Simulation Of Lava Flow Hazards In Mount Etna

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Introduction

Mount Etna is one of the world's most active basaltic volcanoes and the dominant volcanic feature of eastern Sicily. Its frequent eruptions, extensive settlement on its slopes, agricultural value, tourism, roads, utilities, and proximity to Catania make lava-flow hazard assessment a continuing public-safety and land-use problem. Etna's lava usually advances slowly enough for people to move away, but a flow can permanently destroy buildings, roads, crops, and infrastructure. Ash fall, earthquakes, gas, explosive activity, and instability near the summit create additional hazards that must not be confused with lava inundation (Dipartimento della Protezione Civile, n.d., *Etna*).

Simulation is essential because authorities cannot wait for every possible vent to open before planning. A lava-flow hazard model combines the probability of future vent locations, eruption duration and discharge rate, detailed topography, and a numerical representation of how lava moves. Thousands or millions of scenarios can then be aggregated into maps showing where inundation is relatively more or less likely over a stated period. These maps are not predictions of the next eruption. They are decision-support tools that identify persistent exposure, compare scenarios, guide emergency preparation, and show where uncertainty is greatest (Del Negro et al., 2013).

Etna's Eruptive Setting

Etna's activity occurs at summit craters and along fissures that can open on its flanks. Summit eruptions may produce lava fountains, ash plumes, and relatively high-altitude lava flows that often remain within uninhabited areas. Flank eruptions are especially important for territorial risk because vents can open at lower elevations and reduce the distance between the source and populated or cultivated land. The location of a vent can be more important than the total volume of lava: a moderate eruption beginning close to infrastructure may be more damaging than a larger eruption directed into the uninhabited Valle del Bove (Cappello et al., 2024, *Lava flow hazard map from flank eruptions at Etna*).

The volcano's surface changes after every significant eruption. New cones, channels, levees, collapsed areas, and overlapping lava fields alter the routes available to later flows. For this reason, a hazard map based on an old digital elevation model may become less reliable. The Italian Civil Protection Department warns that commercially available maps may not reflect the frequent morphological change of the volcano. Updated topography from satellites, aircraft, drones, and field surveys is therefore a necessary input to credible simulation (Dipartimento della Protezione Civile, n.d., *Etna*).

Historical Evidence of Lava-Flow Damage

Etna's historical record shows that lava flows have repeatedly damaged farmland, forests, roads, and buildings. The 1669 eruption is the best-known destructive event because a low-altitude fissure produced extensive flows that reached Catania and entered the sea. The 1928 eruption destroyed much of Mascali. More recent eruptions have threatened settlements and infrastructure without producing the same scale of urban destruction. The 1991–1993 eruption lasted 473 days and generated more than 300 million cubic meters of lava, threatening Zafferana Etnea. Barriers, channels, concrete blocks, and explosives were used in an effort to slow and divert the advancing flow (Dipartimento della Protezione Civile, n.d., *The Etna eruption*).

Historical catalogues provide evidence about vent locations, flow lengths, durations, and affected areas, but they are incomplete. Older eruptions may be poorly dated or mapped, and the absence of documented damage does not prove that an area was safe. Settlement patterns have also changed. A route that crossed empty land centuries ago may now intersect housing, power lines, tourism facilities, or transportation networks. Hazard analysis must therefore combine eruptive history with present-day exposure.

Components of a Probabilistic Lava-Flow Model

Future Vent Opening

The first component estimates where a future eruptive fissure or vent could open. Researchers use mapped vents, eruptive fractures, structural faults, deformation patterns, and recurrence data to construct a spatial probability distribution. Areas with frequent historical vent opening may receive higher probability, but the method must allow for events outside the densest clusters. A probability map is not a claim that magma will follow a known line; it represents the best statistical description supported by available evidence (Del Negro et al., 2013).

Eruption Classes and Effusion Rates

Lava behavior depends strongly on the rate at which magma is discharged and how that rate changes over time. A high initial effusion rate can send lava rapidly through channels, while a long, lower-rate eruption can continue feeding a front for months. Models divide possible eruptions into classes based on duration, volume, or effusion-rate curves. Each class is assigned an occurrence probability. This approach is more realistic than simulating every eruption with one fixed volume and rate.

Topography and Flow Routing

Gravity directs lava toward lower terrain, but movement is influenced by cooling, crust formation, channel development, levee failure, branching, and local obstacles. Numerical models approximate these processes at a chosen spatial resolution. Fine-resolution terrain can capture channels and ridges that would disappear in a coarse grid, but greater resolution requires more computing power and can create a false impression of precision if the physical assumptions remain uncertain.

Scenario Aggregation

A single simulation produces one possible inundation footprint. Hazard mapping requires a large ensemble of scenarios with different vents and eruption parameters. The model records how often each grid cell is covered and weights the results by scenario probability. The output is a long-term probability or relative hazard surface. INGV's updated datasets for flank and summit eruptions use a probabilistic workflow that includes expected eruption classes, vent-opening probabilities, GPUFLOW simulations, and calculation of the probability that each point will be inundated (Cappello et al., 2024, *Lava flow hazard map from flank eruptions at Etna*; Cappello et al., 2024, *Lava flow hazard map from summit eruptions at Etna*).

Flank and Summit Hazard Maps

Flank and summit eruptions should be modeled separately because their vent distributions, eruptive styles, and exposure patterns differ. INGV's updated flank-eruption dataset is valid for a 2023–2052 assessment window and revises earlier mapping with a contemporary probabilistic approach. It highlights the importance of vent probability and flow routing across inhabited slopes. The summit-eruption map incorporates both longer subterminal eruptions and short paroxysmal events from the main summit craters (Cappello et al., 2024, *Lava flow hazard map from flank eruptions at Etna*; Cappello et al., 2024, *Lava flow hazard map from summit eruptions at Etna*).

These datasets improve planning but do not erase uncertainty. Their values depend on the historical period selected, classification of eruption types, accuracy of topography, and representation of lava physics. A cell with low long-term probability is not risk-free. A rare low-altitude vent can produce severe consequences, while a high-probability zone may remain unaffected in the next eruption. Authorities should communicate both probability and consequence.

What the Simulation Can and Cannot Predict

Long-term hazard maps answer questions such as: Which sectors are repeatedly reached across many plausible scenarios? Which towns or roads lie below likely vent zones? Where would additional barriers, evacuation routes, or monitoring capacity provide value? They do not identify the date, vent, volume, or exact route of the next eruption (Del Negro et al., 2013).

During an eruption, short-term models become possible once the vent location, observed discharge, and active front are known. Satellite thermal imagery, drone mapping, ground observations, and field measurements can update the source parameters. INGV has used drones to rapidly map active lava fields and estimate emitted volume and average effusion rate. Real-time or near-real-time simulation can then support operational decisions, but it remains sensitive to changing conditions such as channel blockage, branching, or a new vent.

Exposure on the Southeastern and Southern Flanks

The southeastern and southern slopes contain dense settlements, roads, farms, and tourism infrastructure. Communities such as Trecastagni, Pedara, Nicolosi, Mascalucia, and other municipalities have appeared in hazard studies because their exposure depends on possible vents and terrain pathways. Naming a community on a hazard map does not mean it will be destroyed. It means that some modeled scenarios reach its territory and that planning should consider those scenarios.

Risk is the interaction of hazard, exposure, and vulnerability. Two locations with similar inundation probability can have different risk if one contains a hospital, major road, electricity substation, or densely occupied housing. Agricultural losses also matter. Vineyards, orchards, and other cultivated land may be economically and culturally important even where life safety can be protected through evacuation.

Risk Mitigation and Civil Protection

Monitoring and Warning

Etna is monitored with seismic networks, ground deformation instruments, cameras, gas measurements, satellite observations, and field surveys. Monitoring helps identify changes in activity, but not every flank eruption can be forecast with exact timing and location. Alerts should therefore be linked to predefined actions and communicated in language that distinguishes unrest, eruption, ash hazard, summit access restrictions, and lava threat to communities (Dipartimento della Protezione Civile, n.d., *Etna*).

Land-Use Planning

Hazard maps can influence where new development is permitted, how critical infrastructure is routed, and what construction or insurance requirements are appropriate. Land-use decisions are difficult because Etna's slopes are already inhabited and economically productive. A map should not be treated as a simple boundary between safe and unsafe land. Planners should consider probability, consequences, evacuation access, and the useful life of a development.

Barriers and Diversion

Earth barriers, channels, and diversion efforts have been attempted during several Etna eruptions. The 1991–1993 response demonstrated that engineering can delay or redirect lava under particular conditions. Such intervention is not guaranteed. It requires time, suitable terrain, safe access, legal authority, and an understanding that diverting lava from one area may increase exposure elsewhere. Simulation can test potential barriers before or during an emergency, but ethical and political decisions remain necessary (Dipartimento della Protezione Civile, n.d., *The Etna eruption*).

Evacuation and Public Education

Because most Etna lava advances slowly, evacuation can protect life. This should not lead to complacency. Explosions near vents, collapse, gas, ash, earthquakes, and traffic congestion can create urgent danger. Residents and visitors need clear information about restricted summit zones, evacuation routes, ash protection, road closures, and reliable official channels. Tourists who approach active areas may have less local knowledge and can be exposed to rapidly changing hazards.

Model Validation

A model should be validated against eruptions not used to calibrate it. Researchers can compare simulated footprints with mapped historical flows, measure overlap, evaluate arrival patterns, and test whether high-probability zones contain a reasonable proportion of observed inundation. Validation must examine more than visual similarity. It should identify systematic errors, such as flows that spread too widely, move too far, or fail to follow known channels.

Uncertainty analysis is equally important. Changing vent probabilities, topography, eruption-class weights, or physical parameters can reveal how stable the hazard pattern is. If small assumptions produce large changes, the map should be communicated cautiously and planning should use multiple scenarios.

Social and Economic Consequences

Lava can remove land from productive use for long periods, destroy homes and businesses, interrupt roads, damage utilities, and alter tourism. Ash emissions can close airports, contaminate equipment, burden roofs, and affect agriculture over a much wider area than the lava field. Risk communication should not focus only on dramatic urban destruction. Repeated moderate disruptions can impose large cumulative costs.

Recovery also creates unequal burdens. Households with insurance, savings, transportation, and alternative housing can respond differently from vulnerable residents. Municipalities may have varying technical and financial capacity. Hazard planning should therefore include social vulnerability, continuity of health services, livestock and farm needs, and support for displaced residents.

Conclusion

Simulation of lava-flow hazards at Mount Etna transforms eruptive history, vent probabilities, discharge scenarios, and updated topography into maps that support planning. The most advanced approach does not produce one deterministic route. It runs large ensembles of plausible summit and flank eruptions and calculates the relative probability of inundation across the volcano. Updated INGV maps demonstrate how GPU-based modeling and probabilistic vent assessment can improve long-term hazard analysis (Cappello et al., 2024, *Lava flow hazard map from flank eruptions at Etna*; Cappello et al., 2024, *Lava flow hazard map from summit eruptions at Etna*).

These tools are valuable only when their limits are understood. Etna’s morphology changes, rare vents remain possible, and risk depends on current settlement and infrastructure. Simulation should be combined with monitoring, land-use policy, emergency exercises, public education, and real-time data during eruptions. The central lesson is not that a map can predict the next flow, but that scientifically organized uncertainty can help communities make better decisions before lava is already moving toward them.

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