

Post-Eruption Lahar Triggers: slope failure and rainfall

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Introduction.

Lahars are a form of debris flow composed of a mixture of pyroclastic materials and water from a volcano. The flows are high-velocity, and produce great discharge volumes of high-density, water-saturated debris mixtures. Lahar deposits are poorly sorted and massive in volume. Of Indonesian/Javanese origin, the term has been translated as “mudstream”, and defined as “a rapidly flowing mixture of rock debris and water (other than normal streamflow) from a volcano” (Lavigne, F, 2000, p. 545). Compared to other streamflows, lahars have a high velocity, discharge, and sediment transport capacity.

Lahars can fall under three categories of classification, syn-eruptive, post-eruptive or non-eruptive. Within the syn-eruptive category, Lavigne further classifies lahars generated during an eruption according to the water source incorporated in the flow, including ice, snow, crater lakes, rainfall etc. “Most syn-eruptive lahars are generated when a drainage system is choked by a pyroclastic flow, a ‘wet’ pyroclastic surge or a debris avalanche” (Lavigne, p. 546).

Post-eruptive lahars can occur any time during the several years following an eruption and are triggered by rain events. Non-eruptive lahars include events such as debris avalanches and lake outbursts (the release of water dammed by glacial ice) and are generated without eruptive activity.

Lahars can be produced in several ways. During an eruption, any source of water including ice, snow, river water or rain can cause sediment to move and be incorporated into a lahar. Following an eruption, there can be various controls on lahar occurrence but primarily they are triggered by rainfall or slope failure.

Lahars have been the cause of major damage and loss of life throughout history. They have buried entire towns, and destroyed cities beyond repair. Their extreme danger makes them

an important topic of research throughout the geosciences in the hopes of mitigating future disaster.

This paper seeks to examine these post-eruption triggers and, with the analysis of published case studies, aims to investigate the factors specific to rainfall events and slope failures that are likely to produce lahar flow. It aims to answer the questions of 1) what specific details of rainfall events are understood to have triggered lahars? and 2) what are the characteristics of source areas of volcanic avalanches and landslides that transform into debris flow and lahars?

Rainfall.

There are several factors to consider with respect to rain-triggered lahars. Rainfall distribution is perhaps the most influential, on both spatial and temporal scales.

Convective rainfall occurs more commonly during the afternoon due to the solar heating of land surfaces throughout the day. Many climates also experience an annual rainy season, where annual rainfall for the region typically peaks. These tendencies are particularly common at lower latitudes and tropical/equatorial regions, where lahars more commonly occur in the afternoon and during monsoon season. (Lavigne, F; Thouret, J C; Voight, B; Suwa, H; Sumaryono, A, 2000, p. 435).

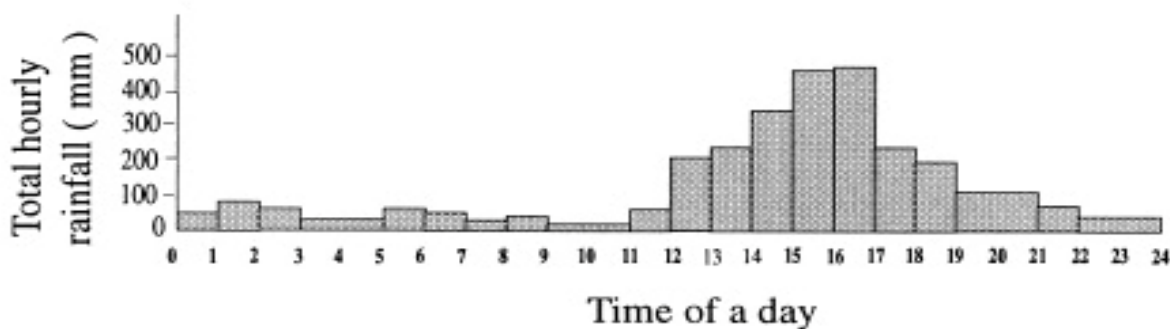


Figure 1: Diurnal rainfall by time of day: Merapi, 1990 (Lavigne et al, 2000).

In addition to temporal patterns of rainfall, the intensity and duration of rain events also impacts the likelihood of a triggering a lahar. “For debris flows generally, as well as for lahars, the rainfall intensity as measured over 1 hour or 10 minute intervals play a key role in the mobilization of debris” (Lavigne et al, p. 435). Commonly, the time of lahar generation coincides with the time of peak rainfall. Often times, however, there is a delay in lahar detection following a rain event as rainwater accumulates and begins to entrain sediment. Sometimes this lag is greater than at other times. Factors influencing these anomalies include: the spatial differences between the rain gage and the lahar source area (rainfall may differ between the two points), between lahar observation point on the channel and the lahar initiation area in the source zone - “due to local formation and subsequent disruption of landslide dams in river channels” (Lavigne et al. p. 439).

Other aspects of rainfall that contribute to triggering relate to the morphology of the upper basin and characteristics of source deposits. These factors may be seen in the later stages of lahar passage and following the event. “The decline of lahars is mainly caused by progressive loss of source pyroclastic debris, by improvement in infiltration, and decrease in runoff, on hillslopes previously covered with pyroclastic tephra.” (Lavigne et al, p. 441). Permeability of the ground surface is a noteworthy example of this, as it influences the amount of runoff generated during rainfall. Whether runoff occurs during a storm is related to the grain size and distribution as well as the sedimentological characteristics of the surface materials. A lahar cannot form unless runoff is significant enough to begin to entrain debris particles.

Similarly, the extent of ground saturation prior to rain event affects the occurrence or nature of runoff. If the ground surface is already near saturation, it may not take very much rainfall to produce runoff. In contrast, a dry and permeable surface may be able to take much

more water by comparison before runoff begins to occur. This particular factor can be related to the amount of time between storms. If there is not sufficient recovery time following a rain event before another one occurs, the previous water will not have fully infiltrated the surface. This can be analyzed using the concept of working rainfall, or the total rainfall that precedes the lahar event for 7 days. Studies indicate a “correlation between working rainfall and 1 hour rainfall for lahar initiation” (Lavigne et al, p. 437).

Rainfall Case Study: Merapi Volcano, Central Java

Merapi is a stratovolcano located in Central Java, Indonesia, characterized by relatively high channel slope and low riverbanks. Not only is it one of the most active volcanoes on Earth, it is also surrounded by a population of 1.1 million people, with about 200,000 people who “live at risk in areas prone mainly to pyroclastic flows and heavy tephra fallout (respectively the *forbidden zone* and the *first danger zone*), and 120,000 more live along the 13 rivers draining lowlands prone to lahars.” (Lavigne et al, p. 423). In the mid 1990s during a period of just over

six months, there were 21 recorded lahar events with a volume of about $1.6 \times 10^6 \text{m}^3$. This has made Merapi of particular interest and important to researchers.

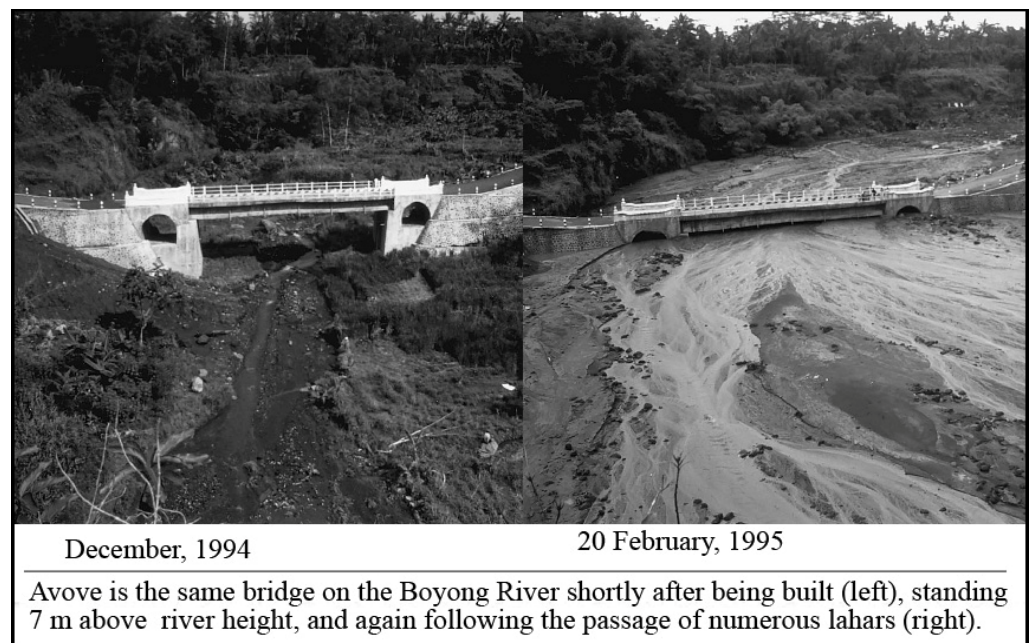


Figure 2. (Lavigne et al, 2002)

Merapi's lahars are almost invariably triggered by rainfall. The climate of Central Java is indeed wet, and experiences a strong monsoon season from November to April. Lavigne et al report measurements, of average annual rainfall over 15 years ranging from 2416 mm to 3253 mm and yearly amount ranging from 2000 mm to 4500 mm (p.434). As much as 80% of yearly rainfall occurs during the rainy season, and during the season's peak rainfall can reach 800 mm/month. On 25 November 1979, Merapi received 466 mm of rain in one day.

The 13 rivers flowing from Merapi range from 30-40 km in length, and their average channel slope is 9%. The upstream valleys are heavily eroded and fans of lahar deposits are found at the base of all downstream channels. Debris-flow material and pyroclastic-flow deposits are poorly sorted.

This case study shows that "the frequency of lahars at an individual channel depends on rainfall characteristics and on the total volume and grain size distribution of fresh pyroclastic deposits in source areas" (p.434). Lavigne et al report that rain lahars occur periodically for about 4 years following small to medium-scale eruptions and that rain-triggered lahars are expected to occur every year (p.434). Most large lahars at Merapi occur during this 4 year period.

Rainfall intensity thresholds of 40mm in 2 hours and 25mm in 1 hour have been proposed for Merapi. The time to initiate a lahar is typically quite short and many times lahar initiation corresponds with peak rainfall. Lahar surge peaks occurred about 10 minutes after peak rainfalls, as recorded at downstream stations. This indicates very little lag time before runoff is produced. This may be related to the frequency of rainfall events, suggesting very little recovery time between events and generally high ground saturation.

Since the mid-1500s Merapi has had 61 reported eruptions, at least 23 of which have had associated lahars. Almost all of these lahars were triggered by rain. This study states that intense rainfall, greater than 25 mm/h is needed to trigger a lahar, although the actual triggering intensity varies with rainfall duration and permeability of the ground surface.

Slope Failure.

Some of the most destructive and far-reaching lahars have been linked to volcano collapse, and subsequent landsliding. (Watters, Zimbleman, Bowman & Crowley, 2000, p. 957). “Volcanic slope failures develop from a combination of factors including steep slopes, weak materials, faults, dikes, high fluid pressures and seismic and intrusive activity.”(Watters et al p. 958). Depending on the physical characteristics of the slope, when a failure occurs the sliding mass may begin to flow and entrain further debris, particularly with the added presence of water. Other external factors include slope height, slope angle, and material properties of the surface such as mineralogy and grain size.

Volcanic slopes may inherently possess certain properties that make them susceptible to failure such as their high clay content, which is a result of hydrothermal processes and exposure of the rock to highly acidic, hot magma. “The hot, acidic fluids cause rock dissolution and formation of clay minerals along geologic structures (joints, faults and dikes) and lithologic boundaries” (Watters et al, p. 966). Not only does this replace stronger rock with weaker, clay-rich rock, but the clay rock may form in a downward inclination away from the volcano, thus weakening slope stability and providing “potential sliding planes or release surfaces for volcano collapse” (Watters et al, p.966).

An important aspect of slope stability is rock mass strength and the amount of jointing and fractures in the rock mass. This can be classified by the system of Rock Quality Designation (RQD), as illustrated.

The Rock Mass Rating (RMR) system makes use of this concept and includes factors such as lithology, weathering and alteration, joint spacing and orientation, ground water and more to assign numerical ratings to rock masses

that tell of their strength, cohesion and frictional behavior (Watters et al, p. 963). Studies using these concepts have indicated that the lowest RMR values can be found in hydrothermally altered volcanic rock, pyroclastic deposits, and along major discontinuities (Watters et al, p. 971).

“Strength information is necessary to better understand initial landslide processes and the mechanical properties of source materials for debris avalanches and lahars” (Watters et al, p. 973). There is limited strength data available for active volcanoes due to the logistical difficulties of field work in a potentially risky environment. To construct a full strength assessment of a volcano, rock structure data is required, and data must also be taken from pyroclastic deposits, interbedded units (rock found between strata of differing type) as well as individual lava flows.

$$RQD = \frac{\text{Total length of rock between fractures} > 10 \text{ cm length}}{\text{Total length measured}} \times 100\%$$

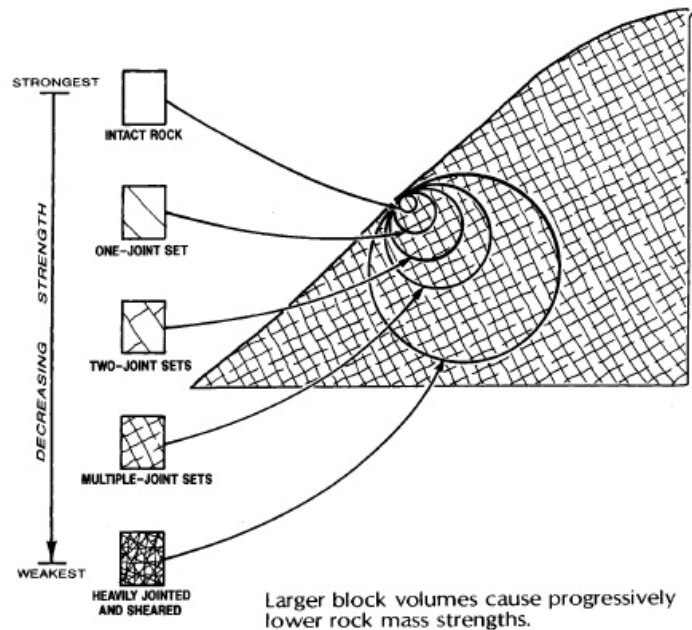


Figure 3: The rock mass concept (Watters et al, p. 962).

Watters et al state that “catastrophic collapse of the summit and (or) flanks of active stratovolcanoes is a normal process” (Watters et al p.973), and that many failures are attributed to large-scale landsliding. Massive and destructive debris flows or lahars have been linked to these large edifice collapse events, which are common to stratovolcanoes in general.

Slope Failure Case Study: Tungurahua Volcano, Ecuador

Situated on the Eastern Cordillera of the Ecuadorian Andes, Tungurahua is a large and eruptive volcano, made up of three volcanic edifices. (Hall, Robin, Beate, Mothes, & Monzier, 1999, p. 2). The volcano is noted for its steep sides and great changes in elevation. Tungurahua has experienced at least two events of sector collapse with accompanying debris avalanches. This type of event is extremely hazardous, having produced debris deposits covering at least 80km², with an estimated volume of 8km³ (Hall et al, p. 8). It is believed that current conditions may favour future collapse, which poses great threat to surrounding villages and a nearby hydroelectric dam and reservoir which is considered the second most important in all of Ecuador (p.3).

Tungurahua has experienced 17 known eruptions in four major eruptive episodes. Two of its three edifices have been partially destroyed by large sector collapses. The small village of Bayushig lies in the hummocky debris of their avalanche caused by the collapse of Sector II, and other towns lie among the surrounding terraces and abandoned stream channels. Avalanche breccia are frequently found (unconsolidated) in the lahar deposit which indicates that the lahar immediately followed the avalanche. “This flow was apparently the result of the mobilization of water and ice-saturated parts of the debris avalanche” (p.8). Mineralogical evidence suggests that an eruptive event accompanied or triggered the collapse.

Tungurahua's eruptive history has resulted in the formation of many large natural dams of water in the river valley below, made up of avalanche deposits. In the event of an eruption, these small, temporary lakes pose a significant source of water to mobilized pyroclastic material. "Lahars associated with collapse events generally form by the remobilization of water-saturated parts of the avalanche deposits or by the incorporation of water and snow" (p. 19). During or following an eruption, the dammed lakes may break out catastrophically, resulting in a violent displacement of a large volume of water.

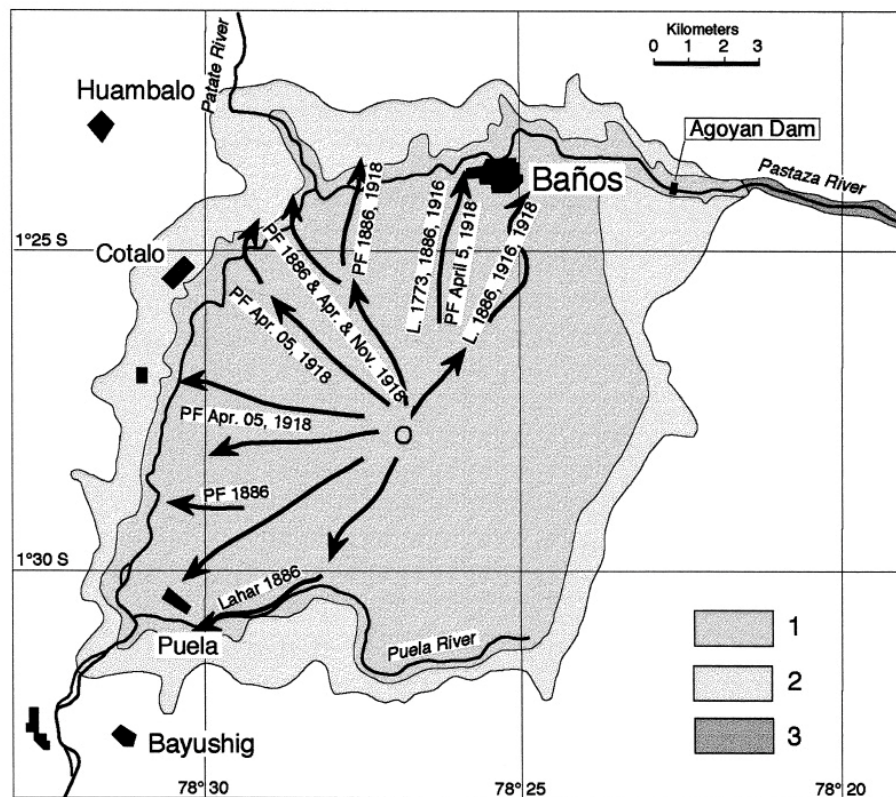


Fig. 4: Hazard map for pyroclastic flows and lahars, showing the main runouts followed by historic flows (PF = pyroclastic flows). 1 = High hazard for directed blasts and fallback pyroclastic flows over the whole area, and lahars in the valleys; 2 = minor hazard area for pyroclastic flows; 3 = high hazard for lahars in the lower Pastaza valley. (Hall et al, 1999)

The authors note the great hazard represented by Tungurahua's blocked drainage and suggest that some of the largest lahars in the volcano's history were likely a result of lake break-outs. "Tungurahua's (current) setting invites such a possibility: even if the next collapse is of

small volume ($<1 \text{ km}^3$), the resulting debris avalanche would likely refill the narrow Chambo Valley, damming it, which would probably generate another lake-breakout debris flow of significant proportions” (p.20). Furthermore, they indicate that future eruptions are to be expected and will be accompanied by the emission of pyroclastic flows and lahars.

Conclusions

The lahar-triggering impact of water cannot be understated. It is widely understood that rainfall is a significant control on lahar occurrence, and this is further quantified in the Merapi case study. Rainfall intensity and duration are of critical importance, particularly in a climate with such high precipitation and strongly seasonal patterns. Basin morphology is indeed an important factor, but perhaps secondarily so, as water is a necessary component for the formation of a lahar.

Slope failure can certainly trigger the formation of a lahar, as illustrated in the Tungurahua case study. This represents a larger and more catastrophic event than rain-triggered lahars, but seems to be a much more infrequent event. This is consistent with the magnitude-frequency concept that is common throughout geomorphic study. Simply put, large, catastrophic events occur infrequently and the most frequently occurring type of events are of smaller or moderate magnitude.

Together, the two areas of focus presented in this paper seem to serve as a conceptual example of the magnitude-frequency concept. While a lahar produced by a catastrophic slope failure may seem like an unlikely occurrence, the immense magnitude of such an event would certainly be of disastrous consequence. On the other hand, the impact of numerous rain-triggered lahars, especially giving consideration to the population of many of the world's volcanic regions, represents a very real and present danger,

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