THE GEOVISUALIZATION OF SETTLEMENT AND CATTLE DISTRIBUTION IN THE KRASAK RIVER, INDONESIA, POST THE 2010 MERAPI ERUPTION

SUDARYATNO SUDARYATNO[*1], SITI ANDARWATI[**], PRIYAJI AGUNG PAMBUDI[***],
ARIF KURNIAWAN PUTRA[****], RADEN RARA FABIOLA ANGGITA LARASATI[****],
BIRTA AYU ANGGARIFTA[****]

Key-words: Geovisualization, settlement distribution, cattle, Merapi, eruption, Indonesia.

Abstract. Mount Merapi, one of Indonesia's active mountains, still has the potential to cause lahar flows. The spatial modelling of lahar flow can be done to determine the characteristics of lahar flow distribution and the area that can be affected through the integration with data on danger zone areas (known in Indonesian as Kawasan Rawan Bencana or KRB), the river network, and the historical lahar volume. Lahar flow modelling produces four classes of lahar volume scenarios, namely 125,000 m^3, 250,000 m^3, 500,000 m^3, and 1,000,000 m^3. The modelling results show that if the scenario of lahar volume with the highest flow class of 1,000,000 m^3 occurs, the impact of lahar flow can reach the KRB I zone, which has the lowest hazard potential compared to KRB II and KRB III. This study aims to map the settlement and cattle distribution after the 2010 Merapi eruption through geovisualization, based on the results of lahar flow modelling. Geovisualization is processed from data such as the road network, the river network, the distribution of settlements, the distribution of evacuation sites, the population of each affected sub-district, the number of cattle, and the lahar flow modelling data around the Krasak River area, which is located on the border of Sleman Regency and Magelang Regency. The geovisualization results of settlement and cattle distribution are used to analyse distribution patterns, evacuation road networks, and the condition of the settlements and the cattle. Through geovisualization, valuable and easy-to-understand information will be presented related to lahar flow schemes, danger zone areas, the distribution of population and the cattle affected by the eruption, the distribution of settlements, the evacuation sites and cowsheds, and the routes to the evacuation sites.

1. INTRODUCTION

Indonesia is included in the Pacific Ring of Fire region, so it has a high level of vulnerability to volcanic eruption disasters. One of the volcanoes in Indonesia that is very active and displays a high risk is Mount Merapi. It is one of the volcanoes on the island of Java with an altitude of 2,968 meters above sea level with an active status (Adri *et al*., 2020). Administratively, Mount Merapi is located on the border between Central Java and Yogyakarta Special Region, in the regencies of Sleman, Magelang, Boyolali, and Klaten. Geographically, it is located at 7°32'30"S and 110°26'30"E. According to Widodo & Hastuti (2020), one of the eruptions of Mount Merapi occurred in 2010 as a large eruption with a Volcanic Explosivity Index (VEI) level of 4, equalling the eruption of the same mountain of 1872. According to Sahagian *et al*. (2022), the Volcanic Explosivity Index (VEI) is a semi-quantitative index

[1] Lecturer, Department of Geographic Information Science, Faculty of Geography, Universitas Gadjah Mada, Sekip Utara. Bulaksumur, Yogyakarta, Indonesia, sudaryatno@ugm.ac.id.
[**] Lecturer, Department of Animal Husbandry Socio-Economics, Faculty of Animal Husbandry, Universitas Gadjah Mada, Bulaksumur, Yogyakarta, Indonesia, andar_siti@ugm.ac.id.
[***] Lecturer, Graduate School of Environmental Science, Universitas Gadjah Mada, Jl. Teknika Utara, Sinduadi, Yogyakarta, Indonesia, priyajiagungpambudi@ugm.ac.id.
[****] Student, Undergraduate Program of Cartography and Remote Sensing, Faculty of Geography, Universitas Gadjah Mada, Sekip Utara, Bulaksumur, Yogyakarta Indonesia, arif.kurniawan.p@mail.ugm.ac.id, raden.rara.fabiola.anggita.larasati@mail.ugm.ac.id, birta.ayu.a@mail.ugm.ac.id.
[1] Corresponding author

used to determine the magnitude of eruption explosivity information, such as eruption duration, volume of ejected material, and eruption column height. Wati *et al*. (2020) explained that, according to BNPB 2010, the 2010 Merapi Eruption was the largest eruption in the past 100 years, resulting in 227 dead, 186 injured, 159,977 people displaced, 2,346 housing units severely damaged, 15 health facilities and 366 education facilities damaged. BNPB, or Badan Nasional Penanggulangan Bencana, is an Indonesian term for the National Disaster Management Agency.

Based on the activity report data of Mount Merapi from November 5, 2020, until now, the activity level of Mount Merapi obtained from the Center for Research and Development of Geological Disaster Technology (in Indonesian known as Balai Penyelidikan dan Pengembangan Teknologi Kebencanaan Geologi or BPPTKG) is at a level III "Watch". There are four mountain status levels: normal, advisory, watch, and warning (BNPB, 2020). The results of the BPPPTKG report explain that the current potential danger in the form of lahar flows and hot clouds in the south-southwest sector includes the Boyong River over a maximum of 5 km, the Bedog, Krasak, Bebeng Rivers over a maximum of 7 km and, in the Southeast sector, the Woro River over a maximum of 3 km and the Gendol River over 5 km. Based on the report data, the south-southwest sector has the potential for lahar flows and the farthest hot clouds, namely in the Bedog, Krasak, and Bebeng Rivers. The three rivers flow into one, the Krasak River. Krasak River is one of the rivers that is heavily affected by the cold lahar of Mount Merapi (Saputro, 2019). Therefore, it is important to know the potential lahar flow that is likely to spill in the Krasak River. According to the Danger Zone Areas Map (known in Indonesian as Peta Kawasan Rawan Bencana or KRB Map) from the Regional Disaster Management Agency of Yogyakarta Special Region (known in Indonesian as Badan Penanggulangan Bencana Daerah or BPBD), Krasak River is included in KRB III, which is an area that is very likely/often hit by hot clouds, lahar flows, volcanic bombs, toxic gases and (incandescent) rockfall.

One way to determine the potential of lahar flow after the eruption of Mount Merapi in 2010 in the area around the Krasak River is by conducting spatial modelling. Modelling is done by using Digital Elevation Model (DEM) data from DEM Nasional (DEMNAS), which is the elevation of the land surface data throughout Indonesia provided by the Geospatial Information Agency (known in Indonesia as Badan Informasi Geospasial). Lahar volume scenarios are based on historical data or literature studies related to the volume released by Mount Merapi. Scenarios are made based on the duration interval of the flowing lahar or the type of lahar. The model that has been made can be used to analyse the characteristics of lahar flow distribution after the 2010 eruption. The characteristics of lahar flow distribution from the spatial model are used as overlay material with data on danger zone areas or KRB obtained from the Online Accreditation System of the Disaster Management Education and Training Center of the National Disaster Management Agency (known in Indonesian as Sistem Akreditasi Daring Pusat Pendidikan dan Pelatihan Penanggulangan Bencana or Siakang).

Characteristics of lahar flow distribution from spatial models can be integrated into various studies. One of the studies that can be done has to do with the geovisualization of residential and livestock distribution. Balla *et al*. (2020) explained that geovisualization is a technique to visually provide information about spatial data so that the information is more understandable. Through this geovisualization, an analysis can be carried out related to the distribution of residential conditions and livestock after an eruption in the form of the lahar flow in the danger zone areas or KRB. According to Lesmana *et al*. (2022), each class of KRB has its potential danger. The KRB I has the potential to be hit by rockfall with a maximum size of 10 mm and heavy volcanic ash rain; the KRB II has a medium potential for lahar flows, lahars, and incandescent rockfall with a maximum size of 64 mm and heavy volcanic ash rain; the KRB III has a high potential for lahar flows, toxic volcanic gases, lahars, (incandescent) rockfall and heavy volcanic ash rain (BNPB, 2019). Therefore, this study aims to determine the spatial distribution characteristics of lahar flows through spatial modelling, and then geovisualize the distribution of settlements and cattle after the 2010 eruption to create valuable and easy-to-understand information. This is done as an eruption disaster mitigation effort for human and cattle evacuation around the KRB zone.

2. STUDY AREA

The research site is located around the Krasak River area, one of several rivers passed by the lahar flow from Mount Merapi, on the border between Sleman Regency and Magelang Regency (Fig. 1). Administratively, this research location is bordered by Magelang Regency to the east and Sleman Regency to the west. The cold lahar flows from Mount Merapi affect several rivers, including Krasak River. Krasak River is highly vulnerable to hot clouds, lahar flows, volcanic bombs, toxic gases, and incandescent rockfall, according to the Danger Zone Areas Map from the Regional Disaster Management Agency. Furthermore, Krasak River is fed by the Bedog and Bebeng Rivers, which underscores its significance as a key area for assessing the potential impact of volcanic hazards, especially during intense periods of rainfall. Considering the high vulnerability Krasak River displays to volcanic hazards, it is essential to assess the potential lahar flow that may impact the river.

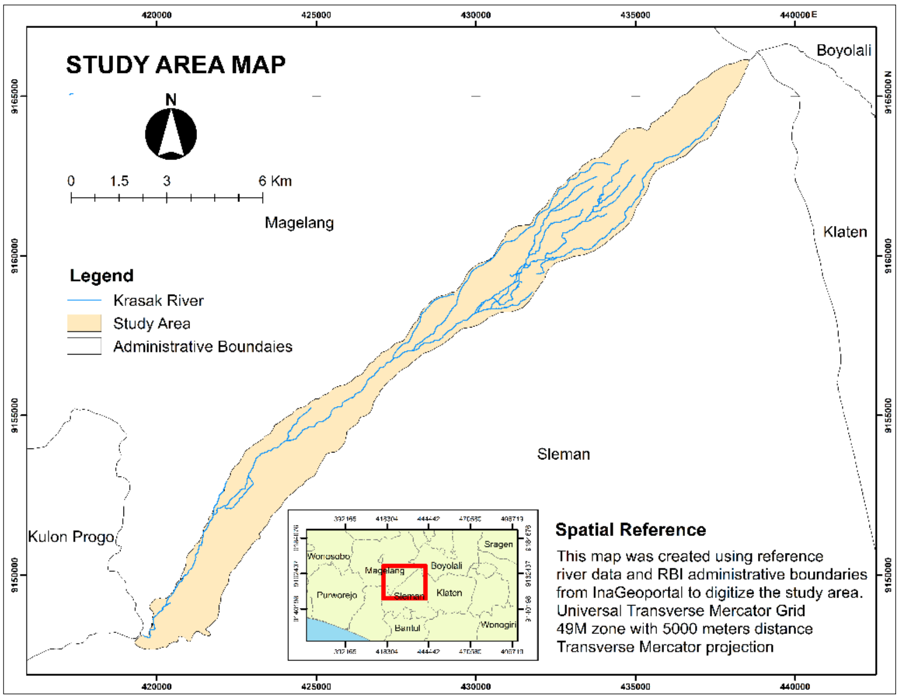

Fig. 1 – Study Area Map.

3. METHODOLOGY

3.1. Data Processing

Based on the research flow diagram (Fig. 2), some data act as inputs, namely satellite imagery, DEMNAS data, historical volume data, and data on danger zone areas (known in Indonesian as Kawasan Rawan Bencana or KRB) of Mount Merapi. These data are used for spatial modelling to analyse the distribution characteristics of lahar flows following the 2010 eruption. The imagery in this research is Sentinel-2A, which is used as the basis for interpretation to obtain information on river hydrology, road networks, settlement distribution, and evacuation sites. The interpretation process will produce a Tentative Map of the Evacuation Road Network and a Tentative Map of Residential Distribution and Evacuation Sites. Meanwhile, other inputs, such as DEMNAS data with a spatial resolution of 8.1m, are used to determine the extent and direction of lahar flow by creating flow direction and flow accumulation data. According to Bilqis *et al*. (2024), DEM is a pixel-based representation model of the earth's surface that describes the ground surface elevation and topographic model derived to identify the direction of lahar flow with certain lahar volume scenarios. The determination of lahar flow direction based on DEMNAS processing can be derived through the determination of lahar flow area by entering the slope value obtained from the calculation of the ratio of H to L (slope H/L), followed by the process of deriving flow direction and flow accumulation data. Historical data of Mount Merapi eruption volume ranges from 125,000 m^3 to 465,000 m^3, as sourced from research conducted by Belizal *et al*. (2013) and Wibowo *et al*. (2015), which are used for lahar volume scenario generation.

The lahar flow model created using the Laharz toolbox in ArcGIS is based on DEM and lahar volume scenarios. Laharz requires simple, non-complex inputs based on experiments and volcanic and non-volcanic original flows. Laharz is a semi-empirical model from the compilation of data from ~30 lahars worldwide (Dille *et al.*, 2020). This study's input for creating the lahar flow model using Laharz is based on the DEM and lahar volume scenarios. Starting from these scenarios, flow direction models are then created, including start points, endpoints, and farthest runout points. The modelling stages using Laharz are used to create surface hydrology, generate a new stream network, hazard zone proximal, lahar distal zone, and raster to shapefile. The result of the lahar flow model will be integrated with the danger zone areas (KRB) data of Mount Merapi to create a Tentative Map of the Lahar Flow Model and KRB Zone.

3.2. Field Validation

There are several field validation activities that can be seen in the flow chart (Fig. 2), such as validation of road network, validation of evacuation sites, and validation of lahar flow model. The validation of road network and evacuation sites was conducted on the tentative map of visual interpretation results that have been done in the data processing stage. Meanwhile, the validation of the lahar flow model is done by giving questionnaires and conducting interviews related to the history or events that have occurred before as an illustration of the range of lahar flow and verifying the danger zone areas, or KRB. The validation of lahar flow model in field activities is achieved in the form of checks related to the history of lahar flow in the visited areas by performing interviews with local communities. Interviews are conducted by providing questionnaires related to historical events or incidents that have occurred, aiming to obtain data or understand the extent of lahar flow on the banks of the Krasak River. The survey was also conducted by looking at Krasak River's current condition to connect its morphological condition with the condition of lahar flow distribution.

The validation lahar flow model was executed by overlaying the processed lahar flow model with the KRB zone. This overlay aims to find out the areas that overlap with KRB Merapi and those that do not. It can show that the model made in this research can be relevant based on the existing map. Although some areas are outside the KRB area, the resulting model can be validated from the overall results.

3.3. Post-Field Processing

Post-field processing resulted in the Lahar Flow Model Map and several geovisualization outputs on the distribution of settlements and cattle after the 2010 Merapi eruption. The Lahar Flow Model Map is based on a tentative map that has been validated through questionnaires and interviews. Meanwhile, the geovisualization output was made based on the road network, river network, distribution of shelters, distribution of refugee camps, population of each affected sub-district, number of cattle, and data from lahar flow modelling around the Krasak River area. The geovisualization process produces several final outputs that can be seen in the flowchart (Fig. 2), namely the Map of Population, Cattle, and Settlement

Distribution; the Distribution of Evacuation Sites and Cowshed Map; and the Merapi Volcano Eruption Evacuation Road Network Map. The Map of Population, Cattle, and Settlement Distribution is derived from data on population and cattle in each sub-district and the spatial distribution of settlements. The map is used to visualize the distribution characteristics related to population, livestock, and settlement aspects in the study location that can be correlated with the level of potential hazard. Furthermore, the Distribution of Evacuation Sites and Cowshed Map is derived from the results of geotagging evacuation sites and cowsheds known during field validation. Meanwhile, the Merapi Volcano Eruption Evacuation Road Network Map is generated from the Distribution of Evacuation Sites and Cowshed Map integrated with road data, lahar volume scenario areas data, and danger zone areas or KRB data.

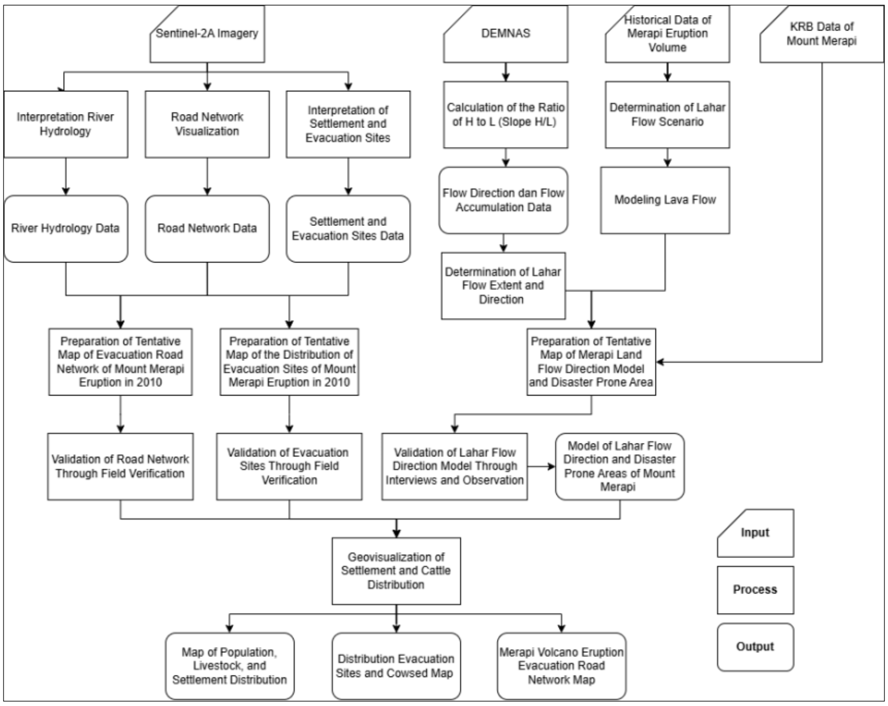

Fig. 2 – Research Flow Chart.

4. RESULTS AND DISCUSSION

4.1. Lahar Flow Direction Model and the KRB Zone of Mount Merapi

The lahar flow direction model of Mount Merapi is processed based on historical lahar volume data using the Laharz toolbox. Lestari *et al*. (2019) explained that Laharz is a tool to calculate the proximal danger zone and automate the equations built in the Geographic Information System (GIS) over three topographic dimensions to estimate the lahar flow danger zone.

Figure 3 shows the modelling results of the Mount Merapi lahar flow in the Krasak River. Five models are made based on the starting point of the lahar flow with four scenarios of lahar volume. Determination of the starting point of the lahar flow is based on the coordinates of the proximal hazard zone processing that leads to the Krasak River. There are two rivers whose flow direction leads towards the Krasak River, namely the Bebeng River and the Bedog River. Visualization of lahar volume scenarios in Figure 3 shows four lahar volume classes, namely 125,000 m^3, 250,000 m^3, 500,000 m^3, and 1,000,000 m^3.

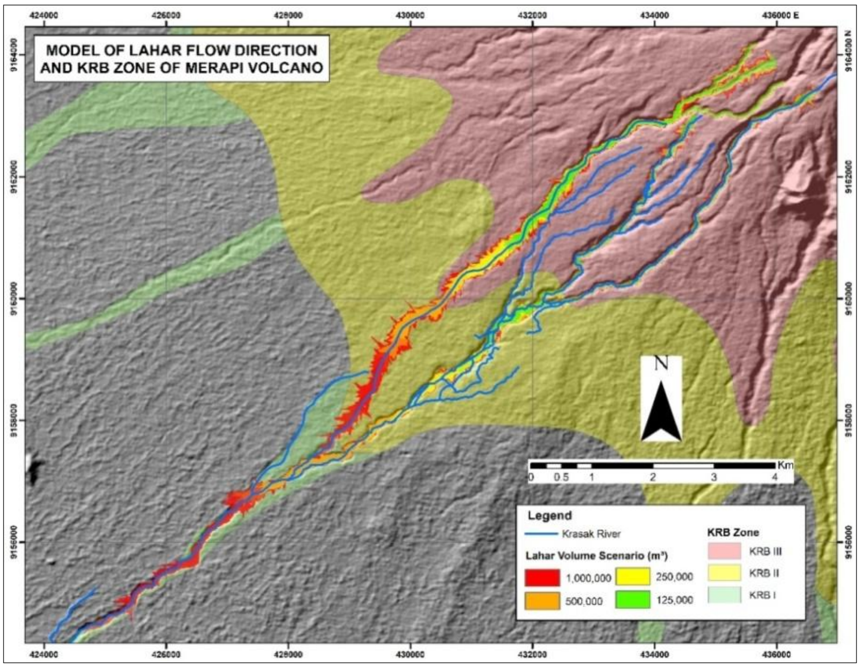

Fig. 3 – Model of Lahar Flow Direction and KRB Zone of Merapi Volcano.

Based on the modelling results of the Mount Merapi lahar flow in the Krasak River, it can be observed that the larger the lahar volume scenario used, the farther the lahar flows. The lahar modelling assumes that the lahar flow's cross-sectional area will be constant according to the volume scenario used (Auditia and Nugroho, 2021). River conditions with a sloping cross-sectional profile generally spread the lahar far outside the river. It can be observed in Figure 3 that the areas with lahar models that extend from the river show a sloping river profile condition so that the lahar can overflow with the given volume scenario, such as the 1,000,000 m^3 lahar volume scenario. This condition becomes one of the analyses in knowing the affected areas so that it can be related to the distribution of settlements and cattle in the study area.

4.2. Population and Cattle Condition in 2010

Based on the map in Figure 4, there are several sub-districts affected by the 2010 Merapi Eruption, namely Pakem, Tempel, and Turi in Sleman Regency, and Ngluwar, Salam, and Srumbung in Magelang Regency. Each sub-district has a potential population and number of cattle, as shown in Figure 4. These conditions date after the 2010 Merapi Eruption. Each sub-district has a population ranging from 29,686 to 51,624 people. Meanwhile, the number of cattle ranges from 712 to a maximum of 4,907. The quantitative data is sourced from the book called Kecamatan Dalam Angka 2011, owned by each subdistrict and published by BPS Sleman District and Magelang District in 2010 and sourced from data provided by the Directorate General of Animal Husbandry and Animal Health of Indonesia (2010).

When the 2010 Merapi eruption occurred, most residents chose to evacuate and did not bring their livestock. Based on studies, the decision was made to prioritize public safety. According to Herfianto *et al*. (2022), the community's attempts to save itself and its members prove that it values its social community and itself more than anything else it owns. Ahmed & Ahmad (2023) emphasized that safety and other crucial documents are given less attention during the rescue operation because livestock and agricultural commodities are renewable resources.

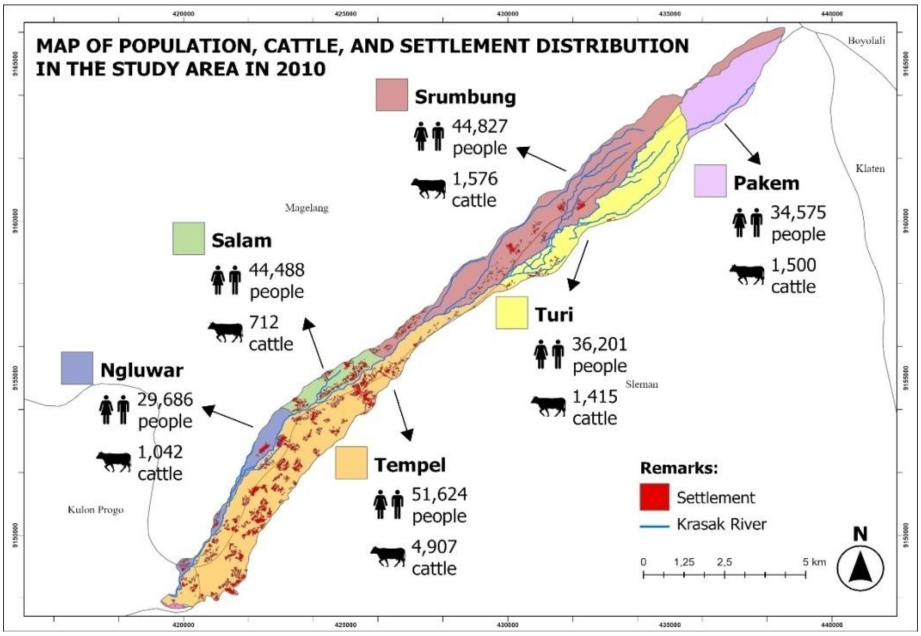

Fig. 4 – Map of Population, Cattle, and Settlement Distribution.

Based on the interview results, they chose to leave their livestock and occasionally return home to feed and water them. This discovery supports previous research by Kimura *et al*. (2024) that there is a more efficient method of ensuring safety and security, since cattleman movement is higher than the accessibility of evacuating with animals. Some residents also chose to sell their livestock due to difficulties finding animal fodder, resulting in decreased cattle numbers. People who decide to sell their cattle do so after carefully weighing the potential benefits and hazards of doing so in an emergency or natural disaster. It was revealed by Saparita *et al*. (2024) that during emergency reaction situations, public safety and the restoration of essential infrastructure should be everyone's priorities while temporarily setting aside other needs. As a result, recurring deadlines are set, and priority activities are determined and implemented. The allocation of priority activities and the recovery periods are well done at this location. A year after the eruption, there was an increase in the cattle population after the government's recovery economy programme, which replaced dead cattle or those left behind at the disaster site because people had to evacuate (Andarwati *et al*., 2017). Susilawati *et al*. (2022) explained that the difficulty in finding animal feed was caused by the volcanic ash rain that fell and covered the ground, making it difficult for grass to grow.

4.3. Distribution of Evacuation Sites and Cowshed Locations of the Merapi Volcano Eruption Livestock Groups

Data on the distribution of evacuation sites during the Mount Merapi eruption in 2010 was obtained through interviews with local communities. Based on the results of the interviews, each village has a different evacuation site, be it in the village hall, evacuation barracks, or Final Evacuation Site (in Indonesian known as Tempat Evakuasi Akhir), as evidenced in Figure 5. The evacuation duration varies from just a few weeks, 1-2 months, to under 6 months. Most people working as farmers did not bring their livestock when they evacuated. They chose to leave their livestock behind and occasionally return to feed them.

Fig. 5 – Final Evacuation Site at Salam Village, Salam Sub-district, Magelang District.
Source: Field Documentation.

Geovisualization is one of the approaches in presenting maps, including in this study, and the distribution of shelter and livestock after the 2010 Merapi eruption. One of the uses of geovisualization is to provide additional insights from data presented in maps that can be combined with other visual aids such as charts, tables, photos, 3D models, and so on (Balla *et al*., 2020). The information presented in this study includes the distribution of settlements and cattle obtained from taking several field samples. The settlements in question are several villages that were affected during the eruption. The samples taken in this study include several villages or hamlets in the KRB I, KRB II, and KRB III zones. The villages or hamlets sampled include areas in Magelang and Sleman Regencies. The villages or hamlets included in Magelang Regency consist of Nglumut, Salam, Jrakah, Kranggan, Jamburejo, and Kaliurang Utara. Meanwhile, the villages or hamlets in Sleman Regency include Kromodangsan Hamlet and Tunggularum.

Based on the results of field surveys, the distribution of housing after the 2010 Merapi eruption found that, in general, residents in several affected villages continued to live in their original places, namely returning to their respective homes after evacuating for approximately three months during the 2010 Merapi eruption. The place of evacuation for the people in the villages or hamlets sampled is spread to several areas, including Sucen Village Hall, Bedongsari Gede Final Evacuation Area (known in Indonesian as Tempat Evakuasi Akhir or TEA), Lumbungrejo Village, Ngluwar Village Hall, Salaman BLK, Bulog Mertoyudan Building, Tanjung and Jumoyo Village Halls. Several factors, such as environmental, social, and economic factors, influence their reasons for returning. Qualitative data was collected through interviews with several residents and community leaders in the villages sampled. The aim is to find out the condition of post-emergency housing and the factors that cause people to return to their original places in danger zone areas. In addition, people return due to the eruption's impact in the form of eruption material, which is still safe from the reach of the Merapi lahar hazard.

Based on the results of the interviews that have been conducted, environmental factors are one of the reasons people return to their original residence. This result is consistent with the findings of Sangha *et al*. (2019), who claim that communities have socio-ecological links to their immediate environment, which promotes the development of sustainability interactions. Impacts related to volcanic material on volcanoes have various benefits for the environment. One of the influential environmental factors is related to soil fertility. Research conducted by Khan *et al*. (2024) shows that the carbon-to-nitrogen ratio (C/N ratio) of volcanic material from the Merapi eruption ranges from 1.44% to 3.22% and contributes to increased fertility by the biogeochemical cycle. This shows that the fertile environmental conditions in the study area are used for several plants, such as salak, vanilla, vegetables, and fruits. This condition is what makes people return to their homes. This result validates a study by Melsandi & Prijono (2015), which found that farming communities in volcanic slope areas prioritize good soil fertility and agricultural productivity when deciding how to maintain their farmed lands.

Social and economic factors are also related to social interaction and community livelihoods. In their research, Sukarman *et al.* (2020) explained that apart from the fertile soil conditions, people who continue to live in danger zone areas are also influenced by the existence of sand, gravel, and stone mines, which make up their livelihood. These findings are supported by Pambudi *et al*. (2023), who found that when people have a source of income in a location, they are more likely to withstand any potential hazards. Based on the results of a survey of people living in the area, the majority of residents make a living as farmers, ranchers, and sand miners. Those working as sand miners are located near rivers with abundant sand material. Mihai *et al*. (2023) claim that volcanic eruptions periodically contribute to releasing volcanic material to provide a steady supply of sand.

Meanwhile, people in other professions, such as farmers, have dependents related to their respective livestock. When the 2010 Merapi eruption occurred, some people brought their livestock to evacuate together at the evacuation site and left them with relatives, while most people just left them behind. The reason people left their cattle was because the impact of the eruption was in the form of volcanic ash and sand that covered the villages so that livestock such as cattle were still relatively safe from the threat of hot lahar coming from the eruption, such as in Tunggularum Village, Turi which has a cattle group called Ngudimakmur. The location of this group's cattle pen, as shown in Figure 6, is in the KRB II zone. However, this impacts animal feed in the form of grass exposed to volcanic ash. Additional adjustments are made to the animal feed given to the livestock in the form of washing the grass that will be fed to the livestock. The purpose of cleaning the grass is to remove ash and dirt so that it is safe for livestock consumption. The livestock in question are cows that require regular animal feed. To accommodate this, people who own livestock provide a stock of grass for animal feed with adjustments. Every morning, people depart from the evacuation site to their respective villages to look for grass to feed their livestock.

Upon visualizing the map in Figure 6, we can see that the evacuation site is dominated by converting the village hall into an evacuation site for the local community. Based on the KRB zone, the evacuation sites are already in the safest zone (KRB I). However, some evacuation sites are near the 1,000,000 m3 lahar volume scenario, namely Bedongsari TEA and Salam Village Hall. This shows that if the 1,000,000 m^3 lahar volume scenario occurs, these two evacuation sites will most likely be affected.

4.4. Evacuation Route to Evacuation Sites During Mount Merapi Eruption

Information on evacuation routes is known based on data on the distribution of evacuation sites and road network data. The map in Figure 7 shows us that the safest evacuation route is the one that does not pass through the lahar scenario area. Tamakloe *et al*. (2021) indicate that evacuation routes need accessibility and safety, and that the total evacuation time should be lower. Wibowo & Hartono (2020) state that time, safety, and accessibility are critical aspects that impact rescue operations for people and animals. But Muhammad & Wu (2023) emphasize that there should be more than one evacuation route to minimize the worst risk.

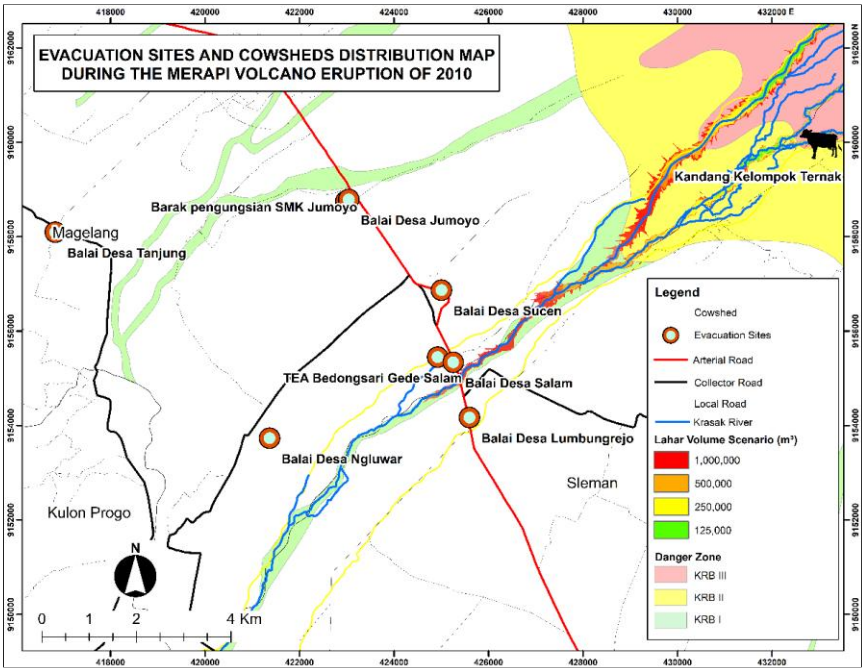

Fig. 6 – Evacuation Sites and Cowshed Distribution Map During the Merapi Volcano Eruption of 2010.

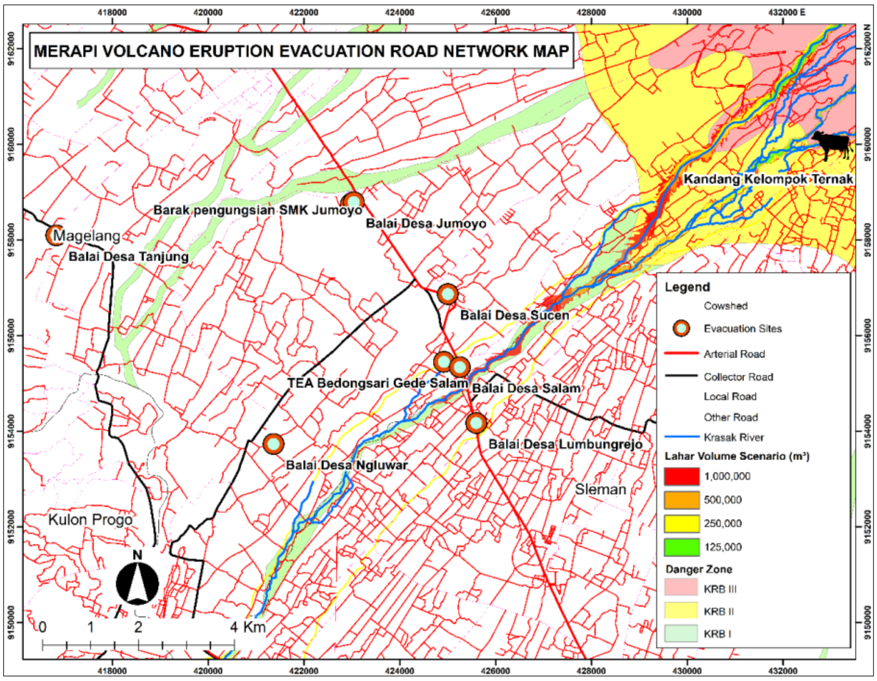

Fig. 7 – Evacuation Road Network Map of Merapi Volcano Eruption.

Based on Table 1, it can be seen that each village or hamlet to the evacuation site has its own estimated distance and estimated time based on the results of field surveys. This estimation considers roads that can be passed by all vehicles, both two-wheeled and four-wheeled. The evacuation time was estimated by considering several factors that affect the travel speed of vehicles (motorcycles and cars). This estimation is based on the distance from the starting point to the evacuation site, taking into account factors such as road contours that may slow down travel, the physical condition of the road, which may be damaged or uneven, the proximity to rivers that could potentially lead to volcanic mudflow and traffic congestion commonly encountered in emergencies. Other relevant variables, such as volcanic ash, which can affect visibility and road stability, were also accounted for. All these factors were integrated into the analysis to provide a more realistic and accurate estimate of the evacuation time to a safe location. This approach aligns with Purwaningsih *et al.* (2024), which examined evacuation path modelling during the Mount Marapi eruption in West Sumatra and used variables such as distance, elevation, river proximity, land cover, and slope. The consideration of road conditions in this study is supported by Putri & Maryono's (2018) research findings. Their research on assessed evacuation routes against Mount Merapi hazards in Boyolali identified variables such as road width, road damage, edge length, and surface type that significantly impacted travel time during evacuation. Based on this research, the closest estimated distance and fastest travel time is the evacuation route between the villages of Kromodangsan and Lumbungrejo, over a distance of 2.3 km and a time of 5 minutes. Meanwhile, the farthest distance and longest travel time were estimated for the evacuation route from Jamburejo Hamlet to Bulog Mertoyudan Building, with 26.6 km over 57 minutes. Nevertheless, the evacuation site is the safest place because it is far from the area affected by the lahar scenario.

Table 1

Estimated Distance and Travel Time for Some Affected Villages or Hamlets to the Evacuation Site

Number	Village/Hamlet– Evacuation Sites	Distance Estimation	Time Estimation
1	Nglumut Hamlet to Sucen Village Hall	7.9 km	21 minutes
2	Salam Hamlet to TEA of Bedongsari Gede, Salam	5.6 km	9 minutes
3	Kromodangsan Village to Lumbungrejo Urban Village	2.3 km	5 minutes
5	Kranggan Lor Hamlet, Sudimoro, Srumbung to Ngluar Village Hall and Salam Karang SHS Sports Hall	9.8 km	22 minutes
6	Jrakah Hamlet to BLK Salaman, Jumoyo Village Hall	9.9 km	26 minutes
7	Jamburejo Hamlet to Bulog Mertoyudan Building	26.6 km	57 minutes
8	Hamlet of Kaliurang Utara to Tanjung Village Hall ll	20.6 km	43 minutes
9	Hamlet Kaliurang Utara to Ngluwar Village Hall	17.4 km	40 minutes
10	Hamlet Kaliurang Utara to Jumoyo Village Hall	12.2 km	32 minutes

Source: Field Survey, 2024.

4.5. Cattle Evacuation Efforts During The 2010 Mount Merapi Eruption

According to data from the District Disaster Management Agency (known in Indonesia as Badan Penanggulangan Bencana Daerah or BPBD) of Sleman Regency, the Indonesian Department of Agriculture, Fisheries, and Forestry established Livestock Service Posts at several points in an effort to respond to the impact of Mount Merapi's 2010 eruption. The Livestock Service Post team comprises technical officers, medical and para-medical personnel, and functional livestock extension workers. According to Wild *et al*. (2019), the efforts made have been proportionate. Post-disaster services need to be provided, including ensuring that livestock is healthy or uninjured (medical personnel screening), ensuring that livestock can still ruminate well (paramedics), and calming owners' concerns about their livestock's condition (livestock extension officer). A study by Yudha *et al*. (2023) highlights that, in the emergency response to a disaster, maintaining the community's psychological well-being, including lowering their fear of losing belongings, is of utmost importance. In this case, it refers to livestock.

On October 26, 2010, at 17.00 Western Indonesia Time (WIB), monitoring was conducted on several dairy farmers. One of the group cattle pens' locations was in Tunggularum Village, Turi (Fig. 8). However, one hour later, there was an eruption. One day after the eruption, the Merapi Volcano Eruption Victims Livestock Handling Team was formed to anticipate the development of the impact on livestock of the Merapi Volcano eruption. The team has several tasks, such as identification and data collection, evacuation, animal health services, feed services, management of livestock carcasses, verification and validation, assistance in procurement and health checks of replacement livestock, and reporting. The actions implemented were proportional, quantitative, and systematic. Therefore, it can be observed that the handling of the post-eruption of Merapi 2010 was one of the best evacuation and emergency responses in Indonesia. To improve community and regional resilience, it is crucial to learn the procedures and technological implementation as best practices to be repeated elsewhere for disaster training initiatives.

Fig. 8 – Condition of cattle in Tunggularum Village.
Source: Field Documentation.

4.6. Research Limitations

This study has several limitations, particularly related to the variables used in the lahar flow model and their influence on predicting hazard zones. External factors such as climate change, unpredictable volcanic activity, and the accuracy of topographic data may affect the accuracy of the generated models. Additionally, data on the behaviour of evacuees and livestock were obtained only through interviews, which may not fully represent the entire affected population. The research is also limited by the availability of resources and field accessibility, which may restrict the scope and depth of the analysis in certain areas.

4.7. Research Utilities

This research provides significant benefits in enhancing the understanding and preparedness towards potential lahar hazards around Mount Merapi, particularly in evacuating residents and managing livestock. By using lahar flow models and hazard zone data, this study allows for the mapping of the most threatened areas and the design of safe evacuation routes, considering factors such as distance, road conditions, and lahar volume. Additionally, this research helps formulate policies for better disaster management, including handling livestock during disasters, which can reduce social and economic losses. The information on the distribution of evacuation sites, as well as the estimated evacuation time and distance, also contribute to planning more effective disaster mitigation efforts in the future and improving community resilience against the impacts of natural disasters.

5. CONCLUSIONS

The processing that has been done shows the spatial distribution of the Mount Merapi lahar flow after the 2010 eruption in the study location using spatial modelling. The resulting model consists of five flow models, each made up of four lahar volume scenarios, namely 125,000 m^3, 250,000 m^3, 500,000 m^3, and 1,000,000 m^3. The modelling results show that if the lahar volume scenario with high flow class occurs, the impact can reach the KRB I zone, which has the lowest hazard potential compared to KRB II and KRB III. The characteristics of lahar flow distribution are also influenced by the physical condition of the river through which the lahar flows. If rivers have high cliffs, lahar overflow is less likely to occur. Meanwhile, if the lahar flow reaches the highest scenario volume of 1,000,000 m^3 based on the model, it can spread to the right and left of the river, with low embankment or riverbank characteristics.

The modelling results can also be integrated with data on the distribution of settlements and field results related to cattle to be geovisualized with the locations of evacuation shelters and road networks. The evacuation road network is used as an evacuation route that connects several affected villages to the evacuation site along with the estimated distance and travel time. Some affected villages in KRB II and III zones were mostly evacuated to and outside the KRB I zone. Regarding the information on cattle, some evacuees brought them or chose to leave their cattle behind, with the majority deciding to do the latter. Cattle owners who leave their cattle will generally return to their respective villages at a certain time to feed them. Some cattle owners are forced to sell their cattle due to the fodder crisis caused by the volcanic ash rain. After the eruption of Mount Merapi is declared safe, people will return to their respective villages. The same goes for some of the livestock they brought with them when they evacuated.

Acknowledgments

The authors would like to express their gratitude towards the Faculty of Geography UGM for funding this research through the 2024 Research Grant Program.

REFERENCES

Adri, W., Sabri, L. M., Wahyuddin, Y. (2020), *Pembuatan Peta Jalur Evakuasi Bencana Gunung Api Dan Persebaran Lokasi Shelter Menggunakan Metode Network Analyst (Studi Kasus: Gunung Merapi, Boyolali-Magelang)*. Jurnal Geodesi UNDIP, **10**(*1*), pp. 189–196.

Ahmed, M., Ahmad, S. (2023), *Disaster Risk Reduction in Agriculture*. In A. K. Gupta, S. Prabhakar, & A. Surjan (Eds.), *Disaster Resilience and Green Growth* (pp. 21–42). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-1763-1_2.

Andarwati, S., Rijanta, R., Widiati, R., Opatpatanakit, Y. (2017), *Strategi Penghidupan Peternak Sapi Perah Di Lereng Selatan Gunungapi Merapi Pasca Erupsi 2010*. Buletin Peternakan, **41**(*1*), pp. 91–100.

Auditia, F., Nugroho, H. (2021), *Evaluation of ASTER, SRTM, and DEMNAS DEM Data for Lahar Modelling: A Case Study of Lahar from Mount Galunggung, Indonesia*. Prosiding FTSP Series, pp. 464–466.

Badan Pusat Statistik (2011), *Kecamatan Ngluwar dalam Angka 2011*. Penerbit Badan Pusat Statistik Kabupaten Magelang.

Badan Pusat Statistik (2011), *Kecamatan Pakem dalam Angka 2011*. Penerbit Badan Pusat Statistik Kabupaten Sleman.

Badan Pusat Statistik (2011), *Kecamatan Salam dalam Angka 2011*. Penerbit Badan Pusat Statistik Kabupaten Magelang.

Badan Pusat Statistik (2011), *Kecamatan Srumbung dalam Angka 2011*. Penerbit Badan Pusat Statistik Kabupaten Magelang.

Badan Pusat Statistik (2011), *Kecamatan Tempel dalam Angka 2011*. Penerbit Badan Pusat Statistik Kabupaten Sleman.

Badan Pusat Statistik (2011), *Kecamatan Turi dalam Angka 2011*. Penerbit Badan Pusat Statistik Kabupaten Sleman.

Balla, D., Zichar, M., Tóth, R., Kiss, E., Karancsi, G., Mester, T. (2020), *Geovisualization Techniques of Spatial Environmental Data Using Different Visualization Tools*. Applied Sciences, **10**(*19*), pp. 1–15.

Bilqis, R. S. A., Awaluddin, M., Hadi, F. (2024), *Analisis Bahaya Bencana Tsunami di Kota Cilegon Menggunakan Sistem Informasi Geografis*. Jurnal Geodesi Undip, **13**(*1*).

BNPB (2019), *Modul Teknis Penyusunan Kajian Risiko Bencana Letusan Gunung Api*. Direktorat Pengurangan Risiko Bencana, Jakarta.

BNPB (2020), *Klasifikasi Tingkatan Gunung Berapi*. Bogor. https://bnpb.go.id/.

De Bélizal, E., Lavigne, F., Hadmoko, D. S., Degeai, J. P., Dipayana, G. A., Mutaqin, B. W., Marfai, M. A., Coquet, M., Mauff, B. Le, Robin, A. K., Vidal, C., Cholik, N., Aisyah, N. (2013), *Rain-triggered lahars following the 2010 eruption of Merapi volcano, Indonesia: A major risk*. Journal of Volcanology and Geothermal Research, **261**, pp. 330–347.

Dille, A., Poppe, S., Mossoux, S., Soulé, H., Kervyn, M. (2020), *Modeling Lahars on a Poorly Eroded Basaltic Shield: Karthala Volcano, Grande Comore Island*. Frontiers in Earth Science, **8**, 369.

Ernawati, D., Panjaitan, R. U. (2020), *Gambaran Post Traumatic Stress Disorder Pada Korban Bencana Alam Post Erupsi Merapi Satu Dekade*. Jurnal Ilmu Keperawatan Jiwa, **3**(*2*), pp. 12–101.

Herfianto, A., Suparno, B. A., Afifi, S. (2022), *Volcanic crisis communication: The case of the Mt. Merapi eruption emergency response.* Communications in Humanities and Social Sciences, **2**(*2*), pp. 71–76. https://doi.org/10.21924/chss.2.2.2022.38.

Khan, K., Wilopo, W., Sadono, R., Hermawan, M. T. T. (2024), *The characteristics of soils impacted by the Merapi eruption in Plawangan Hill of Mount Merapi National Park, Yogyakarta, Indonesia*. Journal of Degraded and Mining Lands Management, **11**(*2*), pp. 5361–5373. https://doi.org/10.15243/jdmlm.2024.112.5361.

Kimura, R., Sato, S., Yi, T., Nakazawa, K., Matsukawa, A., Tsujioka, A., Ohtsuka, R. (2024), *Elucidations of Present Situation of Preparedness for Natural Disasters at Home in Japan and its Effective Factors*. Journal of Disaster Research, **19**(*5*), pp. 818–828. https://doi.org/10.20965/jdr.2024.p0818.

Lesmana, R. B., Rachmawati, T. A., Rukmi, W. I. (2022), *Pengurangan Risiko Bencana Erupsi Gunung Bromo Berbasis Political Security di Kecamatan Sukapura Kabupaten Probolinggo*. Planning for Urban Region and Environment Journal (PURE), **11**(*2*), pp. 77–88.

Lestari, N. K. D. A., Trigunasih, N. M., Dibia, I. N., Suyarto, R. (2019), *Interpretasi Citra untuk Analisis Kapasitas Sungai Unda sebagai Tampungan Lahar Dingin Erupsi Gunung Agung Bali*. Jurnal Agroekoteknologi Tropika, **2301**, 6515.

Melsandi, H., Prijono, S. (2015), *The use of volcanic ash from the eruption of Mount Kelud in East Java for improving yield of sweet potato grown on a sandy soil*. Journal of Degraded and Mining Lands Management, **2**(*4*), pp. 403–408. https://doi.org/10.15243/jdmlm.2015.024.409

Mihai, R. A., Espinoza-Caiza, I. A., Melo-Heras, E. J., Cubi-Insuaste, N. S., Pinto-Valdiviezo, E. A., Catana, R. D. (2023). *Does the Mineral Composition of Volcanic Ashes Have a Beneficial or Detrimental Impact on the Soils and Cultivated Crops of Ecuador?* Toxics, **11**(*10*). https://doi.org/10.3390/toxics11100846.

Muhammad, A., Wu, T. (2023), *Examining the evacuation routes of the sister village program by using the ant colony optimization algorithm.* Open Geosciences, 15(1), pp. 1–13. https://doi.org/10.1515/geo-2022-0512.

Pambudi, P. A., Utomo, S. W., Soelarno, S. W., Takarina, N. D. (2023), *Coal mining reclamation as an environmental recovery effort: a review*. Journal of Degraded and Mining Lands Management, **10**(*4*), pp. 1001–1011. https://doi.org/10.15243/jdmlm.2023.104.0000

Purwaningsih, E., Liusti, S.A., Purnamasari, E., Ramadhan, R., Nasution, A.F.R. (2024), *The Mount Marapi Eruption Disaster Evacuation Path Model Using a Local Wisdom Approach*. International Journal of GEOMATE, **26**(*116*):pp. 64–71, DOI: https://doi.org/10.21660/2024.116.4353.

Putri, L.K.R., Maryono, M. (2018), *Assessing Evacuation Route Against Mount Merapi Hazard by Using Least Cost Path Method in Mriyan-Boyolali, Indonesia*. IOP Conf. Ser.: Earth Environ. Sci. 123 012008, DOI: https://doi.org/10.1088/1755-1315/123/1/012008.

Sahagian, D., Tintle, L., Wygel, C. (2022), *Measurement of the Volcanic Explosivity Index (VEI) in Real Time*. Authorea Preprints.

Sangha, K. K., Russell-Smith, J., Costanza, R. (2019), *Mainstreaming indigenous and local communities' connections with nature for policy decision-making*. Global Ecology and Conservation, 19, e00668. https://doi.org/10.1016/j.gecco.2019.e00668.

Saparita, R., Wahyono, E., Prayoga, R. A., Fatimah, S., Purbandini, L., Solekhah, N., Hakim, F. N., Azni, U. S., Wibowo, D. P. (2024), *Exploring the Dynamics of Community Transformation in the Indonesian Volcanic Region: An Analysis of Socioeconomic Metamorphosis*. International Journal of Safety and Security Engineering, **14**(*4*), pp. 1169–1180. https://doi.org/10.18280/ijsse.140414.

Saputro, C. D. (2019), *Evaluasi Kondisi Kerusakan Bangunan Pengendali Lahar di Sungai Krasak*. Rekayasa Sipil, **13**(*2*), pp. 110–117.

Sukarman., Dairah, Ai., Suratman. (2020), *Tanah Vulkanik Di Lahan Kering Berlereng dan Potensinya untuk Pertanian di Indonesia*. Jurnal Litbang Pertanian, **39**(*1*), pp. 21–34.

Susilawati, D., Rachmawati, P., Maurine, R. S. (2022), *Pemberdayaan Kelompok Ternak Melalui Pengolahan Tabungan Pakan Sapi Dengan Teknik Silase Di Desa Sangup Boyolali*. SELAPARANG: Jurnal Pengabdian Masyarakat Berkemajuan, **6**(*3*), pp. 1203–1209.

Tamakloe, R., Hong, J., Tak, J., Park, D. (2021), *Finding evacuation routes using traffic and network structure information*. Transportation Research Part D: Transport and Environment, 95(April), 102853. https://doi.org/10.1016/j.trd.2021.102853.

Wibowo, B., Hartono, B. (2020), *Integrating Human Behavior and Safety Measure into Evacuation Route Planning in a Volcanic Crisis*. Jurnal Teknik Industri, **22**(*2*), pp. 103–110. https://doi.org/10.9744/jti.22.2.103-110.

Wibowo, S. B., Lavigne, F., Mourot, P., Métaxian, J., Zeghdoudi, M., Virmoux, C., Sukatja, C. B., Hadmoko, D. S., Mutaqin, B. W. (2015), *Analyse couplée d'images vidéo et de données sismiques pour l'étude de la dynamique d'écoulement des lahars sur le volcan Merapi, Indonésie*. Géomorphologie: relief, processus, environnement, **21**(*3*), pp. 251–266.

Widodo, E., Hastuti, H. (2019), *Riwayat Aktivitas Gunung Merapi: Potensi dan Ancamannya Bagi Sektor Pariwisata*. Geo Media: Majalah Ilmiah dan Informasi Kegeografian, **17**(*1*).

Wild, A. J., Wilson, T. M., Bebbington, M. S., Cole, J. W., Craig, H. M. (2019), *Probabilistic volcanic impact assessment and cost-benefit analysis on network infrastructure for secondary evacuation of farm livestock: A case study from the dairy industry, Taranaki, New Zealand*. Journal of Volcanology and Geothermal Research, 387, 106670. https://doi.org/10.1016/j.jvolgeores.2019.106670.

Yudha, D. D., Ririanty, M., Nafikadini, I. (2023), *Preparedness Behavior of the Destana Group in Management of Mountain Raung Eruption*. Journal of Health Science and Prevention, **7**(*2*). https://doi.org/10.29080/jhsp.v7i2.941.

Received November 17, 2024