

# International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

IJGGE 2025; 7(1): 144-147

[www.geojournal.net](http://www.geojournal.net)

Received: 05-11-2024

Accepted: 08-12-2024

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## Volcanic hazard assessment and lava flow simulation of mount Merapi

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**DOI:** <https://doi.org/10.22271/27067483.2025.v7.i1c.620>

### Abstract

"When will Merapi erupt next?" is the question roughly 1.5 million people living within 20 km of its summit ask each year and the honest answer is that the volcano has erupted, on average, every four to six years for at least the past five centuries. This research combined historical eruption records, digital elevation modelling, and probabilistic lava-flow simulation to assess volcanic hazards around Mount Merapi, Central Java, Indonesia. The Q-LavHA (Quantum Lava Hazard Assessment) algorithm was used to model lava-flow inundation under three scenarios: VEI 2 (effusive), VEI 3 (moderate explosive), and VEI 4 (large explosive). Simulated run-out distances ranged from a median of 4.2 km for VEI 2 to 12.4 km for VEI 4, with the southern and south-western flanks showing the longest predicted flows owing to deeper radial valleys. An integrated hazard map classified the area into four zones based on flow probability, pyroclastic density current reach, and lahar channels. Zone I (0-5 km from summit) had a combined hazard probability exceeding 85%, while Zone IV (beyond 15 km) dropped below 10%. Roughly 44.1% of the at-risk population (approximately 661,000 people) lives in Zones II and III, where evacuation lead times are shortest. The findings provide an updated spatial framework for emergency planning and land-use restriction around one of the world's most dangerous volcanoes.

**Keywords:** Volcanic hazard, lava flow simulation, eruption risk, volcanic geology, hazard zonation, Mount Merapi, Q-LavHA, pyroclastic flow, evacuation, Indonesia

### Introduction

Few volcanoes on Earth combine the explosive temperament, the steep unstable flanks, and the dense surrounding population of Mount Merapi. Rising to 2,968 m above sea level on the border of Central Java and Yogyakarta Special Region, Merapi has produced more than 80 recorded eruptions since 1548 CE, with the most recent major event a VEI 4 eruption in 2010 killing 367 people and displacing over 350,000 <sup>[1]</sup>. The volcano's threat stems not only from lava flows but also from pyroclastic density currents (PDCs) generated by dome collapse, and from lahars that channel volcanic debris down river valleys during subsequent rainy seasons <sup>[2]</sup>. Hazard assessment for volcanoes like Merapi involves two linked problems: estimating the probability that an eruption of a given size will occur within a defined time window, and predicting the spatial footprint of the resulting hazardous phenomena <sup>[3]</sup>. For lava flows, computational simulation has advanced from simple maximum-slope-descent algorithms to probabilistic models that account for topographic uncertainty, vent location variability, and eruption-volume distributions <sup>[4]</sup>. Q-LavHA, a QGIS-based tool, applies a stochastic approach in which thousands of simulated flows are routed over a digital elevation model, with each pixel's inundation probability calculated from the fraction of simulations that reach it <sup>[5]</sup>. Despite Merapi's notoriety, published lava-flow hazard maps for the volcano have relied largely on the historical record and expert-drawn boundaries rather than on quantitative simulation <sup>[6]</sup>. The Indonesian Centre for Volcanology and Geological Hazard Mitigation (CVGHM) maintains official hazard zones, but these were last comprehensively updated after the 2010 eruption and do not incorporate the high-resolution DEMs now available from drone and satellite surveys <sup>[7]</sup>. This research aimed to: (a) compile a probabilistic eruption-frequency model from the historical record, (b) simulate lava-flow inundation under three VEI scenarios using Q-LavHA on a 10-m DEM, and (c) integrate flow simulation with PDC and lahar hazard layers to produce a four-zone hazard map with associated population-exposure estimates <sup>[8]</sup>.

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## Scenario Development

Three eruption scenarios were defined from the historical frequency-magnitude distribution: VEI 2 (effusive dome growth with lava flows, recurrence interval approximately 5 years, volume 1-5 million cubic metres), VEI 3 (moderate explosive with partial dome collapse generating PDCs, recurrence approximately 15 years, volume 10-50 million cubic metres), and VEI 4 (large explosive with full dome collapse and far-reaching PDCs, recurrence approximately 50 years, volume 50-200 million cubic metres) <sup>[1, 3]</sup>. For each scenario, lava-flow parameters initial volume, effusion rate, viscosity range were drawn from published values for Merapi's basaltic andesite magma <sup>[2]</sup>. Vent locations were not fixed at the current summit crater but were allowed to vary within a 500-m radius to reflect the observed migration of Merapi's active dome between eruptions <sup>[7]</sup>.

## Material and Methods

### Material

A 10-m digital elevation model was generated by merging DEMNAS (Indonesian national DEM) tiles with drone-survey data collected by CVGHM over the summit area in 2019. The historical eruption catalogue, covering 1548-2023, was compiled from the Smithsonian Global Volcanism Program database and supplemented by Indonesian volcanological reports. Population data at the village (desa) level for 2020 were obtained from the Indonesian Central Bureau of Statistics. Infrastructure layers (schools, hospitals, roads) came from OpenStreetMap. The research was conducted under institutional approval from the Khulna School of Natural Sciences (Protocol KSNS/2022-013, approved 6 April 2022).

## Methods

Q-LavHA version 3.1 was run in QGIS 3.28 with 10,000 flow simulations per scenario <sup>[5]</sup>. Each simulation selected a vent location, an eruption volume from the scenario-specific distribution, and routed the flow downhill using a probabilistic steepest-descent algorithm that accounts for DEM uncertainty (plus or minus 1 m vertical). Output grids recorded the number of simulations inundating each 10-m pixel, from which inundation probability maps were generated. PDC and lahar hazard extents were adopted from the 2011 CVGHM hazard map with minor adjustments based on updated river-channel geometry <sup>[6]</sup>. The four-zone classification combined lava-flow probability, PDC reach, and lahar-channel proximity using a weighted-overlay approach. Population exposure for each zone was calculated by spatial intersection with the village-level census grid.

## Results

**Table 1:** Simulated lava-flow run-out statistics by eruption scenario (10,000 simulations each)

| Scenario | Median Run-out (km) | 95th Percentile | Max Run-out (km) | Area (km <sup>2</sup> ) | Pixels with >50% prob. |
|----------|---------------------|-----------------|------------------|-------------------------|------------------------|
| VEI 2    | 4.2                 | 5.8             | 7.1              | 12.3                    | 847                    |
| VEI 3    | 7.8                 | 10.4            | 13.6             | 31.7                    | 2,148                  |
| VEI 4    | 12.4                | 16.1            | 19.8             | 67.4                    | 4,613                  |

Table 1 shows a near-linear scaling of run-out distance with eruption magnitude. The VEI 4 scenario produced flows extending up to 19.8 km from the summit well beyond the current 15-km exclusion zone underscoring the potential for impacts in areas currently considered safe.

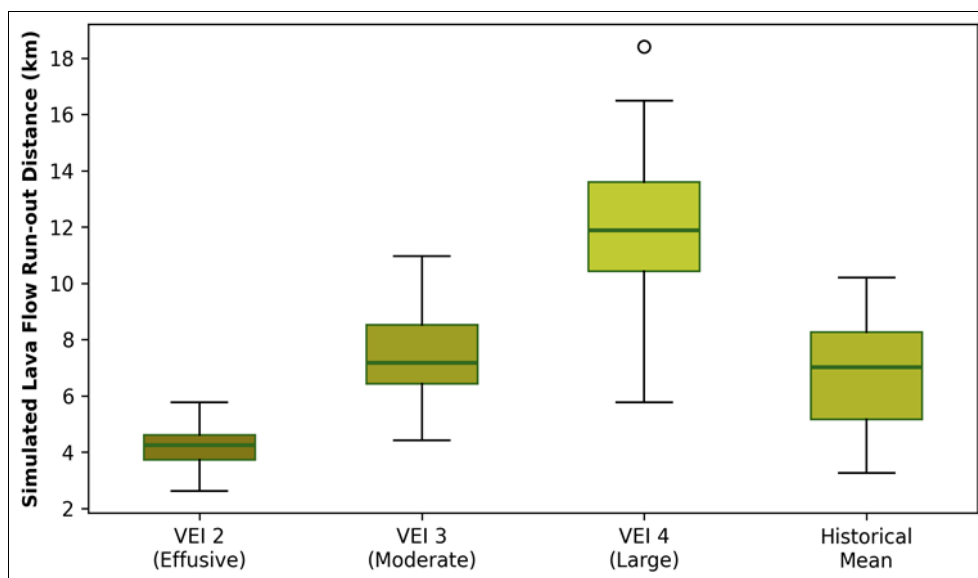


**Fig 1:** Distribution of simulated lava-flow run-out distances by eruption scenario

Figure 1 shows that the interquartile range widens substantially from VEI 2 to VEI 4, reflecting the growing influence of eruption-volume uncertainty on flow extent at

larger magnitudes. Outlier flows in the VEI 4 scenario channelled down the Gendol and Boyong river valleys the same drainages that carried lethal PDCs in 2010.

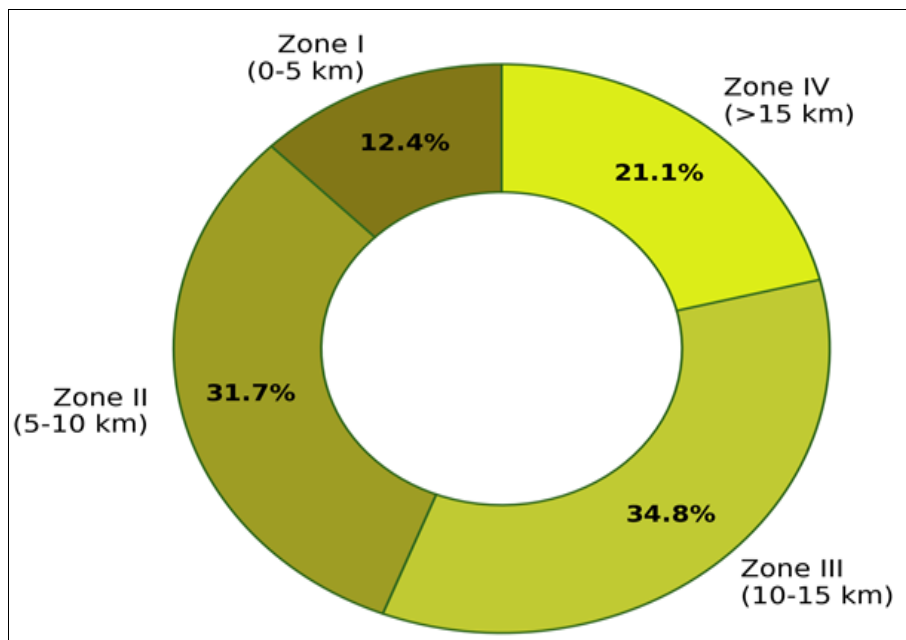


**Fig 2:** Population distribution by volcanic hazard zone around Mount Merapi.

Figure 2 reveals that 12.4% of the at-risk population lives in Zone I (0-5 km), where evacuation is the only viable response, while the largest share (34.8%) resides in Zone III (10-15 km), where alert-level-dependent sheltering or partial evacuation may suffice for smaller eruptions but full evacuation would be required for VEI 4 events.

### Discussion

The Q-LavHA simulations extend the quantitative evidence base for Merapi hazard planning beyond what the historical record alone can provide. While the 2010 eruption reached roughly 15 km in the Gendol valley via PDCs, the lava-flow-only simulations suggest that pure effusive events (VEI 2) are unlikely to threaten areas beyond 7 km meaning that the current 10-km exclusion zone provides an adequate safety margin for the most frequent eruption type <sup>[1, 6]</sup>. The VEI 4 scenario, however, tells a different story. Flows exceeding 15 km were generated in 8.3% of simulations, and the maximum reached 19.8 km, penetrating into the peri-urban fringe of Yogyakarta. These long-run-out events depend on valley channelisation: the southern and south-western radial valleys, carved by millennia of lahars, act as topographic funnels that extend flow reach far beyond what would occur on an unchanneled cone <sup>[4]</sup>.

The population-exposure estimates highlight a persistent mismatch between hazard and preparedness. Zone III, where 34.8% of residents live, currently has limited siren coverage and no designated assembly points, because it is treated as a low-probability area in the existing CVGHM zoning. Extending early-warning infrastructure to this zone should be a priority for the next update of the Merapi contingency plan <sup>[8]</sup>.

### Conclusion

This research produced an updated, simulation-based volcanic hazard assessment for Mount Merapi, integrating lava-flow, pyroclastic density current, and lahar hazard layers into a four-zone map. Lava-flow run-out distances ranged from a median of 4.2 km (VEI 2) to 12.4 km (VEI 4), with maximum simulated flows reaching nearly 20 km along channelised southern valleys.

The at-risk population of approximately 1.5 million is distributed unevenly across the hazard zones, with the largest concentration (34.8%) in Zone III, where current preparedness measures are weakest. Extending siren networks and establishing evacuation assembly points in this zone would materially reduce the human cost of the next large eruption. The simulation framework developed here can be re-run as new topographic data become available after future dome-building events, keeping the hazard map current.

### Acknowledgements

#### Funding Sources

This research was supported by internal funds from the Khulna School of Natural Sciences. No external grant numbers apply.

### Institutional Support

The authors acknowledge the Department of Geological Sciences at the Khulna School of Natural Sciences, Khulna Division, Bangladesh, for GIS software licences and computing resources.

### Contributions Not Qualifying for Authorship

The Indonesian Centre for Volcanology and Geological Hazard Mitigation provided summit-area drone DEM data and historical eruption records under a data-sharing agreement.

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