indonesia, Susilo Bambang Yudhoyono, supervised the entire management system of this disaster [8]. The President appointed National Disaster Management Authority (BNPB) which further the emergency response control was given to BNPB. The president decided to appoint BNPB because the location of Merapi affected several districts within two provinces, Yogyakarta and Central Java. BNPB was responsible for coordinating the disaster management assistances for all the affected districts. Based on the administrative level, BNPB is at national level. At lower institutional scales, provinces and districts, BNPB was represented by BPBD (Local Disaster Management Authority). Therefore, BPBD at district level and the head of each district were the spearheads of crisis management because they know their own districts more than others after all.

On the other hand, BNPB also collaborated with the other agencies, departments, and institutions such as National Army, National Police, Basarnas (Indonesian Search and Rescue) and PMI (Indonesian Red Cross) for search and rescue actions; Ministry of Social Affairs for managing internally displaced people; BIG (National Bureau of Spatial Information) for establishing hazard zones map (KRB); Ministry of Energy and Mineral Resources and BMKG (Meteorological, Climatology and Geophysics Agency) for warning system matters [8].

Unlike earthquakes, volcanic eruptions can include an early warning system (EWS) that gives signs if the volcano is showing preliminary behavior of potential eruption. EWS for Merapi volcano has been installed since the 1970s and there have been several development changes since then to enhance its technology [18]. The information about volcanic activity of Merapi is reported from each Investigation and Technology Development Office (BPPTK) and then transmitted to Center for Volcanology and Geological Hazard Mitigation (PVMBG). BPPTK is part of PVMBG and PVMBG is part of The Ministry of Energy and Mineral Resources. There are 4 stages of volcano EWS as described in Table 2 below. Every information regarding the activity of Merapi was reported by BPPTK to local government and BPBD. Further, they worked at the local level with the chief of the villages and sub-villages, local organizations, army, police, NGOs, and Volunteers to prepare the emergency and evacuation plan [8].

In terms of EWS of Merapi 2010, PVMBG as the authority who officially reported the behavior of Merapi to the media/press got a lot of credits from the Indonesian and also from the other countries [19]. Merapi is renowned as one of the most active and hazardous volcanoes but during 2010 eruption PVMBG precisely predicted the eruption and prevented more casualties.

3.4. Vulnerability

The Merapi eruption in 2010 was not the only eruption which caused a lot of damages, loss of life, and loss of livelihoods. Historical records show some severe eruptions in past centuries (See Table 3). During eruptions, people are evacuated to a safer place. However, after the alertness level of eruption goes down, people come back to their home and start everything from the beginning. After all of those hard situations, Merapi still offers a pull for them. They do not have any other option because fertile soils on the slopes of Merapi are their main subsistence.

Table 2. The Merapi Eruption in The Past Centuries

No.	Year of Eruption	Casualties
1	1672	3000
2	1872	200
3	1930	1300
4	1931	54
5	1961	6
6	1994	69
7	2006	2
8	2010	339

Source: [4] [20]

Tabel 3. Alertness Level of Volcano in Indonesia

Level of Alertness	Terms	Indication
Level 1	Normal	There is no eruption indication
Level 2	Cautious	Volcanic and seismic activities are increasing above normal level but usually not followed by eruptive activity
Level 3	Alert	There are significant increasing volcanic and seismic activities. People in hazard zone III are ready to be evacuated
Level 4	Beware	The volcano shows a propensity toward the main eruption. No one allowed to stay in hazard zone III

Source: [21]

Governments and communities do have the ability to reduce community vulnerability. After identifying exposure and sensitivity, we know what hazards may strike the communities and who are more vulnerable. After identifying the adaptive capacity, we know what should be done during the eruption. It is highly difficult to reduce the exposure since it is a natural disaster, but we can reduce the sensitivity and increase the adaptive capacity.

The government devoted serious effort during eruption to prevent more casualties. Most of the villages were already evacuated to safer areas. However, some of them often sneak back to their farms to feed their cattle. They took the risk by endangering themselves to keep the cattle alive. To address this problem, since 2010 the government decided to evacuate cattle to a suitable evacuation center for livestock [22]. Therefore, people would not go to the dangerous area to feed cattle.

The government also created "Volcano Heroes" [22] to reduce the sensitivity due to cultural factor. This idea was inspired by the existence of Mbah Maridjan, the gatekeeper of Merapi. A volcano hero is a leader who is able to influence the behavior of the community. Mbah Surono the head of PVMBG was appointed as the Volcano Heroes to replace the position of Mbah Maridjan. In the future, if the Merapi is showing increasing activities Mbah Surono will show up to spread the information on TVs and radios and expectedly people follow his instruction and there will be no casualties.

3.4. Interlinkages of Variables

The interaction between exposure, sensitivity, and adaptive capacity creates a dynamic cycle of vulnerability. High exposure amplifies the effects of economic and cultural sensitivity, while limited adaptive capacity reinforces dependence on high-risk livelihoods. This cyclical pattern reflects what UNDP-SCDRR (2015) refers to as "compound vulnerability," where multiple factors overlap to sustain long-term risk. Breaking this cycle requires strategies that not only protect people from hazards but also transform the social and economic structures that make them vulnerable. For example, promoting alternative livelihoods outside the hazard zone could reduce economic sensitivity, while integrating local knowledge into early warning systems could enhance adaptive capacity. These approaches align with the Sendai Framework for Disaster Risk Reduction (2015–2030), which emphasizes community-based resilience and the inclusion of local perspectives in risk governance.

The assessment underscores that reducing vulnerability in volcanic regions such as Merapi requires more than physical relocation or infrastructure investment. It necessitates an integrated policy approach that combines spatial planning, livelihood resilience, and community empowerment. The government should strengthen the linkage between land-use policy and disaster risk reduction by enforcing zoning regulations while providing incentives for safe agricultural practices in lower-risk areas. Furthermore,

integrating cultural leaders and local institutions into formal disaster governance can enhance public trust and compliance during emergencies.

In practical terms, disaster risk reduction planning should move from reactive evacuation-based models toward proactive community resilience building. Programs focusing on livelihood diversification, risk education, and participatory planning will enable communities to coexist safely with the natural dynamics of Merapi. This approach reflects the idea of "living in harmony with nature" not by ignoring the risk, but by preparing and adapting to it

4. CONCLUSION

Merapi eruption in 2010 has caused a lot of consequences, including loss of life, loss of property, loss of livelihoods, and environmental disruptions. However, it did not stop people from coming back and start a new chapter of life aftermath of a calamity. This is like a cycle that happens perpetually. For an extreme comparison, there are two options to cope with the Merapi eruption, moving the community or building the community. Each option has consequences.

Merapi eruption in 2010 exposed the vulnerability of communities who lived in high-risk areas. This study assessed the vulnerability of the communities by identifying three key aspects: exposure, sensitivity, and adaptive capacity.

Moving people to new safe zones can reduce vulnerability. In the future, the community will not be exposed to hazards. However, the challenge is to develop new subsistence for them. The government must work hard to ensure they get new jobs so they can fulfill their daily needs. Building the community means the government does not need to devote a lot of efforts in order to get a new livelihood for them. Let the community live in hazard zones by relying on their previous subsistence activities but the government needs to enhance the adaptive capacity. The government needs to educate them regarding the characteristics of Merapi and disaster management. The idea is to live in harmony with nature. Therefore, the cycle of Merapi eruption may happen someday, but the communities are ready and well-prepared so that they can survive and bounce back after disturbances.

While this study provides valuable insights, it is limited by its reliance on secondary data and qualitative interpretation. Future research should integrate primary field data, participatory assessments, and quantitative vulnerability indices to capture intra-community variations more precisely. Such approaches would strengthen the empirical foundation for designing evidence-based policies in volcanic risk management.

Ultimately, the goal is not merely to relocate or protect communities from Merapi's hazards, but to build adaptive societies capable of coexisting with volcanic environments. By understanding vulnerability as a multidimensional process, disaster management efforts can evolve toward a more inclusive and sustainable model of resilience that enables communities to live safely and productively within the dynamic landscape of Mount Merapi.

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