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Hazard as Resource: Post-Eruption Land Cover Change and the Spatial Growth of Sand Mining and Tourism in the Mount Semeru

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Abstract

Continuous eruptions of Mount Semeru since 2021 have continuously altered the landscape on its southern slopes; however, the extent to which post-eruption land-cover changes have triggered new economic activities remains understudied. This study analyzes land-cover changes in the Candipuro and Pronojiwo Districts of Lumajang Regency between 2022 and 2026 on multitemporal Sentinel-2A imagery, while examining the spatial distribution of sand mining and tourism activities in relation to volcanic hazard zones (KRB), original land-cover types, and distance from the summit. Kernel Density Estimation and cross-tabulation heatmaps reveal that sand mining sites are concentrated in KRB Zones 2–3 and predominantly originate from land containing lahar deposits, indicating a resource-based and material-oriented locational pattern. In contrast, tourism sites are more evenly distributed across various hazard zones and largely emerge from agricultural land and forests, reflecting a pattern oriented toward landscape attractions within volcanic material areas. Neither activity occurs in the immediate vicinity of the summit, suggesting a shared risk-tolerance threshold that does not strictly adhere to formal KRB boundaries. Further in-depth interviews reveal that sand miners view lahar flows through a dual perspective as both a threat and an indicator of economic opportunity. In contrast, tourism operators consciously leverage lahar-affected landscapes as attractions, halting operations only when perceived risks become excessive. These findings indicate that post-eruption land-cover changes serve not merely as ecological damage but also as a foundation for economic transformation; consequently, disaster risk management and spatial planning on Semeru's slopes should adopt distinct strategies for the mining and tourism sectors.

Keyword: Land cover change; Volcanic eruption; Sand mining; Risk perception; Mount Semeru

Introduction

Mount Semeru, located in Lumajang Regency, East Java, is the highest volcano on the island of Java (3,676 meters above sea level) and is classified as one of the most active and dangerous volcanoes in Indonesia (PVMBG, 2022). Mount Semeru exhibits continuous, intense eruptive activity characterized by periodic explosive eruptions. (Basuki et al., 2023; Suhadha & Harintaka, 2024). The eruption triggered a complex series of volcanic hazards, such as pyroclastic flows and rain-induced lahars. The periodic eruptions occurring from 2021 to the present have constituted a series of destructive volcanic disasters in Indonesia (Bachri et al., 2024; Perwita et al., 2023). The explosive eruption during this period was recorded as occurring on December 4, 2021, which caused a pyroclastic flow (PDC) as far as 11 kilometers along the Rejali watershed (BNPB, 2022; PVMBG, 2022). Pyroclastic flows caused damage to agricultural land and buried residential areas along the Rejali watershed (BNPB, 2022; PVMBG, 2022).

Intense eruptive activity continued through 2025. A major eruption also occurred in November 2025, expanding the areas damaged by pyroclastic density currents (PDCs) and rain-induced lahars; this was driven by the continuous accumulation of material. (Bachri et al., 2025). The accumulation of volcanic material causes new danger threats that can be triggered by factors other than volcanic activity (Baumann et al., 2019; Lavigne et al., 2016; Tierz et al., 2017). Furthermore, volcanic activity resulting in the accumulation of volcanic material can also alter the landscape and change existing land-use patterns on the southern slopes of Semeru (Bachri et al., 2025). Volcanic material comprising sand, gravel, and rock

fragments deposited en masse in river valleys has not only permanently altered the morphology of the watershed but also triggered complex land-cover transformations, such as the conversion of protected forest areas and productive agricultural land into zones for intensive volcanic sand mining. (E. Dingle et al., 2021; Lebedeva & Лебедева, 2019).

Land cover changes resulting from volcanic eruptions are a phenomenon extensively studied in scientific literature, particularly in the context of change detection using remote sensing technology (Orynbaikyzy et al., 2023, 2025). Various studies have successfully calculated the extent of physical damage caused by pyroclastic flows, lahars, and volcanic ash through multitemporal satellite image analysis (Dávila et al., 2019; Kadavi et al., 2017). However, Post-eruption land-cover change is not merely a physical phenomenon that can be quantitatively measured through remote sensing approaches. The changes involve more than just physical factors; they encompass complex socio-economic dynamics—such as why communities persist in or return to high-risk areas, why ecologically damaged land becomes a source of new livelihoods through volcanic sand mining, and how local belief systems shape human adaptation patterns on volcanic slopes (Dávila et al., 2019; Kadavi et al., 2017; Lavigne et al., 2008)

Research on the impact of volcanic eruptions on land cover has advanced rapidly, driven particularly by developments in remote sensing technology and the open availability of high-resolution satellite imagery, such as Sentinel-2A (More, 2024; Phiri et al., 2020). Numerous studies have been conducted in the context of Indonesian volcanoes particularly, following the 2010 eruption of Merapi, which serves as a methodological benchmark for much research on volcanic hazards in Southeast Asia. (Surono, et al., 2012; Yulianto et al., 2013a). These studies examine the use of spatial analysis methods to analyze the physical impacts of eruptions, map lahar paths, and identify affected areas. However, most research conducted to date remains partial and fragmented: remote sensing-based studies tend to focus on physical-spatial dimensions without considering the socio-economic context underlying the community's land-use patterns (Hamud et al., 2019; Lavigne et al., 2008), In contrast, social studies that examine community responses to volcanic disasters do not integrate sufficient spatial data to describe the geographic context underlying community decisions and behavior (Bronfman et al., 2024; Suud et al., 2025). Gaps in the research conducted have resulted in a limited understanding of why land-cover changes occur, not merely as a physical consequence of the eruption, but also as a result of the economic and cultural decisions made by the inhabitants of the affected land.

There is currently no research explicitly mapping how physical disturbances caused by eruptions, traditionally viewed solely as ecological damage, also serve as a spatial foundation for the emergence of new economic activities, specifically volcanic sand mining and tourism, on the southern slopes of Mount Semeru. Volcanic material that buries agricultural land and forests transforms into a high-value economic commodity through sand mining, while the resulting post-eruption landscape simultaneously attracts tourists. More specifically, there is a lack of research explicitly integrating multi-temporal satellite imagery-based land-cover change analysis with socio-economic studies of communities in the Candipuro and Pronojiwo Districts of Lumajang Regency. The Mount Semeru region presents a unique complexity: while massive ecological damage has occurred due to volcanic material, that same material has simultaneously become an economic commodity through volcanic sand mining, driving changes in land use. Therefore, this study aims to analyze land cover changes in the Candipuro and Pronojiwo Districts resulting from the series of Mount Semeru eruptions between 2022 and 2026, utilizing multitemporal Sentinel-2A image classification, and to examine the correlation between these land cover changes and the distribution and expansion of volcanic sand mining sites and tourism spots, including their locations relative to Mount Semeru's Disaster-Prone Zones (KRB).

Material and Methods

Research Location

The research was conducted in the Pronojiwo and Candipuro subdistricts, located on the southern slopes of Mount Semeru in Lumajang Regency, East Java, Indonesia. These districts were selected as spatial units of analysis because they constitute the primary pathways for the flow of lahars and volcanic materials from the summit of Semeru to the lowlands. The area has undergone the most significant land-cover changes due to a series of eruptions since 2021. Administratively, the study area encompasses several districts in Lumajang Regency situated within the zones of direct and indirect impact from the eruptions. The research sites were categorized into two zones: (1) the directly impacted zone, comprising areas physically affected by pyroclastic density currents (PDCs), lava, volcanic ash, and lahars; and (2) the indirectly impacted zone, consisting of settlements, agricultural lands, and volcanic sand mining areas that have changed land use.

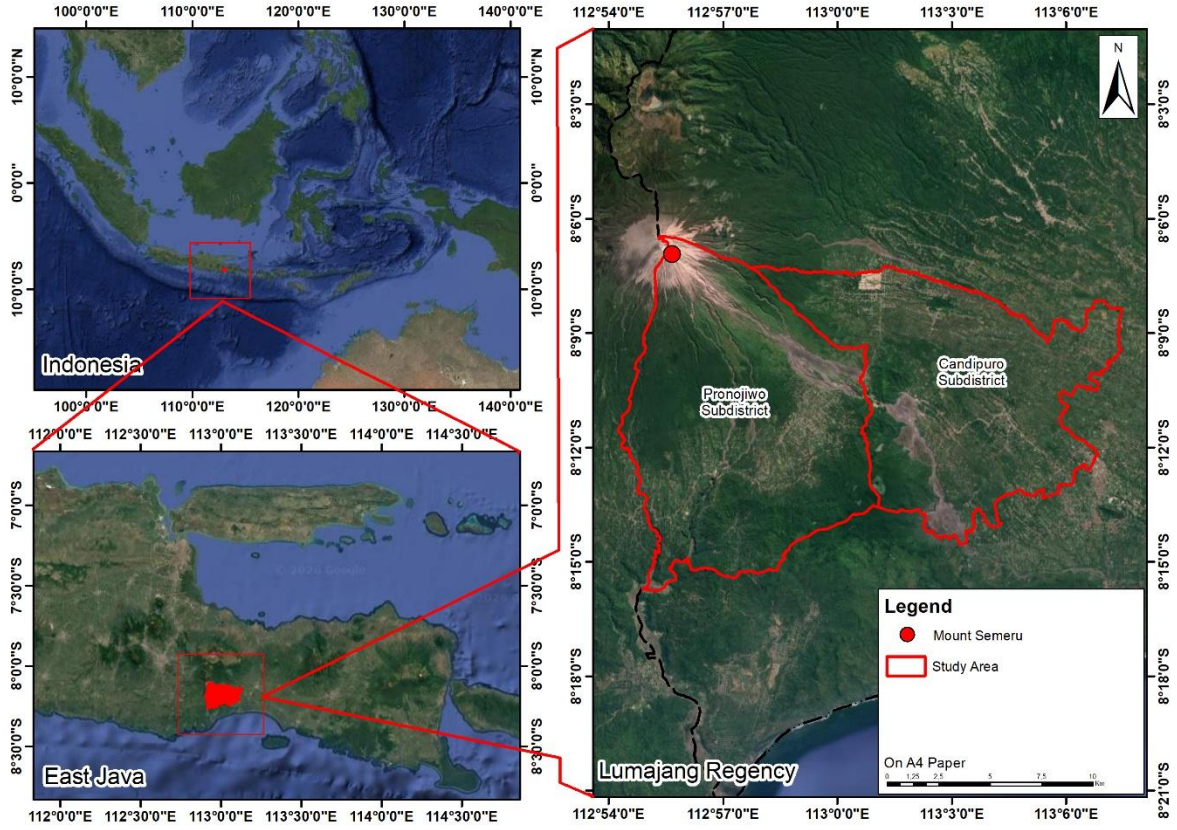


Figure 1. Research location: Pronojiwo and Candipuro subdistricts, Lumajang Regency

Data Source

Primary Data

Primary data were obtained through observation and interviews. Field observations were conducted to verify land cover derived from satellite image classification (ground-truthing), involving direct inspection of physical land conditions at sample points distributed across the study area. Sample points were determined using a stratified random sampling method based on land cover classes identified from the imagery (Ding et al., 2022; Yan et al., 2023). Field observations also include documentation of geomorphological conditions, sand

mining activities, and tourism activities that are not identified by remote sensing data. In-depth interviews were conducted with informants selected purposively, including people living in the affected areas, volcanic sand miners, tourism actors, and village governments. An interview guide was prepared to examine disaster risk perceptions, community understanding of spatial and mining regulations, as well as livelihood adaptation strategies through tourism (Barclay et al., 2019; Xu et al., 2018)

Secondary Data

The secondary data used consists of multi-temporal Sentinel-2A satellite imagery specifically, images from the period following the major eruption (2022) and from 2026, downloaded from the Copernicus Open Access Hub (ESA) platform. Sentinel-2A features a spatial resolution of 10 m for the visible and NIR bands, which is sufficient for detailed-scale land cover change analysis at the sub-district level (Drusch et al., 2012; ESA, 2022). This study also utilizes several sets of supporting data, including: (1) administrative boundary data from the Geospatial Information Agency (BIG); (2) demographic and economic statistical data from the Lumajang Regency Statistics Agency (BPS); and (3) disaster data and hazard maps from the Center for Volcanology and Geological Hazard Mitigation (PVMBG) and the National Agency for Disaster Countermeasure (BNPB).

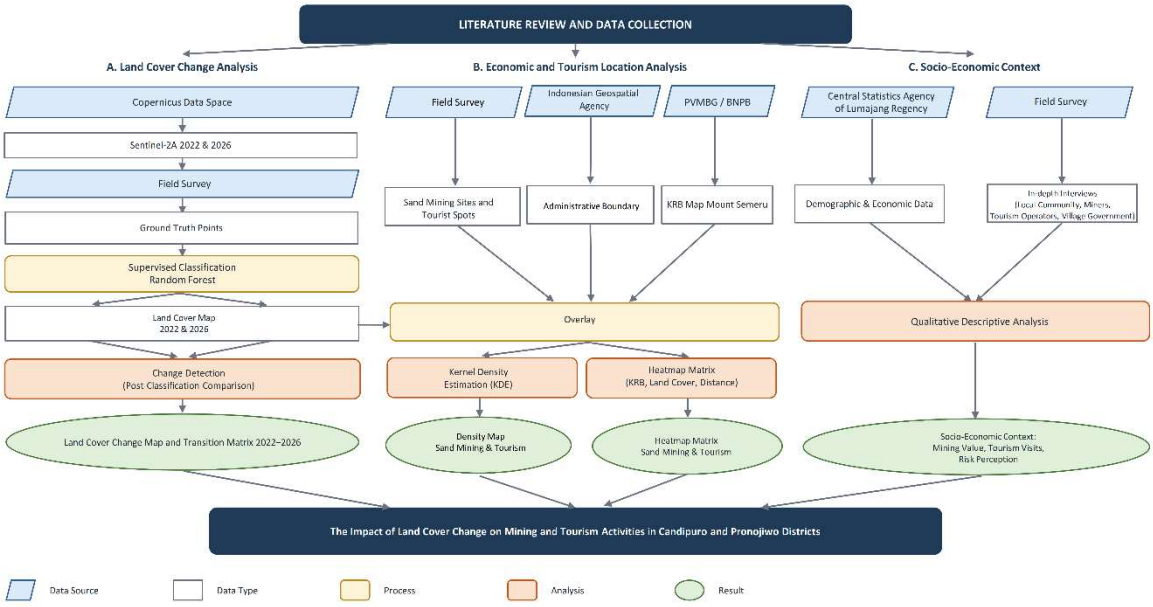


Figure 2. Research Flowchart

Data Analysis

Land Cover Classification

Land cover classification is carried out using the Supervised Classification method with the Random Forest algorithm (RF) (Arfa-Fathollahkhani & Minaei, 2024; Noi & Kappas, 2017). The classified land cover categories include: forest, shrub, crops, build-up, volcanic material/lahar. Training samples were collected through field observations combined with visual interpretation of high-resolution Google Earth imagery. Classification accuracy was assessed using a confusion matrix based on Overall Accuracy (OA) and Kappa Coefficient (κ) parameters, with a minimum acceptable accuracy threshold of 80% (Foody, 2020; Yılmaz & Demirhan, 2023)

Land Cover Change Detection

Land cover change detection was conducted using the post-classification comparison technique by overlaying land cover maps from 2022 and 2026 to generate a change map and a land cover class transition matrix. The change matrix indicates the area (in hectares) of each land cover class transition from one period to the next, enabling the identification of dominant land change patterns resulting from the Semeru eruption (Bachri et al., 2026).

2Sand Mining and Tourism Location Analysis

The spatial distribution of sand mining and tourism sites was analyzed using the Kernel Density Estimation approach to observe concentration patterns of these activities. Heatmap matrix analysis was employed to examine the statistics regarding the distribution of sand mining and tourism operations. Data on land cover classification, Disaster-Prone Zones (KRB), and distance from the summit of Mount Semeru were synthesized into three heatmap matrices, presented as color-coded cross-tabulations, that compare economic activity types (sand mining and tourism) against each of these variables. The first matrix compares the count and percentage of tourism and mining sites across KRB zones (I, II, and III) to assess the extent to which these activities are concentrated in high-risk zones. The second matrix compares the count and percentage of sites based on the original land cover class prior to conversion, specifically forest, agriculture, or volcanic material/open land, to identify which land types are most frequently converted for each activity. The third matrix juxtaposes the count and percentage of sites based on distance intervals from the summit of Mount Semeru to observe distribution patterns relative to the proximity to the hazard source.

Result and Discussion

Land Cover Change in the Candipuro and Pronojiwo Sub District, 2022–2026

Land cover classification results using the Random Forest algorithm on Sentinel-2A imagery from 2022 and 2026 demonstrate an accuracy level sufficient to serve as a basis for analyzing land cover changes in the Candipuro and Pronojiwo districts. The Overall Accuracy (OA) for 2022 was recorded at 87.5% with a Kappa Coefficient of 0.854 while the 2026 data yielded an OA of 88.0% with a Kappa Coefficient of 0.865. Both values exceed the minimum accuracy threshold of 80%. The classification results for both periods are deemed valid and suitable for further change analysis. A detailed comparison of the area of each land cover class between 2022 and 2026, including the magnitude and percentage of change, is presented in Table 1.

Table 1. Land Cover Change Statistics

Land Cover Class	Area 2022 (Ha)	Area 2026 (Ha)	2026 – 2022 (Ha)	% 2022	% 2026
Forest	13.832	13.772	-60	52,32	52,09
Crops	5.777	5.771	-6	21,85	21,83
Build-up	571	555	-16	2,16	2,1
Lahars Material	1.957	2.029	72	7,4	7,68
Shrub	4.300	4.309	10	16,26	16,3
Total	26.437	26.437	0	100	100

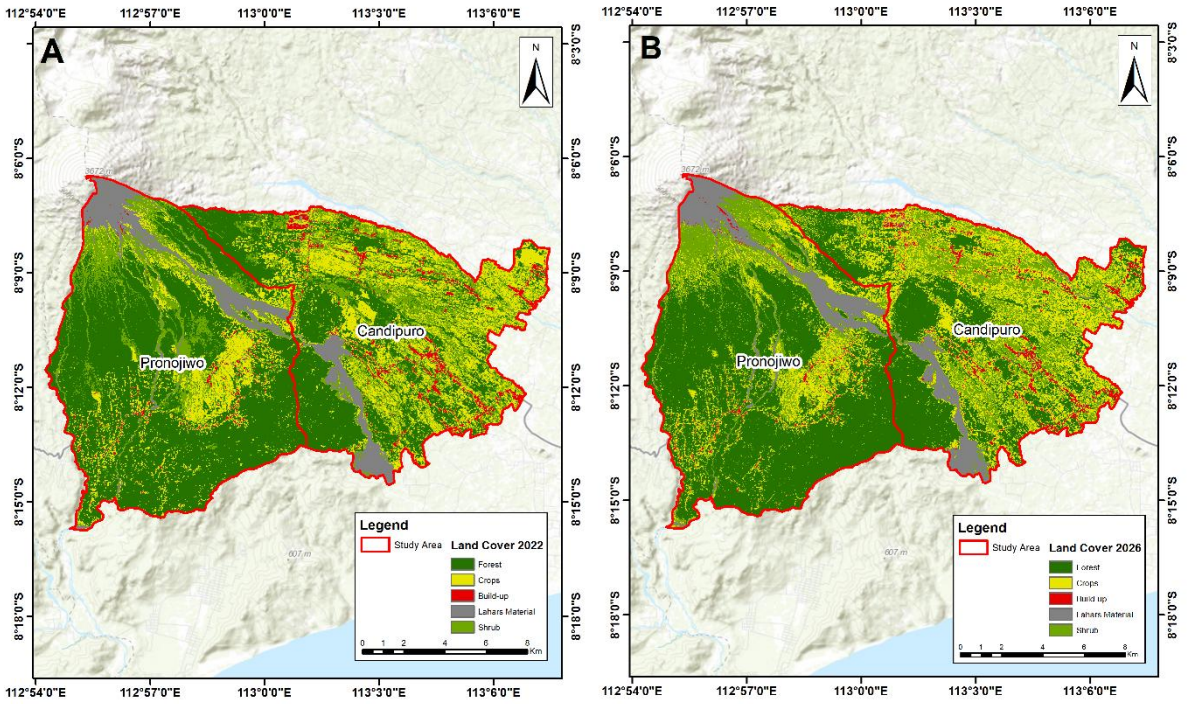


Figure 3. Land cover in Pronojiwo and Candipuro. (a) 2022 (post-December 2021 eruption); (b) 2026 (post-November 2025 eruption)

The findings regarding the consistent growth of lava material on the southern slopes of Semeru are in line with patterns found in studies of post-eruption volcanic sedimentation in other locations. E. H. Dingle et al., (2021) and Lebedeva, (2019) stated that the accumulation of volcanic clastic material in post-eruption river valleys is progressive and sustainable as long as the supply of material from the upper slopes continues. This agreement strengthens the validity of the finding that the lava flows on the southern slopes of Semeru are in an active sediment accumulation phase, not a post-disaster stabilization phase. However, the findings regarding the reduction in built-up land on the southern slopes of Semeru are actually different and contradict the pattern found in the study of land cover changes after the 2010 Merapi eruption (Surono et al., 2012; Yulianto et al., 2013b), and the study of land cover in relation to tourism development (Bachri et al., 2026).

These studies consistently describe the expansion of built-up areas following eruptions, driven by rehabilitation, reconstruction, and tourism sector growth in the affected regions. This divergence in patterns likely stems from the differing temporal characteristics of the eruptions in the two cases. The 2010 Merapi eruption was a single, large-scale event followed by a relatively quiet period, allowing sufficient time for reconstruction to proceed and for built-up areas to recover and expand. In contrast, Mount Semeru has exhibited a pattern of periodic, recurring eruptions from 2021 to 2025; consequently, settlement reconstruction on its slopes has likely been repeatedly disrupted by new cycles of damage before full recovery could be achieved. These differing outcomes highlight a fundamental distinction in disaster risk management between volcanoes that experience a single massive eruption and those that erupt repeatedly over time.

This pattern also warrants discussion within the broader context of post-disaster recovery literature. Recovery trajectories typically assume a progressive path toward pre-disaster conditions or even an improvement upon them, "building back better". However, findings from Mount Semeru indicate that this assumption does not always hold in the context of periodic volcanic hazards that show no signs of subsiding. Instead, recovery

trajectories can be repeatedly disrupted, causing the recovery process to align with eruption cycles. The linear recovery framework commonly employed in conventional post-disaster studies requires re-evaluation when applied to areas facing active and recurring volcanic hazards, such as Mount Semeru, where "post-disaster" is an indefinable category, given that new events can occur at any time before recovery from a previous event is complete.

Implications of the land-use change detection approach in areas subject to recurrent volcanic activity require considering potential non-linear patterns associated with repeated events, rather than solely focusing on the unidirectional recovery trends typically observed in studies of single post-disaster events. Meanwhile, the relatively minor changes in forest and agricultural land-use classes, accompanied by a slight increase in shrubland, align with general findings in volcanic disturbance ecology; these findings indicate that the physical impacts of eruptions tend to be spatially concentrated along pyroclastic and lahar flow corridors, whereas areas outside these paths experience minimal disturbance and may even exhibit signs of secondary vegetation succession during the early post-disturbance phase. This pattern of spatial concentration is also consistent with remote sensing-based observations of physical eruption impacts at other Indonesian volcanoes, which highlight the importance of analyzing river flow zones to understand the spatial variability of eruption impacts

Concentration of Economic Activities Relative to Hazard Zone, Origin Land Cover, and Distance from the Summit

The concentration of sand mining and tourism activities can be explained through three spatial variables, including the Disaster Prone Area (KRB) zone, the original land cover class, and the distance from the summit of Semeru. These three variables are used because they can explain the relationship between volcanic hazards and economic activity from different perspectives, namely the formal level of risk exposure (KRB zone), the source of economic value of a location (the original land cover class), and the physical intensity of the hazard that is continuous with distance (distance from the summit). Figure 4 and 5 below present the spatial distribution of sand mining and tourism locations.

Figure 4 and 5 display contrasting spatial patterns. The mining sites in (Figure 4) appear to be tightly clustered along the two main river channels that divide the Rejali River Basin from the peak to the downstream, with the density of these sites increasing in the river segments directly adjacent to the lahar land cover class and KRB 2 and KRB 3 zones. Field photographs accompanying the map also visually confirm this situation, showing a riverbed filled with boulders and large-scale volcanic deposits, some of which have been supported by heavy equipment infrastructure for extraction activities. In contrast, the tourism sites in (Figure 5) exhibit a much looser distribution pattern and span a wider area, not limited to the river corridor alone. Several tourism sites, such as Kali Tayeng and Gladak Perak, are located on or adjacent to the same high-risk river channels as the mining sites.

Based on (Figure 4), the concentration pattern of mining sites within Disaster-Prone Zones (KRB) 2 and 3 indicates that sand mining locations directly follow the distribution of eruption deposits, which naturally accumulate in areas most exposed to pyroclastic flows and lahars. The selection of mining sites is not random with respect to disaster susceptibility; rather, it aligns with the hazard zones themselves, as a higher level of susceptibility corresponds to a greater availability of mineable volcanic material. This pattern implicitly reveals a structural relationship: the greater a zone's hazard potential, the greater the exploitable economic potential, meaning that both risk and economic opportunity arise from the same physical phenomenon.

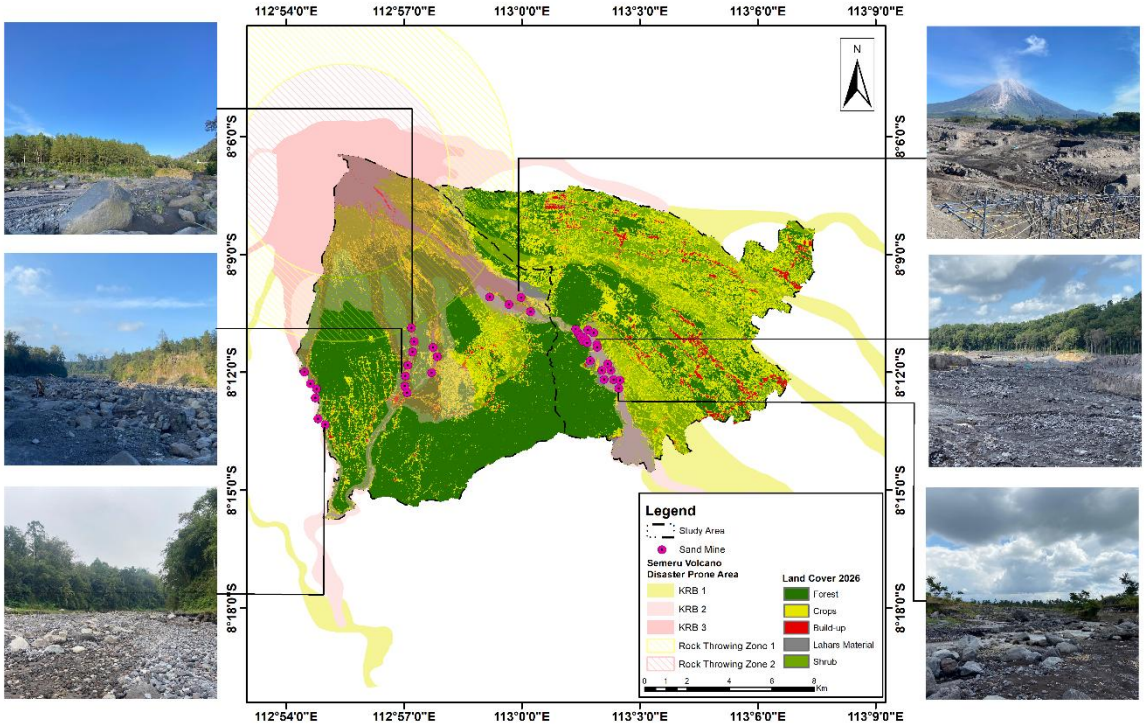


Figure 4. Spatial Distribution of Sand Mining Location in Pronojiwo and Candipuro

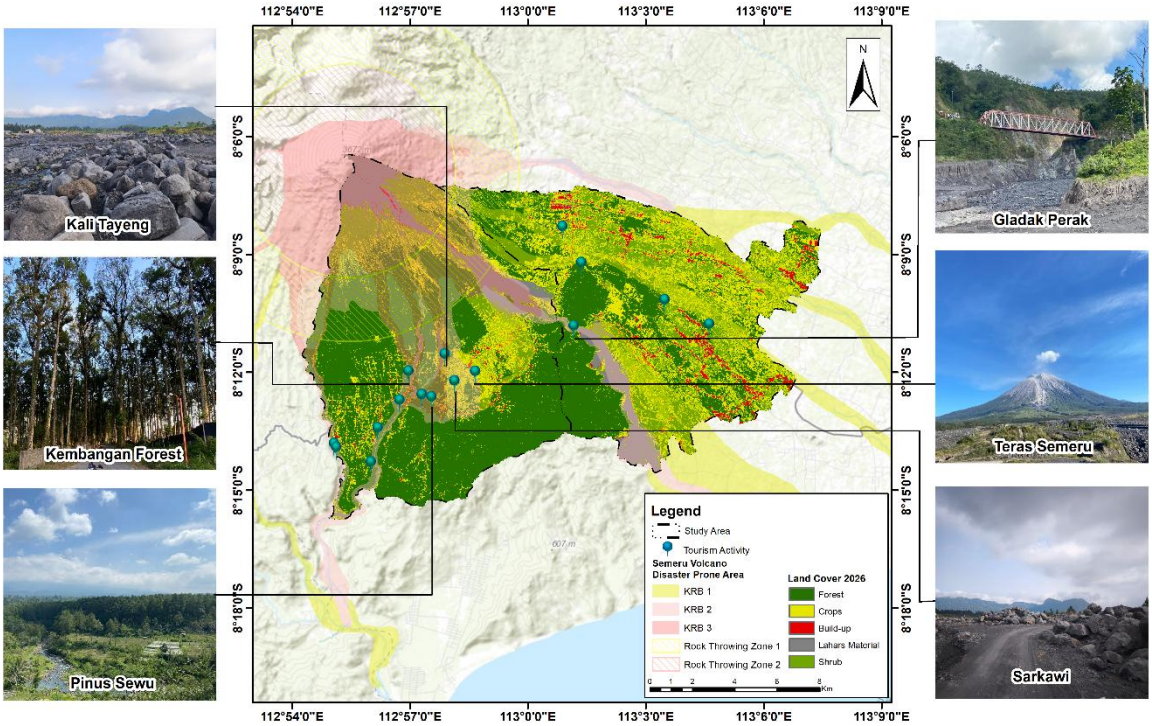


Figure 5. Spatial Distribution of Tourism Locations in Pronojiwo and Candipuro

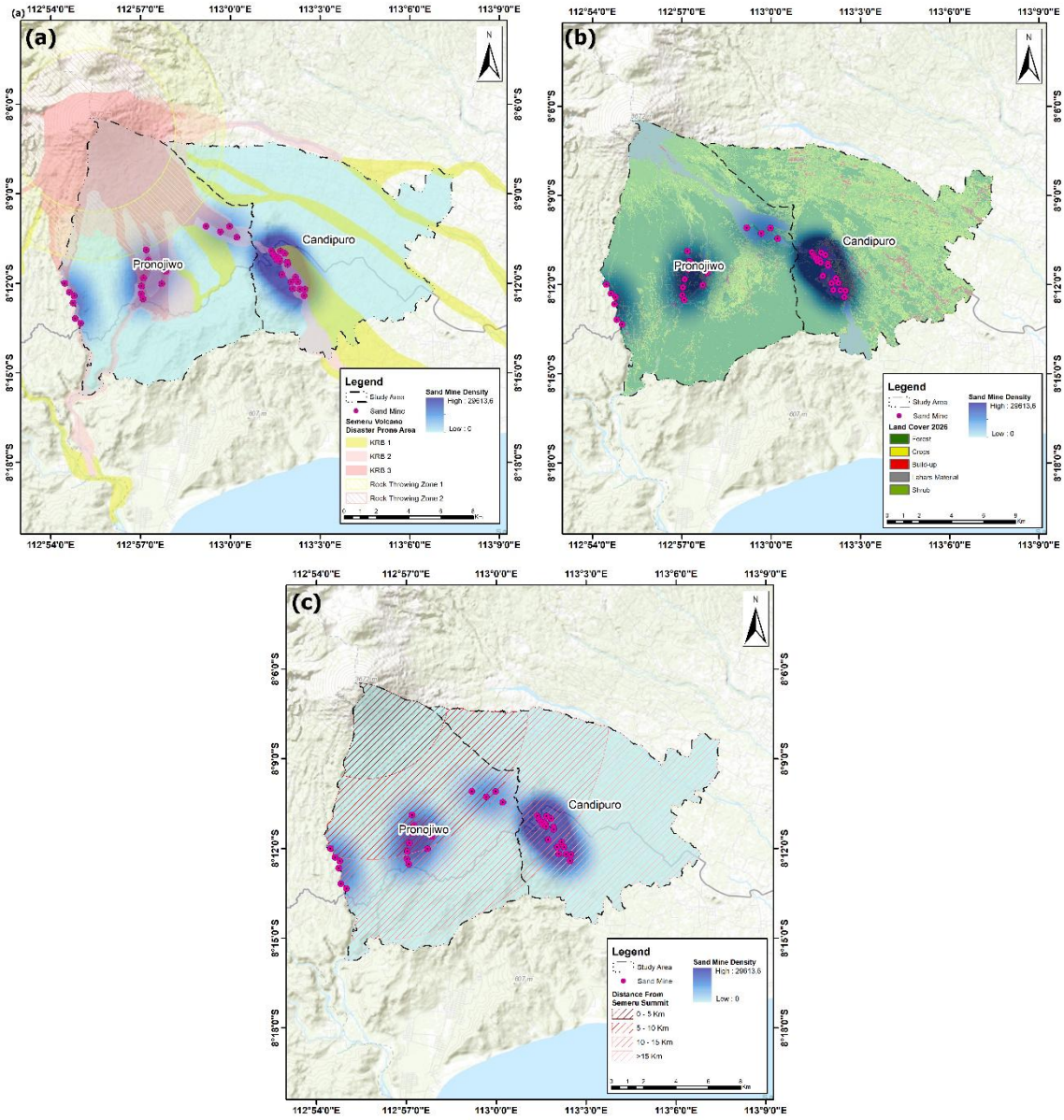


Figure 6. Sand Mine Density Map. (a) Overlay with KRB Map; (b) Overlay with Land Cover Map; (c) Overlay with Distance Map From Mount Semeru's Summit

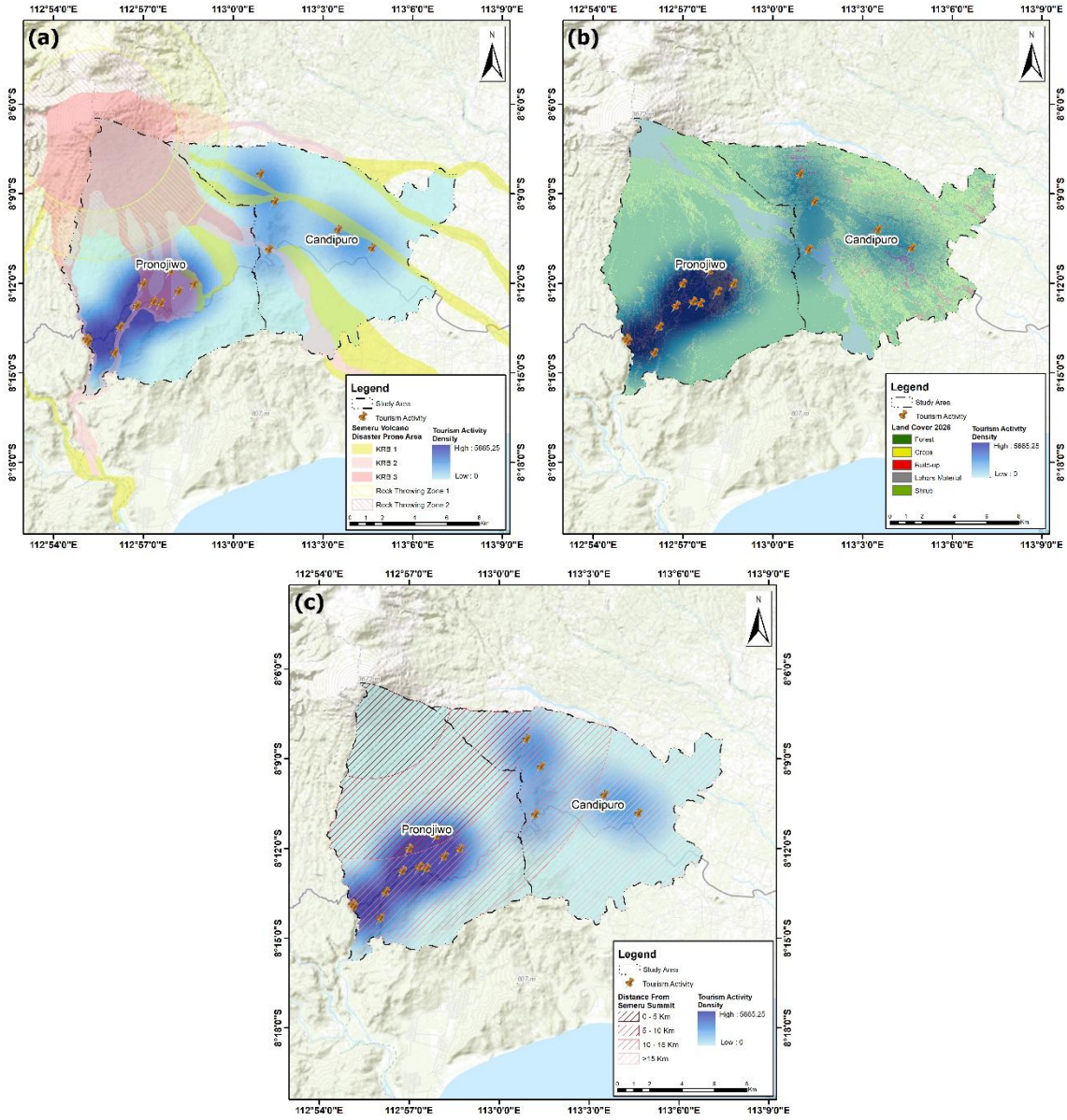


Figure 7. Tourism Activity Density Map. (a) Overlay with KRB Map; (b) Overlay with Land Cover Map; (c) Overlay with Distance Map From Mount Semeru's Summit

Conversely, the more even distribution of tourism sites across zones both inside and outside the Disaster-Prone Areas (KRB) (Figure 7a) indicates that decisions regarding their placement were not directly dictated by disaster vulnerability; rather, they were likely influenced by factors other than hazard levels. This dispersed pattern also suggests that tourism activities on the slopes of Mount Semeru lack full integration, having instead emerged from fragmented initiatives, whether by individuals, community groups, or village governments, without a unified locational planning strategy based on vulnerability levels. Consequently, the tourism sector exhibits a more heterogeneous risk exposure profile than the mining sector (Figure 8a); therefore, mitigation strategies cannot simply be standardized across all sites but must instead be tailored to each site's specific location relative to the KRB zones.

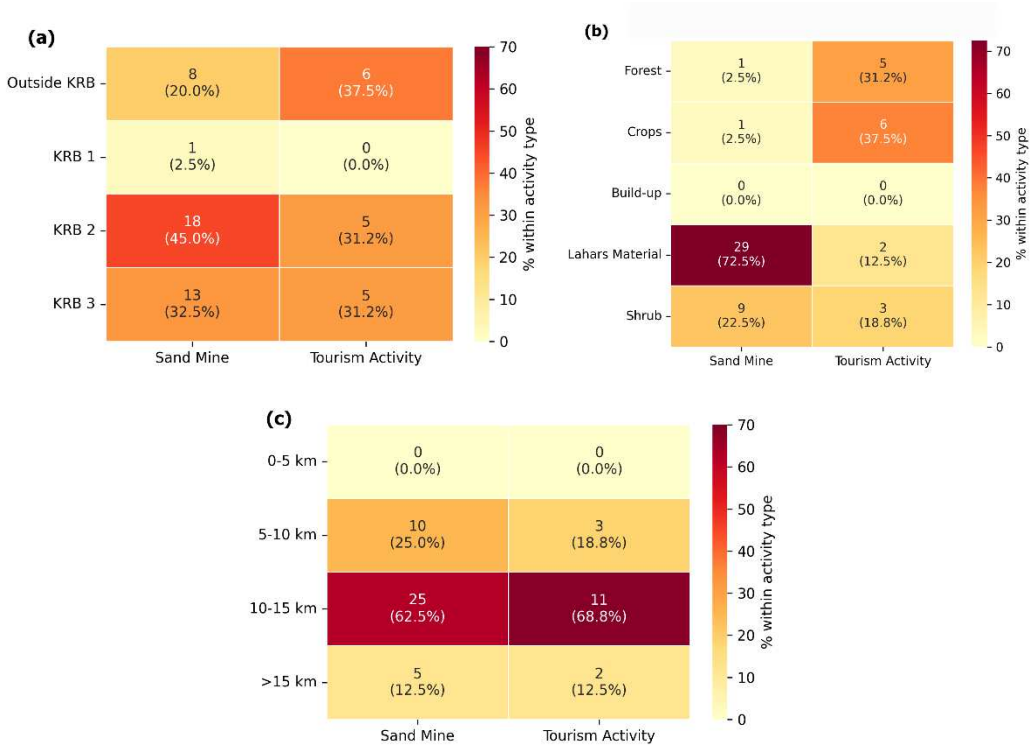


Figure 8. Heatmap Graph of Tourism and Sand Mining. (a) Activities Across Volcanic Hazard Zones (KRB); (b) Activities Across Land Cover; (c) Activities Across Distance Map From Mount Semeru's Summit

This pattern is further reinforced by the analysis of original land-cover classes. The dominance of the lahar material class as the source for the majority of mining sites confirms that mining activity is resource-driven (Figure 8b); the location of a mine is directly determined by the presence of the material resource itself, rather than by other considerations such as proximity to settlements or infrastructure (Figure 6b). This pattern contrasts with tourism sites, which predominantly originate from agricultural and forest land-cover classes (Figure 7b), indicating that tourism development on Mount Semeru largely utilizes relatively intact agrarian and vegetated landscapes, despite the existence of some tourist attractions situated in areas of volcanic material, such as Kali Tayeng and Gladak Perak (Figure 5).

Differences in land-cover changes reveal two parallel yet independent mechanisms of economic transformation: one that directly converts land degradation into economic value (mining, through material extraction), and another that utilizes land degraded by disasters to complement or support disaster-themed tourism activities. Thus, while the argument that "disturbance generates economic opportunities" implies that the disturbance itself constitutes the resource in the mining sector, in the tourism sector, the disturbance serves primarily as a thematic attraction accompanying the surrounding landscape rather than as a direct raw material. Meanwhile, the spatial distribution pattern relative to the summit of Mount Semeru indicates that both types of economic activity tend to cluster within a medium-range distance (Figure 8c); this creates an agglomeration of economic activities situated far enough from the summit to be considered relatively accessible, yet still within the reach of volcanic material. The absence of activity in the immediate vicinity of the summit suggests the observance of a safety threshold by both miners and tourism operators, even though this threshold does not necessarily align with the boundaries of the Disaster-Prone Area (KRB) zones. Interview findings indicate that location decisions on the ground appear to be driven more by the perceived actual distance from the hazard source than by the static administrative boundaries

of the KRB zones, which do not always correspond to the risks directly experienced by those operating in the area.

The pattern of mine locations, which follows the availability of lahar material (Figure 4 and Figure 6b), can be understood through the classical industrial location theory framework proposed by Gaillard, (2008); Rasmussen & Lund, (2018) which classifies industries based on the nature of their raw materials: industries processing "weight-losing" raw materials (where a significant portion of the raw material's weight is lost during the production process) will tend to locate as close as possible to the source of those materials to minimize the transportation costs of the unused material.Volcanic sand mining on the slopes of Mount Semeru can be categorized as an activity driven by material orientation. Because the economic value of the mine depends entirely on the physical presence of the material at a specific point, the mine's location lacks the spatial flexibility found in other economic activities, it must be situated exactly where the material is available. It is this principle of material orientation that theoretically explains why the pattern of mine locations consistently follows the flow risk.

The pattern of tourism distribution, which does not fully align with the Disaster-Prone Area (KRB) zones (Figure 7c), receives a more robust explanation from the study Saptaningtyas, (2024) regarding public perceptions of safety in the disaster-prone zones of Mount Merapi. The study reveals that the hazard zone boundaries formally established by the government often do not fully align with how local communities interpret and experience daily risks; this is because public perceptions of safety are shaped more by years of living in the area than by disaster-prone zone maps. These findings help explain why certain tourist spots on Mount Semeru are actually located within these zones, as decisions regarding their location were likely driven more by the experience and practical considerations of local tourism operators than by direct reference to disaster-prone zone maps.

The two perspectives, material-oriented for mining and amenity-oriented for tourism, provide a more robust conceptual explanation than merely describing pattern differences empirically. Both economic activities emerged in response to post-eruption conditions. Patterns regarding distance from the summit (Figure 8b), indicate that mining and tourism activities are concentrated in the intermediate range and are absent from the area immediately surrounding the crater. These findings can be explained from the perspective of the non-linear relationship between distance and risk perception (non-linear distance-risk perception). Liu et al., (2026) shows that the risk tolerance threshold of individuals and community groups is not formed linearly following the physical distance from the source of danger, but is influenced by the interaction between cognitive, affective, and direct experience (experiential exposure) factors to the danger, which is not always identical to the risk limits determined scientifically or administratively. The absence of activity in the closest radius from the peak, regardless of the type of economic activity, indicates the existence of a risk tolerance threshold that is empirically adhered to by both mining and tourism actors. This compliance is most likely formed from the accumulation of direct community experience with the reach of Semeru's volcanic hazards over time.

This distance difference also needs to be read in a more contextual multi-hazard interaction framework with the conditions of the Indonesian volcanic islands, as shown Lessy et al., (2024) found that communities in active volcanic areas tend to develop livelihood strategies that simultaneously respond to multiple interacting hazards, rather than just a single volcanic hazard. These findings strengthen the argument that mining and tourism location decisions on Mount Semeru are likely the result of complex risk adaptation, rather than simply responding to a single threat.

Risk Perception and Reasons for Remaining in Affected Areas

Sand miners on the slopes of Mount Semeru have developed an informal early warning system built on repeated observations of the surrounding environment, rather than formal reference to hazard zoning maps. Cloudy skies are the first warning for miners to leave the river area and move to higher ground. A second, more specific warning is a cold gust of wind from upstream to downstream, which miners interpret as a sign of an imminent lava flood. One of the most striking findings from the interviews was that miners don't merely perceive lahars as a threat. The high frequency of rain-induced lahars is interpreted as a sign of increasing material volumes that can be processed into economic commodities, making the same natural event both a sign of danger and a signal of opportunity.

In the tourism sector, interviews revealed that a number of business owners previously worked in other sectors before transitioning to providing tourism services. This finding indicates that the tourism sector also serves as a pathway for post-eruption livelihood diversification. Tourism activities were reportedly frequently disrupted during an eruption, primarily due to visitor safety concerns, indicating that business owners have a high level of risk awareness and are adapting their activities reactively to Mount Semeru's status. However, interviews also revealed that many tourism services utilize areas exposed to lava flows, as these areas offer attractive views for visitors, despite their hazard-prone status. This finding indicates a recognized trade-off among business owners between the aesthetic-commercial value of a location and the associated risk.

The informal early warning system used by sand miners is characterized by local community knowledge related to reading sky conditions and wind direction, strengthening the latest findings Solekhah et al., (2025) on the co-production of knowledge in communities on the slopes of Mount Merapi and Mount Kelud after the eruption. The study shows that knowledge of volcanic hazards in affected communities grew organically from repeated life experiences of eruption cycles, and this knowledge ultimately shaped the community's adaptive behavior, including the decision to continue utilizing volcanic materials through large-scale sand mining at both locations. The similarity of patterns between Mount Semeru and Mount Merapi-Kelud strengthens the argument that the phenomenon of post-eruption sand mining in Indonesia is generally supported by local knowledge that is formed independently, rather than by formal instructions or education from government authorities

The dual meaning of lava as both a threat and a marker of the arrival of resources provides qualitative evidence that strengthens the hazard-resource duality argument based on the (Gaillard, 2008). These interview findings suggest that the same duality is also cognitively internalized at the individual miner level, where one natural event triggers two responses at once: awareness of danger and anticipation of economic opportunity. The willingness of tourism business actors to utilize areas exposed to lava for the sake of scenic value is in line with the argument Putra et al., (2023) emphasized that the elements of risk and threat are actually a selling point for volcanic tourism. However, Putra et al., (2023) focuses on the perspective of tourists, while the findings of this study come from the perspective of service providers. These two perspectives complement each other: businesses intentionally position their services in risky areas, knowing that tourists in volcanic areas seek such experiences. However, they still cease operations when the risk is deemed too high, suggesting a practical risk tolerance threshold that is maintained despite its significant economic appeal.

Conclusion

This study shows that post-eruption land cover changes of Mount Semeru in Candipuro and Pronojiwo Districts during the period 2022–2026 not only indicate ecological damage, but also as landscape changes that foster new economic activities, namely volcanic sand

mining and tourism. Sentinel-2A image classification using Random Forest (OA 87.5–88.0%; Kappa 0.854–0.865) confirms an increase in lahar material classes between 2022 and 2026, indicating that the southern slope of Semeru is still in the active sediment accumulation phase, not the post-disaster stabilization phase.

Distribution analysis shows two distinct locations for these two economic activities. Sand mining is concentrated in KRB zones 2–3 and originates predominantly from the lava material land cover class, indicating a resource-driven pattern consistent with the principle of material orientation. Mining locations follow the physical availability of the material. In contrast, tourism sites are more evenly distributed within and outside the KRB zone and utilize more agricultural and forest land, indicating that the distribution pattern of tourism locations is influenced by the attraction of views and other supporting facilities that are relatively far from the impact of the eruption. Both activities were not found within the closest radius of the peak, indicating a shared risk tolerance threshold, regardless of the administrative boundaries of the KRB zone

Qualitative findings reinforce these spatial patterns: sand miners developed an informal early warning system based on environmental observations and interpreted lahars as both a threat and a marker of economic opportunity (hazard-resource duality). At the same time, tourism operators consciously utilized the lahar-exposed landscape as an attraction, but still halted operations when the risk was deemed too high. Both groups demonstrated that location decisions in the field were shaped more by lived experience and risk perceptions than by formal reference to KRB maps. Practically, these findings indicate that mitigation strategies and spatial planning in the Semeru slopes need to differentiate approaches between the mining and tourism sectors, given the heterogeneity of risk exposure patterns in both and cannot be standardized solely based on formal KRB zone boundaries. Future research is recommended to expand the study area to other sub-districts on the Semeru slopes and further explore how local knowledge can be formally integrated into hazard zoning policies, without neglecting the economic dimensions that have emerged from the affected areas.

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Author contribution

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Conflict of interest

The Author declares that there is no conflict of interest in this research.

Generative AI Use

For language review and structure, the author used Grammarly to help refine the language. No Generative AI tools were used to create the writing, research data, or statistical results.

Reference

Arfa-Fathollahkhani, A., & Minaei, M. (2024). Utilizing Multitemporal Indices and Spectral Bands of Sentinel-2 to Enhance Land Use and Land Cover Classification with Random Forest and Support Vector Machine. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2024.08.062

Bachri, S., Murao, O., Fathoni, M. N., & Hakiki, A. R. R. (2025). The Role of Geospatial Technology and Landform Mapping for Volcanic Secondary Hazard Anticipation in Semeru Volcano, Indonesia. *Forum Geografi*, *39*(2), 163–187.

https://doi.org/10.23917/forgeo.v39i2.10060
Bachri, S., Sanjaya, E. H., Sendari, S., Shrestha, R. P., Irawan, L. Y., Nursari, E., Prastiwi, R. H., Hakiki, A. R. R., & May, T. (2024). *The Development of Disaster Risk Map for Semeru Volcano Eruption 2021-2022, East Java, Indonesia*. *54*(3), 446–455. https://doi.org/10.22146/ijg.89918
Bachri, S., Wibowo, S. B., Sunardi, Lavigne, F., Sumarmi, Prastiwi, M. R. H., Hakiki, A. R. R., Hidiyah, T. M., & Putri, N. R. C. (2026). Integration of Topography Map and Land Use Change Modeling for Sustainable Tourism Development in Merapi Volcano, Indonesia. *Forum Geografi*, *40*(2), 178–196. https://doi.org/10.23917/forgeo.12924
Barclay, J., Few, R., Armijos, M., Phillips, J., Pyle, D., Hicks, A., Hicks, A., Brown, S., & Robertson, R. (2019). Livelihoods, Wellbeing and the Risk to Life During Volcanic Eruptions. *Frontiers in Earth Science*. https://doi.org/10.3389/feart.2019.00205
Basuki, A., Purnamasari, H. D., & Syahbana, D. K. (2023). The 2021 Semeru volcano eruption: An insight from visual, seismic, and deformation monitoring data. *IOP Conference Series: Earth and Environmental Science*, *1227*(1). https://doi.org/10.1088/1755-1315/1227/1/012030
Baumann, V., Bonadonna, C., Cuomo, S., Moscariello, M., Biass, S., Pistolesi, M., & Gattuso, A. (2019). Mapping the susceptibility of rain-triggered lahars at Vulcano island (Italy) combining field characterization, geotechnical analysis, and numerical modelling. *Natural Hazards and Earth System Sciences*, *19*(11), 2421–2449. https://doi.org/10.5194/nhess-19-2421-2019
Bronfman, N., Nikole, G., Castañeda, J., Cisternas, P., & Repetto, P. (2024). Relationship between social vulnerability and community resilience: A geospatial study in the context of natural disasters. *International Journal of Disaster Risk Reduction*. https://doi.org/10.1016/j.ijdrr.2024.104774
Dávila, N., Capra, L., Ferrés, D., Gavilanes-Ruiz, J., & Flores, P. (2019). Chronology of the 2014-2016 Eruptive Phase of Volcán de Colima and Volume Estimation of Associated Lava Flows and Pyroclastic Flows Based on Optical Multi-Sensors. *Remote. Sens.*, *11*, 1167. https://doi.org/10.3390/rs11101167
Ding, Y., Yang, X., Wang, Z., Fu, D., Li, H., Meng, D., Zeng, X.-P., & Zhang, J. (2022). A Field-Data-Aided Comparison of Three 10 m Land Cover Products in Southeast Asia. *Remote. Sens.*, *14*, 5053. https://doi.org/10.3390/rs14195053
Dingle, E. H., Kusack, K. M., & Venditti, J. G. (2021). The gravel-sand transition and grain size gap in river bed sediments. *Earth-Science Reviews*, *222*, 103838. https://doi.org/10.1016/j.earscirev.2021.103838
Dingle, E., Kusack, K., & Venditti, J. (2021). The gravel-sand transition and grain size gap in river bed sediments. *Earth-Science Reviews*. https://doi.org/10.1016/j.earscirev.2021.103838
Foody, G. (2020). Explaining the unsuitability of the kappa coefficient in the assessment and comparison of the accuracy of thematic maps obtained by image classification. *Remote Sensing of Environment*. https://doi.org/10.1016/j.rse.2019.111630
Gaillard, J.-C. (2008). Alternative paradigms of volcanic risk perception: The case of Mt. Pinatubo in the Philippines. *Journal of Volcanology and Geothermal Research*, *172*(3–4), 315–328. https://doi.org/10.1016/j.jvolgeores.2007.12.036
Hamud, A., Prince, H. M., & Shafri, H. (2019). *Landuse/Landcover mapping and monitoring using Remote sensing and GIS with environmental integration*. *357*, 12038. https://doi.org/10.1088/1755-1315/357/1/012038
Kadavi, P. R., Lee, W.-J., & Lee, C.-W. (2017). Analysis of the Pyroclastic Flow Deposits of Mount Sinabung and Merapi Using Landsat Imagery and the Artificial Neural Networks Approach. *Applied Sciences*, *7*, 935. https://doi.org/10.3390/app7090935

Lavigne, F., De Coster, B., Juvin, N., Flohic, F., Gaillard, J.-C., Texier, P., Morin, J., & Sartohadi, J. (2008). People's behaviour in the face of volcanic hazards: Perspectives from Javanese communities, Indonesia. *Journal of Volcanology and Geothermal Research*, *172*(3–4), 273–287. https://doi.org/10.1016/j.jvolgeores.2007.12.013

Lavigne, F., Thouret, J., Hadmoko, D., & Sukatja, C. (2016). *LAHARS IN JAVA: INITIATIONS, DYNAMICS, HAZARD ASSESSMENT AND DEPOSITION PROCESSES*. *21*. https://doi.org/10.23917/forgeo.v21i1.1822

Lebedeva, E., & Лебедева, Е. (2019). Impact of volcanic and post volcanic activity on fluvial relief. *Geomorphology RAS*. https://doi.org/10.31857/s0435-42812019449-66

Lebedeva, E. V. (2019). Impact of volcanic and post volcanic activity on fluvial relief. *Geomorphology RAS*, *4*, 49–66. https://doi.org/10.31857/S0435-42812019449-66

Lessy, M. R., Lassa, J., & Zander, K. K. (2024). Understanding Multi-Hazard Interactions and Impacts on Small-Island Communities: Insights from the Active Volcano Island of Ternate, Indonesia. *Sustainability*, *16*(16), 6894. https://doi.org/10.3390/su16166894

Liu, L., Feng, Z., Paes, D., & Lovreglio, R. (2026). The role of spatial distance to hazards in risk perception : A systematic literature review. *Journal of Safety Research*, *97*(July 2025), 376–394. https://doi.org/10.1016/j.jsr.2026.03.012

More, N. (2024). A Complete Study of Remote Sensing- Sentinel-2 Satellite Data for Land Use / Land Cover (LULC) Analysis. *Panamerican Mathematical Journal*. https://doi.org/10.52783/pmj.v35.i1s.2311

Noi, P. T., & Kappas, M. (2017). Comparison of Random Forest, k-Nearest Neighbor, and Support Vector Machine Classifiers for Land Cover Classification Using Sentinel-2 Imagery. *Sensors (Basel, Switzerland)*, *18*. https://doi.org/10.3390/s18010018

Orynbaikyzy, A., Plank, S., Vetrita, Y., Martinis, S., Santoso, I., Ismanto, R., Chusnayah, F., Tjahjaningsih, A., Suwarsono, Genzano, N., Marchese, F., Khomarudin, M., & Strunz, G. (2023). Joint use of Sentinel-2 and Sentinel-1 data for rapid mapping of volcanic eruption deposits in Southeast Asia. *Int. J. Appl. Earth Obs. Geoinformation*, *116*, 103166. https://doi.org/10.1016/j.jag.2022.103166

Orynbaikyzy, A., Santoso, I., Rösch, M., Martinis, S., Ismanto, R., Vetrita, Y., Khomarudin, M., Strunz, G., & Plank, S. (2025). Land surface change detection after major volcanic eruptions in Indonesia using Machine learning and Spatial-Temporal transferability. *Int. J. Appl. Earth Obs. Geoinformation*, *145*, 104965. https://doi.org/10.1016/j.jag.2025.104965

Perwita, C. A., Aprilia, F., Maryanto, S., Arrasyid, H., & Tsabitah, A. F. (2023). Hazards Mitigation of Lahar Flows on Semeru Volcano after the 4 December 2021 Eruption Based on PS-InSAR. *International Journal of Disaster Management*, *5*(3), 193–202. https://doi.org/10.24815/ijdm.v5i3.29098

Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V., Murayama, Y., & Ranagalage, M. (2020). Sentinel-2 Data for Land Cover/Use Mapping: A Review. *Remote. Sens.*, *12*, 2291. https://doi.org/10.3390/rs12142291

Putra, A. K., Rizal, S., Alam, M., Sustika, L., Huda, I. A. illah S., & Yembuu, B. (2023). Volcano Tourism in Volcanic Risk Areas: Exploration of the Higher Experience in Mount Semeru - Indonesia. *Geojournal of Tourism and Geosites* , *46*(1), 99–107. https://doi.org/10.30892/gtg.46111-1005

Rasmussen, M. B., & Lund, C. (2018). Reconfiguring Frontier Spaces : The territorialization of resource control. *World Development*, *101*, 388–399. https://doi.org/10.1016/j.worlddev.2017.01.018

Saptaningtyas, H. (2024). *The hazard zone of Mount Merapi and the community ' s perception of (in) securities*. *8*(3), 408–417.

Solekhah, N., Hakim, F. N., Wahyono, E., Prayoga, R. A., Fatimah, S., Purbandini, L.,

Wibowo, D. P., Saparita, R., Febriyandi YS, F., & Humaedi, M. A. (2025). Learning from volcanic eruptions: Co-production of knowledge at Merapi and Kelud, Indonesia. *Jàmbá: Journal of Disaster Risk Studies*, *17*(1). https://doi.org/10.4102/jamba.v17i1.1881

Suhadha, A., & Harintaka, H. (2024). Multidimensional displacement analysis of Semeru Volcano, Indonesia following December 2021 eruption from multitrack InSAR observation. *Earth Science Informatics*, *17*, 1539–1552. https://doi.org/10.1007/s12145-024-01248-z

Surono, Jousset, P., Pallister, J., Boichu, M., Buongiorno, M., Budi-Santoso, A., Costa, F., Andreastuti, S., Prata, F., Schneider, D., Clarisse, L., Humaida, H., Sumarti, S., Bignami, C., Griswold, J., Carn, S., Oppenheimer, C., & Lavigne, F. (2012). The 2010 explosive eruption of Java's Merapi volcano—A '100-year' event. *Journal of Volcanology and Geothermal Research*, *241*, 121–135. https://doi.org/10.1016/j.jvolgeores.2012.06.018

Surono, Jousset, P., Pallister, J., Boichu, M., Buongiorno, M. F., Budisantoso, A., Costa, F., Andreastuti, S., Prata, F., Schneider, D., Clarisse, L., Humaida, H., Sumarti, S., Bignami, C., Griswold, J., Carn, S., Oppenheimer, C., & Lavigne, F. (2012). The 2010 explosive eruption of Java's Merapi volcano—A '100-year' event. *Journal of Volcanology and Geothermal Research*, *241–242*, 121–135. https://doi.org/10.1016/j.jvolgeores.2012.06.018

Suud, M. M., Bachri, S., Sumarmi, Astina, I. K., & Nadhiroh, A. (2025). *Assessing The Resilience Index of Villages Affected By The Semeru Eruption In Lumajang, Indonesia*. *23*(4), 691–706.

Tierz, P., Woodhouse, M., Phillips, J., Sandri, L., Selva, J., Marzocchi, W., & Odbert, H. (2017). A Framework for Probabilistic Multi-Hazard Assessment of Rain-Triggered Lahars Using Bayesian Belief Networks. *Frontiers in Earth Science*, *5*, 73. https://doi.org/10.3389/feart.2017.00073

Xu, D., Peng, L., Liu, S., & Wang, X. (2018). Influences of Risk Perception and Sense of Place on Landslide Disaster Preparedness in Southwestern China. *International Journal of Disaster Risk Science*, *9*(2), 167–180. https://doi.org/10.1007/s13753-018-0170-0

Yan, X.-Y., Li, J., Smith, A., Yang, D., Tianyue, & Su, Y. (2023). Rapid Land Cover Classification Using a 36-Year Time Series of Multi-Source Remote Sensing Data. *Land*. https://doi.org/10.3390/land12122149

Yılmaz, A. E., & Demirhan, H. (2023). Weighted kappa measures for ordinal multi-class classification performance. *Appl. Soft Comput.*, *134*, 110020. https://doi.org/10.1016/j.asoc.2023.110020

Yulianto, F., Sofan, P., Khomarudin, M., & Haidar, M. (2013a). Extracting the damaging effects of the 2010 eruption of Merapi volcano in Central Java, Indonesia. *Natural Hazards*, *66*, 229–247. https://doi.org/10.1007/s11069-012-0438-4

Yulianto, F., Sofan, P., Khomarudin, M. R., & Haidar, M. (2013b). Extracting the damaging effects of the 2010 eruption of Merapi volcano in Central Java, Indonesia. *Natural Hazards*, *66*(2), 229–247. https://doi.org/10.1007/s11069-012-0438-4