LAHARS IN JAVA: INITIATIONS, DYNAMICS, HAZARD ASSESSMENT AND DEPOSITION PROCESSES

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ABSTRACT

Lahar has been applied as a general term for rapidly flowing, high-concentration, poorly sorted sediment-laden mixtures of rock debris and water (other than normal streamflow) from a volcano. Lahars are one of the most destructive phenomena associated with composite volcanoes, which are dominant in Java Island. Resulting deposits of lahar are poorly sorted, massive, made up of clasts (chiefly of volcanic composition), that generally include a mud-poor matrix. The aim of this research is threefold: to discuss the initiation of lahars occurrences, their dynamics, to assess the hazard and to analyse the deposition. Lahars are either a direct result of eruptive activity or not temporally related to eruptions. Syn-eruptive lahars may result from the transformation on pyroclastic flows or debris avalanches which transform to aqueous flows (e.g. at Papandayan in November 2002); They may be also generated through lake outburst or breaching (e.g. at Kelut in 1909 or 1966), and through removal of pyroclastic debris by subsequent heavy rainstorms. Post-eruptive lahar occurs during several years after an eruption. At Merapi, lahars are commonly rain-triggered by rainfalls having an average intensity of about 40 mm in 2 hours. Most occur during the rainy season from November to April. Non-eruptive lahars are flows generated without eruptive activity, particularly in the case of a debris avalanche or a lake outburst (e.g., Kelut). A lahar may include one or more discrete flow processes and encompass a variety of rheological flow types and flow transformations. As such, lahars encompass a continuum between debris flows and hyperconcentrated flows, as observed at Merapi, Kelut and Semeru volcanoes. Debris flows, with water contents ranging from 10 to no more than about 25% weight, are non-newtonian fluids that move as fairly coherent masses in what is thought to be predominantly laminar fashion. However, the relative importance of laminar versus turbulent regime is still debatable. Hyperconcentrated streamflows contain 25- to about 40%-weight-water; these flows possess some yield stress, but they are characteristically turbulent. Hazard-zone maps for lahar were produced for most of the the Javanese volcanoes, but these maps are on too small-scale to meet modern zoning requirements. More recently, a few large-scale maps (1/10,000 and 1/2,000-scale) and risk assessments have been completed for a few critical river systems at Merapi.

Key-words*: lahar, lahar deposit, hazard, flow behaviour, deposition, rheology.*

INTRODUCTION

Lahar is a Javanese term that means a rapidly flowing, high concentration, poorly sorted sediment-laden mixture of rock debris and water (other than normal streamflow and flood) from a volcano. A lahar belongs to a continuum of flow types which includes debris flows, hyperconcentrated streamflows, and mudflows. A

Figure 1. Difference between non-cohesive debris flow at Semeru, East Java in January 2002 (left), and cohesive debris flow (mudflow) at Papandayan, West Java, in November 2002 (right)

debris flow is a non-newtonian fluid with a sediment concentration ^{3} 60% volume or 80% weight (Smith and Lowe, 1991: Figure 1a). A hyperconcentrated streamflow has a lower sediment concentration which ranges from 20 to 60% volume (Vallance, 2000, Lavigne and Thouret, 2000). A mudflow is a cohesive, relatively fine-rich flow (Figure 1b), whose behaviour and sediment concentration (20-40%) are quite distinct (see discussion in Coussot and Meunier, 1996).

Because lahars are water saturated, both liquid and solid interactions determine their unique behaviour and distinguish them from other related phenomena common to volcanoes such as debris avalanches and floods. Rock fragments make lahars among the most destructive phenomena associated with composite volcanoes in Java; abundant liquid contained in them allows them to flow over gentle gradients and inundate areas far away from their sources. Between the 17th and 19th century, lahars were responsible for 17% of the people loss due to volcanic eruptions, essentially in Indonesia. During the 20th century, lahars took a toll of 31,500 victims, owing to two deadly disasters at Kelud (1919) in Java (Figure 2) and Nevado del Ruiz (1985) in Colombia. In 1909, post-eruptive lahars from Mt Semeru have had already seriously damaged the city of Lumajang.

The aims of this research are to discuss the initiation of lahars occurrences, their dynamics, to assess the hazard and to analyse the deposition processes at different volcanoes in Java. We used four volcanoes as representative examples of Javan volcanoes i.e. Merapi, Semeru, Papandayan and Kelud because their activities are relatively more dynamic compared than others.

Lahars can be produced in several ways. Primary lahars are syn-eruptive, that is deriving from pyroclastic flows and surges churning and melting snow and ice or generated by a crater lake expulsion during eruptions (e.g., Kelud in 1919, Galunggung in 1822; Figure 2). Most syn-eruptive lahars are generated when a drainage system is choked by a pyroclastic flow, a ‘wet’ pyroclastic surge or a debris avalanche, as examplified during the 2002’ eruption of

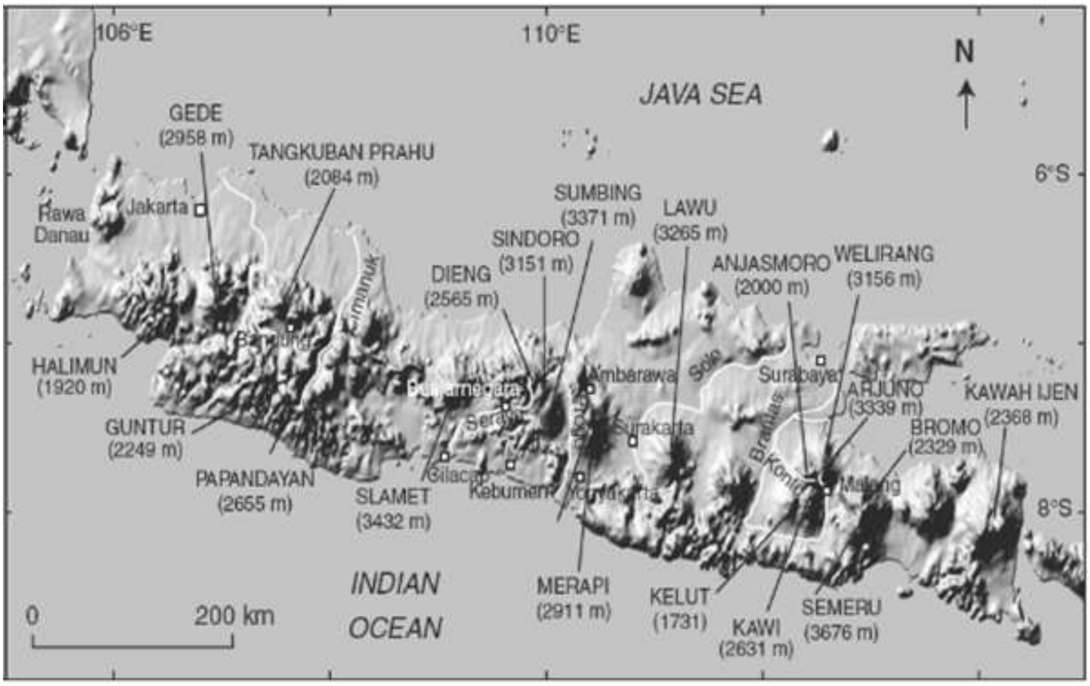

Figure 2. The location of main volcanoes in Java

Papadayan. During the Papandayan eruption in November 2002, repeated volcanic earthquakes, induced by a series of phreatic and phreatomagmatic explosions, triggered three main landslides on the caldera rim. One of the landslides was rapidly transformed into a debris avalanche, having a volume of 1.7 x 10^6 m^3. Moving outside the caldera rim, this debris avalanche entered a series of three landslide-dammed lakes and released a large volume of water to the River Cibeureum. The mixture of water and sediment generated a primary lahar that destroyed 245 houses.

The majority of lahars are secondary and post-eruptive, i.e. triggered by rainfall on loose pyroclastic material (e.g., Merapi in 1984 and 1994). Yet another set of secondary lahars are unrelated to eruptions when, less predictably, they occur through processes common to volcanic terrains, such as landslides or flank collapse and heavy rainfall on steep slopes (e.g., Semeru in 1981). Post-eruptive lahar occurs during several years after an eruption. At Merapi, lahars are commonly rain-triggered by rainfalls having an average intensity of about 40 mm in 2 hours. Most occur during the rainy season from November to April. Hazards that they pose to people and goods are enhanced by the fact that they can be triggered on volcanoes without any eruption.

Non-eruptive lahars are flows generated without eruptive activity, particularly in the case of a debris avalanche or a lake outburst. Lake outburst is commonly caused by the breaching of a crater wall which has been weakened by weathering), former explosive eruptions (e.g., Kelud on 29 january 1875), or by an earthquake. Rockfall or landslide entering a crater lake or a dam lake may generate a surge which can empty the lake.

METHODS

This paper is based on some research projects conducted by authors during several years on four Javan Volcanoes such as Merapi, Semeru, Papandayan and Kelud. We combined several methods such as secondary data analysis, field investigations, field instrumentations of channels at Merapi and Merbabu.

Lahars initiation and rainfall thresholds were analysed by correlate the minutely rainfall data and lahars occurrences from installed automatic rain gauges and Acoustic Flow Meters (AFM). We assessed the sediment concentration through repeated direct sampling. A heavy-duty plastic container was tossed into the flow at the end of a rope from the left river bank of the channel. The sampler was sunk into the lahar using a bamboo pole. Samples were transferred into a 10 l-graduated bucket, and the volume of sediment was measured after a 24-h period of deposition. Lahar dynamic can also be monitored by using novel instrumentation, such as video and cinematography with wire or ground-vibration triggers, ultrasonic (non-contact) water level recorders, various telemetry systems, and sampling devices for muddy water and debris. Acoustic Flow Monitors (AFM) and Real-time Seismic Amplitude Measurement (RSAM) were used in this work. Sedimentary facies analysis has been conducted by visual interpretation in the field on several slope profiles across the channels and completed by using grain size in laboratory.

Hazard assessment was conducted by using geomorphological investigations in order to delineate the lahar-prone areas on the SW flank of Merapi and the SE flank of Semeru volcanoes, and to produce six hazard 1/10,000 and 1/2000 scale maps for highly populated areas, such as the perimeter of Yogyakarta (Lavigne et al., 2000a; Figure 10). Micro-zonation was based on lahar scenarios in which four discharge categories correspond to four lahar-prone areas (area 1= d”200 m^3/s, area 2= 200-300 m^3/s, area 3= 300-500 m^3/s, and area 4= 500-700 m^3/s). The method encompasses: location, frequency, and scale of the past lahar events; measurements of the channel geometry, riverbed gradient, and degree of meandering in relation to possible lahar overflows, calculation of mean velocity, calculation of maximum flow discharge per section, and location of probable overflow points, based on empirical models for discharge assessment. Finally, risk assessment and maps were performed, based on enquiries to assess vulnerability and the cost of potential loss.

RESULT AND DISCUSSION

Initiation: Rainfall Intensities and Duration

Lahar genesis requires: (1) an adequate water source; (2) abundant unconsolidated debris that typically includes pyroclastic-flow and -fall deposits, colluvium, soil, etc., (3) steep slopes and substantial relief at the source; and (4) a triggering mechanism. Water sources include pore or hydrothermal water, rapidly melted snow and ice, subglacially trapped water, crater or lake water, and rainfall runoff (Vallance, 2000).

The triggering of secondary lahars depends firstly on rainfall intensity and secondly on the total amount and duration of rainfall, as evidenced at Mayon, Unzen, and Merapi (Rodolfo and Arguden, 1991; Lavigne et al., 2000a). At Merapi, rainfalls having an intensity of about 40 mm in 2 h

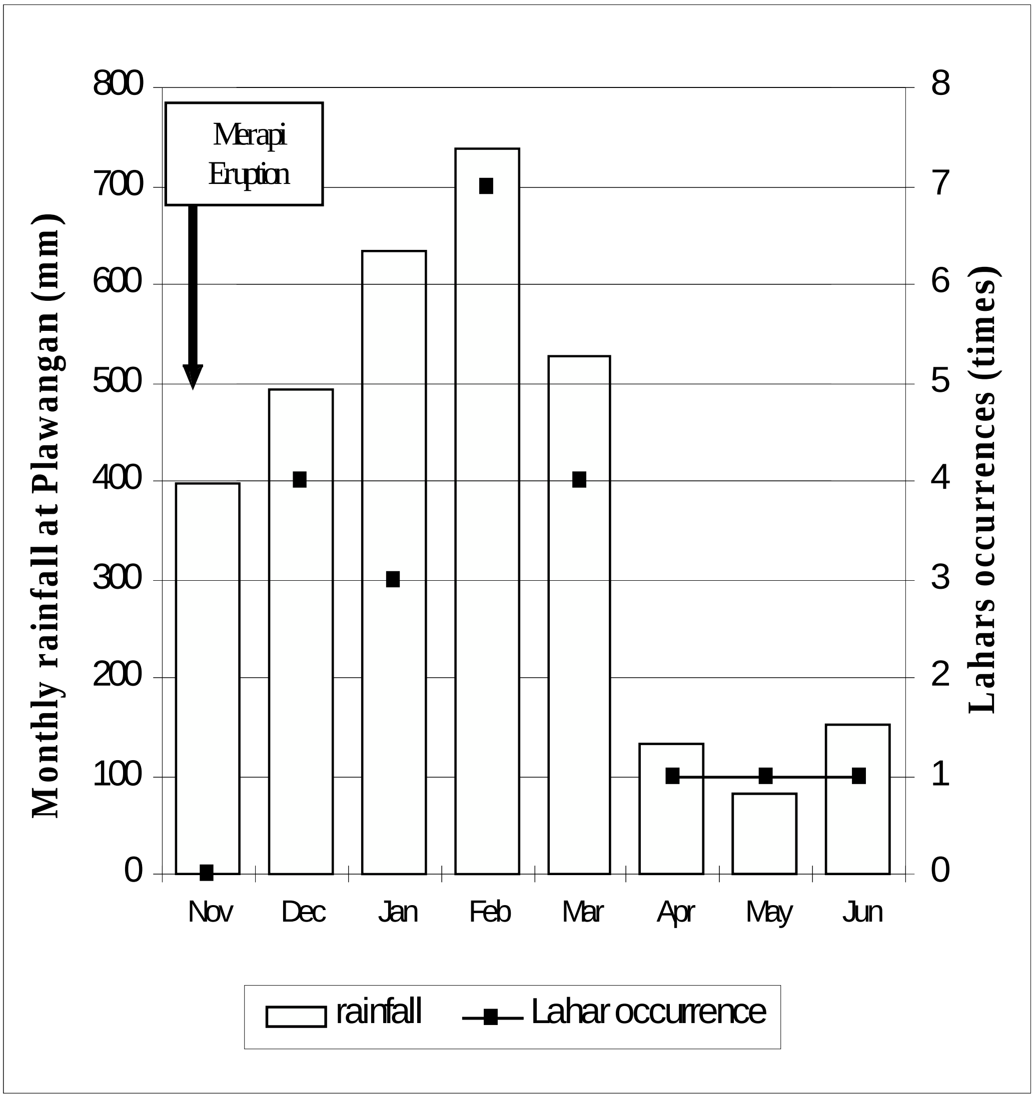

Figure 3. Monthly rainfall and lahars events in K.Boyong during the 1994-1995 rainy seasons.

commonly trigger lahars, mostly from November to April (Figure 3). Actual triggering-rainfall intensity can vary widely, due to such factors as rainfall duration and permeability of pyroclastic deposits. Rainfall thresholds for triggering lahars are not similar on volcanoes even if they are located in one climatic area, and can vary on one single edifice, because topography, windward side, and elevation exert an influence on advection and convection of air masses, hence on subsequent distribution of rainfall. In addition, the rainfall thresholds increase with time after an eruption, and depend on the geographical origin of rain-generating air masses with respect to the volcano sides.

At Merapi, two types of triggering rainfalls are commonly distinguished: local, stationary or orographic rainfall confined to slopes above 1200 m in elevation, and regional, migratory rainfall, that is transported from the NW or the SW. The lahars generated by stationary rainfalls are all small- or medium-scale debris flows (80,000 m^3 of sediment deposits), whereas all the large-scale debris flows (> 80,000 m^3 of deposits) are generated by migratory rainfalls (Lavigne et al., 2000a). The influence of ground saturation prior to a rain event can also be substantial: a critical parameter is the 'working rainfall", defined as total rainfall that precedes the lahar event for 7 days. The VSTC defined the correlation between working rainfall and 1-h rainfall for lahar initiation in the Putih River. The data distribution suggests the critical relationship as $y = 54 - 0.22x$ (Lavigne et al., 2000a).

Lahar Dynamics and Hydraulic Characteristics

Lahar velocity, discharge, and transport capacity are much higher than that of normal streamflows. The velocities range between 2.5 and 6 m/s on a slope of 4% (Merapi, 1994), and as much as 11 m/s on steep slopes (Kelud, 1990). Since 1980, all the rivers prone to lahars at Merapi have been dammed by Sabo dams, which slow down the lahars. Frontal mean velocity of debris flows in the Boyong River in 1994-1995 ranged from 2.7 to 3.6 m/s on slope of 6.6 %. The peak flow velocity is greater than the average velocity of the flow front: 5-7 m/s to 11 m/s in 1934 and in 1984, and as much as 15 m/s at Kaliurang on 20 May 1995. The maximum peak flow velocity is observed 1 to 5 minutes after passage of the flow front. The examples of measurement results of AFM and SSAM can be presented at Figure 4 and Figure 5 respectively.

Figure 4. Two example of application RSAM data in lahars occurrences monitoring in K. Boyong (Lavigne, et al, 2000b)

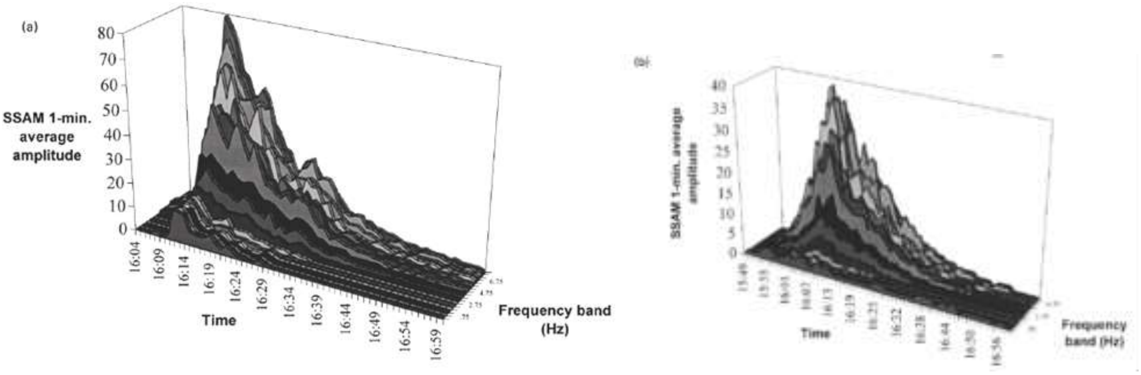

Figure 5. Data recorded by SSAM for lahar monitoring system at Kaliurang (Lavigne, et al, 2000b)

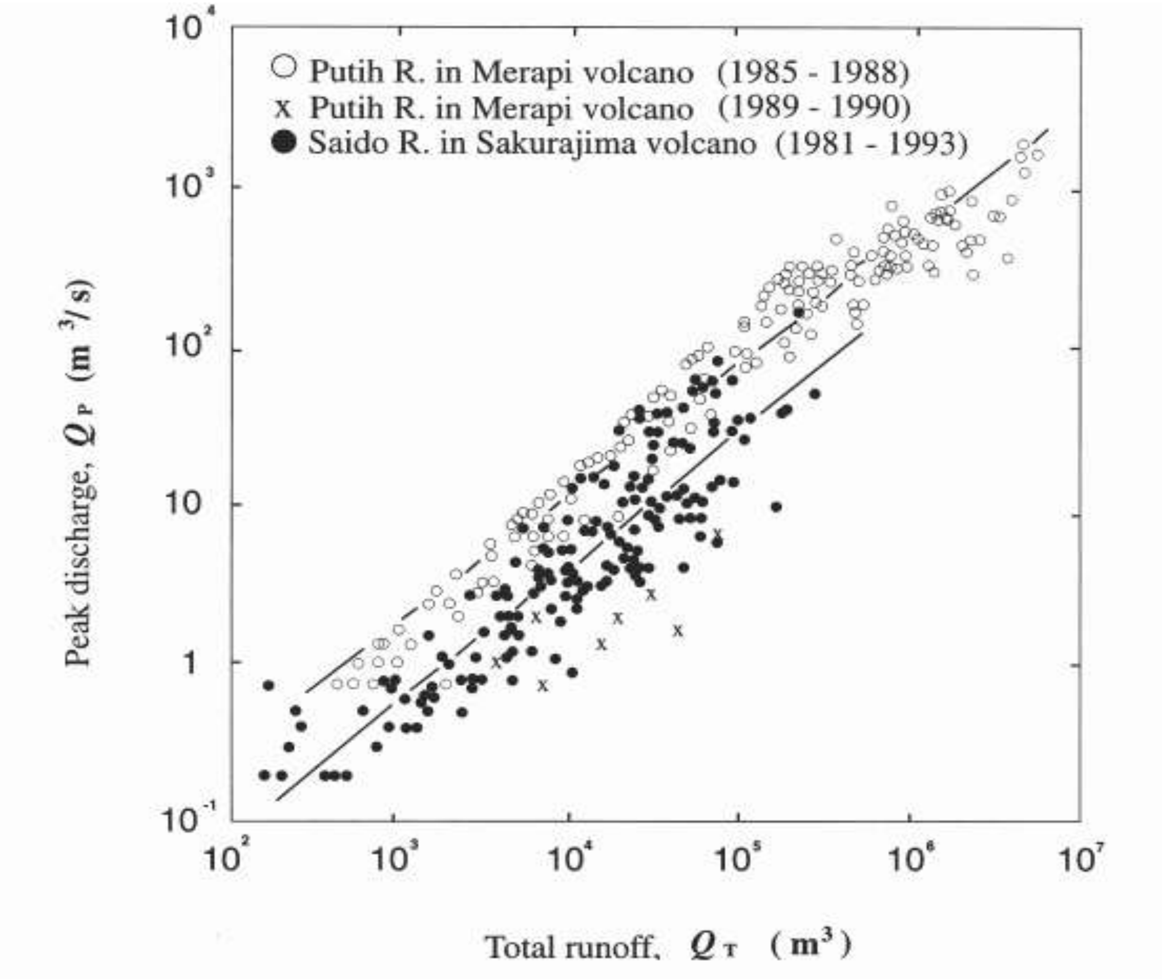

Figure 6. Relationship between peak discharge and total runoff of lahars and flashfloods at Mt Merapi and Mt Sakurajima (Jitousono et al., 1995).

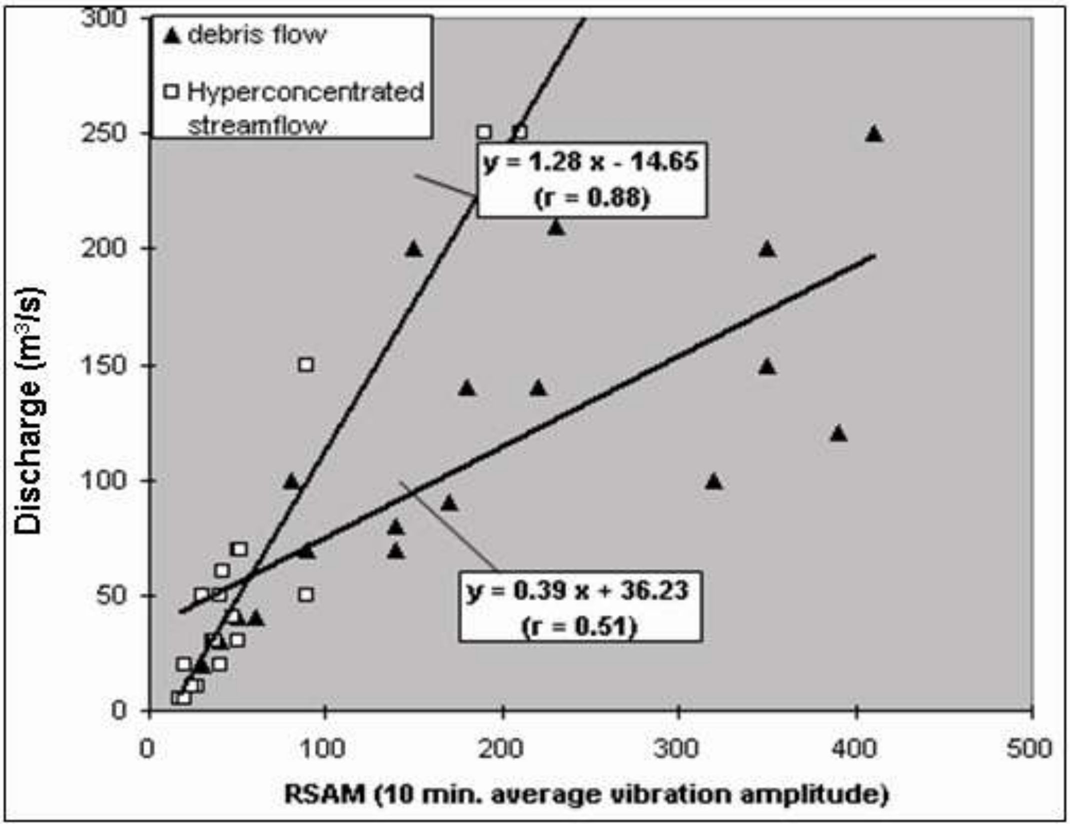

Figure 7. Correlations between RSAM data representing 10-min average amplitudes and the instantaneous discharge variations (Lavigne, et al, and 2000b)

The discharge of lahars is calculated by multiplying the cross-section area by the mean flow velocity. At Merapi, recorded peak discharges (Qp) range in magnitude from about 1 to about 2000 m^3/s in the Putih drainage in 1985-1990. The corresponding total runoff (Qt) in lahars and flood event ranges from about 500 to 5 million m^3 (Figure 6). A linear correlation links peak discharge and total runoff, with the regression as follows: $Qp=0.00558Qt^{0.831}$ (r= 0.977) (Figure 5). Maximum discharge per unit drainage area is 131 $m^3/s/km^2$ close to values recorded at Sakurajima, Japan (165 $m^3/s/km^2$). For small-scale lahars in the Boyong River in 1994-95, peak discharges ranged from 50 to 360 m^3/s, and runoffs varied from 7 x 10^4 to 5 x 10^5 m^3.

Lahars in Java are usually characterized by only one or two main pulses, but may have three events lasting 2 h or more. Lahars at Merapi are short-period events related to short-period rainfall (commonly 1 or 2 h). The lahar flow duration recorded in 1994-95 in the Boyong River at Kaliurang, 8 km from the vent, ranged from 30 min to 2 h 30 min. A lahar can show a succession of debris flows phases, hyperconcentrated flow phases, and sometimes transient streamflow phases. Pulsing of the flows may result from the variation of intensity during a storm, variable distribution of rainfall over the drainage basin, arrival of an additional lahar surge initiated in tributary, inherent flow instability, and natural self-damming and rapid release. Information on sediment concentration is necessary to discriminate between the different flow types, such as debris flows and hyperconcentrated flows. Quantitative data on sediment concentration is provided by the AFM system at Merapi. The ratio between the low and high acoustic frequency signal strength can yield a rough estimation of the flow concentration. Preliminary results obtained by AFM data processing and visual observations show that flow behaviour can change very rapidly over a few kilometres.

Non-contact detection instrumentation was installed on the slopes of Merapi during the first rainy season following the nuées ardentes of 22 November 1994 (Lavigne et al., 2000b; Lavigne and Thouret, 2002). These devices include RSAM, SSAM and AFM systems. Calibration of the various systems was accomplished by field measurements of flow velocities and discharge, contemporaneously with instrumental monitoring (Figs. 7 and 8). More than 50 lahars were generated around Merapi during the first rainy season following the 1994 nuées ardentes. They were relatively short events in the Boyong River, commonly ranging between 30 min and 1 h 30 min. Almost 90% of the lahars were recognized at Kaliurang village be-

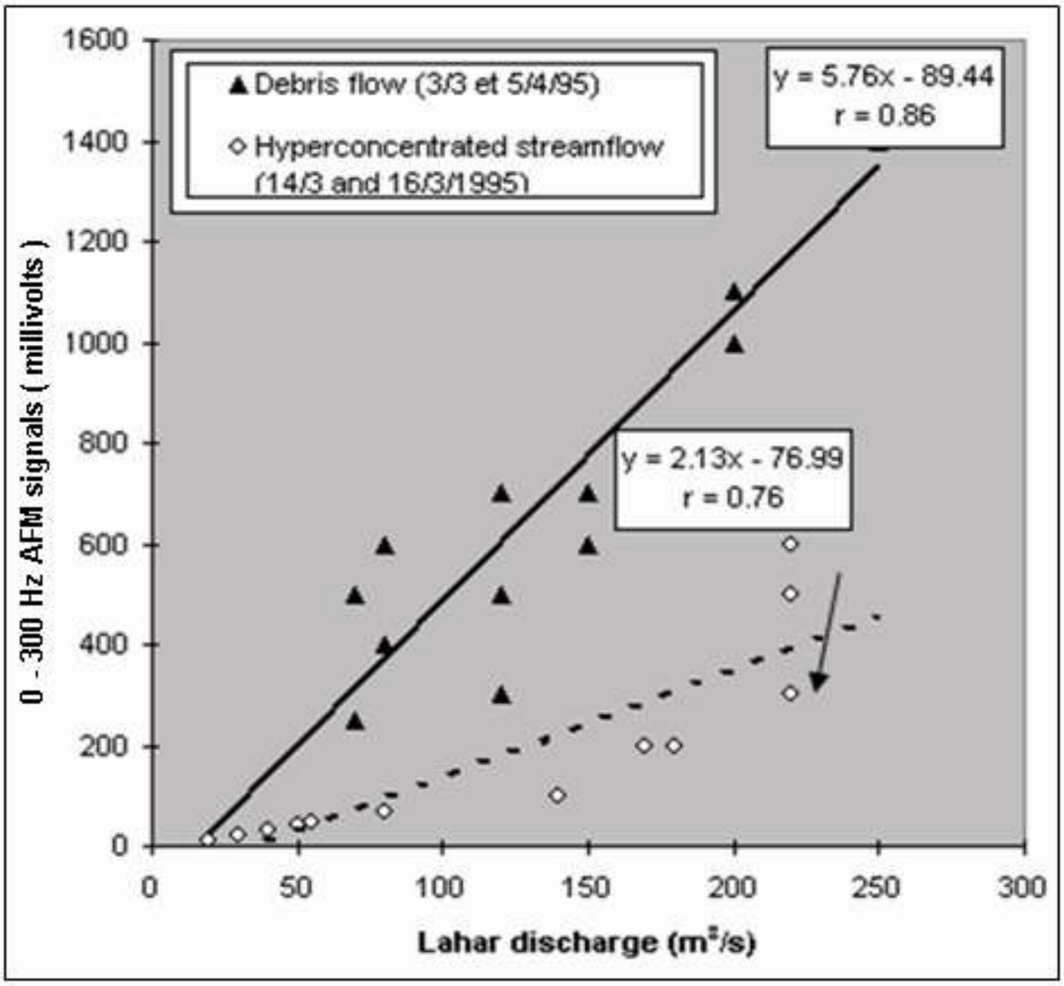

Figure 8. AFM low gain all frequency calibration data (Lavigne, et al, 2000b)

tween 13:00 and 17:30 h, due to the predominance of afternoon rainfalls (Figure 5). The observed mean velocity of lahar fronts ranged between 1.1 and 3.4 m/s, whereas the peak velocity of the flows varied from 11 to 15 m/s at Kaliurang. Peak discharges recorded in various events ranged from 33 to 360 m^3/s.

Flow behaviour

At Kelud, at least 33 post-eruption lahars followed the 10 February 1990 plinian eruption and deposited as much as 30 x 10^6 m^3 (Thouret et al., 1998). Subtle but significant sedimentologic differences in the deposits relate to four flow types. A) Early, massive deposits are coarse, poorly sorted, slightly cohesive, and commonly inversely graded. They are inferred to record hot lahars that incorporated pumice and scoria from pyroclastic-flow deposits, probably by rapid remobilisation of hot proximal pyroclastic-flow deposits by rainfall runoff. Sedimentary features, such as clasts subparallel to bedding and thick, inversely to ungraded beds, suggest that these flows were laminar. B) Abundant, very poorly sorted deposits include non-cohesive, clast-supported, inversely graded beds and ungraded, finer-grained, and cohesive matrix-supported beds. These beds display layering and vertical segregation/density stratification, suggesting unsteady properties of pulsing debris flows. They are interpreted as deposited from segments of flow waves at a middle distance downstream that incorporated pre-eruption sediments. Sedimentologic evidence suggests unsteady flow properties during progressive aggradation. C) Fine-grained, poorly sorted and ungraded deposits are interpreted as recording late hyperconcentrated flows that formed in the waning stage of an overflow and transformed downvalley into streamflows. D) Ungraded, crudely stratified deposits were emplaced by flows transitional between hyperconcentrated flows and streamflows that travelled further down valley as far as 27 km from the vent.

At Semeru Volcano, the 19 January debris flow peaked only 4 seconds after the passage of the 4.5 m deep boulder dam. The peak discharge (571 m^3/s) was the largest value recorded in the Curah Lengkong River since September 1998. The recurrence of such discharge is therefore estimated to be about 2 years in a period of "normal" activity of the volcano. The peak flow lasted five minutes, and then the flow rapidly decreased (Figure 9a): the discharge reduced to half of the peak only six minutes after the front, and then stagnated at 40 m3/s after the first 20 minutes of the lahar. A small secondary surge was recorded at 14:32. Although the 22 January hyperconcentrated flow peaked at 220 m^3/s only, its volume (in excess of 644 x 103 m3) exceeded that of the debris flow. Indeed, its discharge decreased more gradually during more than 1 h 30 min, and some secondary peaks were recorded (Figure 9b). The number of boulders carried by both lahars is also related to the flows discharge (Figure 9). Following the November 11 2002 eruption of Papandayan, three valleys became the routes that were used by rain-triggered lahars. One of these events, in the River Cibeureum Gede, has been studied in detail using a synoptic approach which has combined *in-situ* measurements during a flow, together with laboratory analysis of the sediments after the event. This small-scale cohesive lahar (maximum flow discharge 17 m^3/s; clay content in excess of 35%) carried at least 5,000 m^3 of sediment, including 2,333 boulders larger than 0.5 m (main axis).

Owing to abrupt initiation, flow instabilities, and particle segregation processes, lahars contrast with water floods in at least three ways: the flow behaviour is unsteady and non-uniform, the capacity of sediment transport is exceptional, and the effects on valley channels are severe, commonly exceeding the effects from non-volcanic debris flows. Past work on lahar mechanics used models based on the Bagnold or the Bingham theories. Recent work emphasizes that lahar consist of mixture of solids and fluids, which have mechanical properties distinct from either solids or fluids in isolation. Recent advances in theory and experimentation show that a lahar moves as a surge or a series of surges, driven by gravity, by porosity fluctuation, and by pore fluid pressures, in accordance with the Coulomb grain flow model. Grain size distribution and sorting control pore pressure distribution (Iverson, 1997).

Processes of deposition are complex and poorly known. Interpretation of massive and unsorted lahar deposits commonly ascribe the deposition regime to a freezing process. However, recent laboratory experiments have highlighted that debris flows deposits may result from incremental deposition processes (Major, 1997). The boundary between debris flows, hyperconcentrated flows and transitional flows may act and fluctuate within the flow itself. Several parameters play a role on this boundary: grain size distribution, physical and chemical composition of sediments, shear stress, and yield stress (Iverson, 1997). Therefore, caution should be applied when transport processes and lahar behaviour are inferred from the deposit thickness and the maximum clast size.

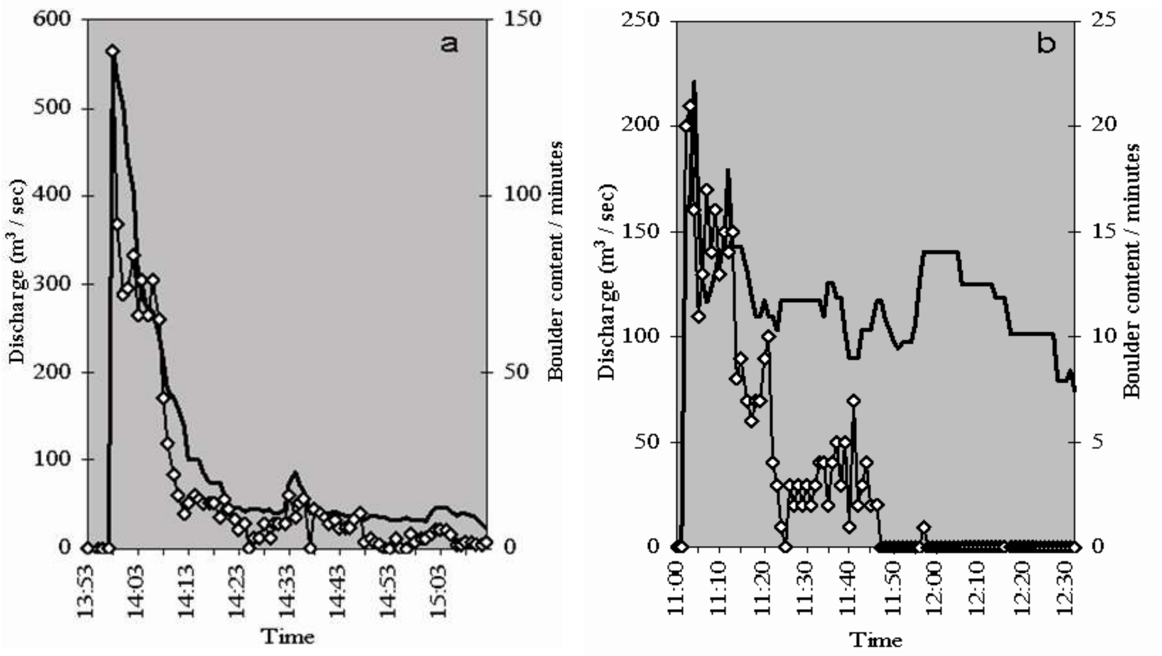

Figure 9. Time changes in the lahar discharge (black line) and the content of large boulder particles (white dots). (a) 19 January 2002 debris flow. (b) 23 January 2002 hyperconcentrated flow.

Hazard assessment in lahar-prone areas

Rock fragments make lahars among the most destructive phenomena associated with composite volcanoes; abundant liquid contained in them allows them to flow over gentle gradients and inundate areas far away from their sources (e.g., 400 km^2 around Mt Pinatubo and 286 km^2 in area around Merapi; Vallance, 2000; Rodolfo, 2000). The total elements at risk in the K. Boyong/ Code valley escalate to as much as 100 million US dollars (Lavigne et al., 2000).

Along the Code river, 144 ha are prone to lahar or flood hazard within area 3 (300–500 m^3/s), and 674 ha are threatened within area 4 (500–700 m^3/s). About

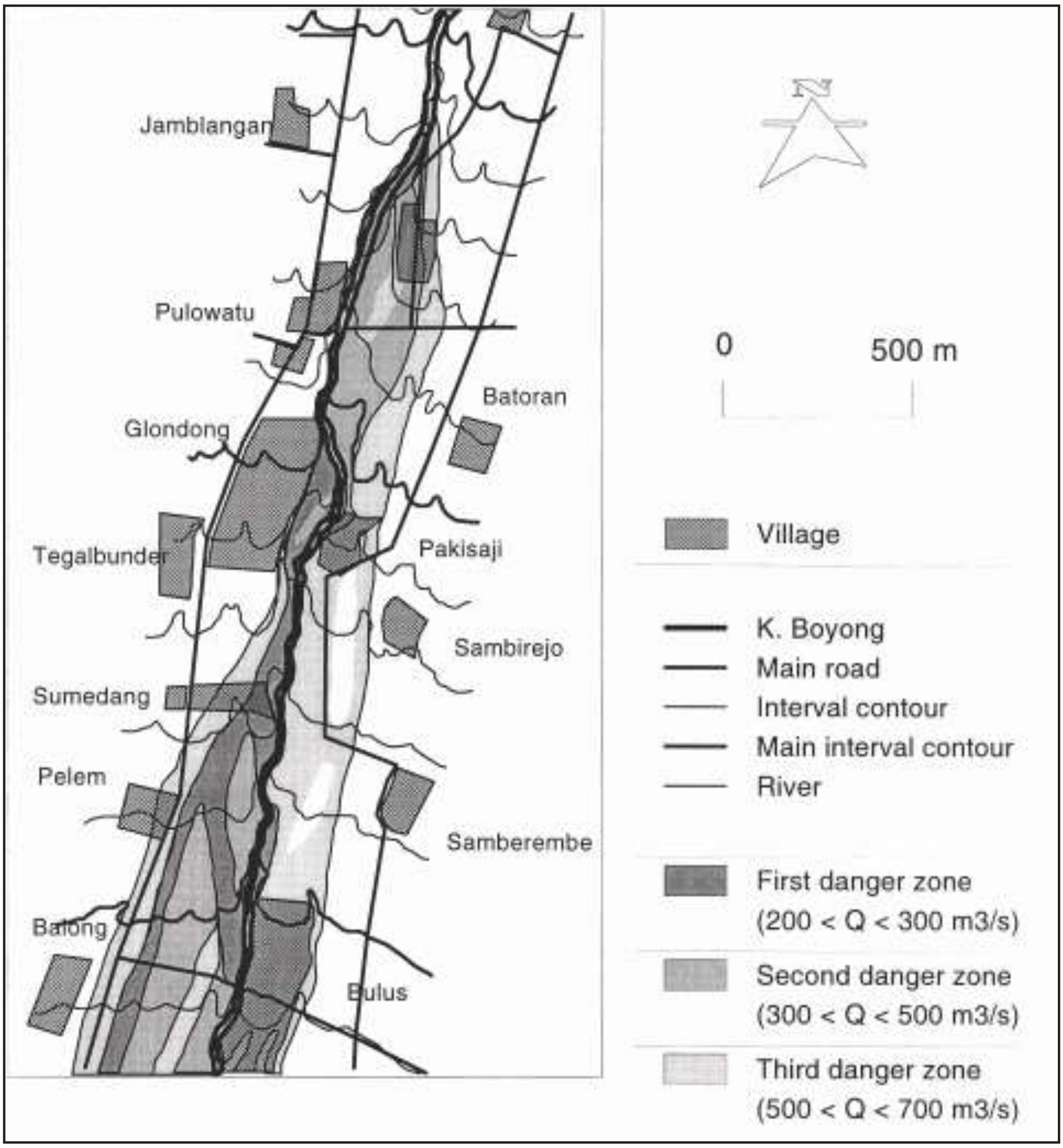

Figure 10. Lahar-hazard zones in the Boyong River. Several villages are threatened by lahars of relatively small magnitudes (Lavigne, et al, 2000a)

13,000 people live at risk along the river, where population density exceeds 5,600/km^2 (Figure 10). Population growth is 2% a year, partly due to urban migration from the Merapi countryside. The approximate value of likely loss for the upper level of hazard is 52 - 106 US $, mainly due to the high density of houses.

Sediment erosion and transportation processes, and budget

Lahar is one of the strongest erosive agents worldwide following a major eruption. Lahars remove deposits on volcano slopes and in channels at variable rates that depend partly on the volume of newly erupted pyroclastic debris, which is on the eruption magnitude. The lower the eruption magnitude, the quicker the removal of pyroclastic deposits, e.g., spanning one year after the small-scale 1994 eruption at Merapi but exceeding 10 years after the large-scale 1991 eruption at Pinatubo. Sediment yields reached 10^6 m^3 per km^2 during the first post-eruption year at Pinatubo, nearly one order of magnitude greater than the maximum sediment yield following the 1980 eruption of Mt St. Helens. Large volumes of lahar deposits in excess of 10^7 m^3 (Mt St. Helens, Pinatubo) result from the bulking capacity of primary lahars which scour and incorporate most of the material from former deposits that mantle valley slopes and channels. On volcanoes devoid of glaciers, as in Indonesia, lahars commonly flow shorter distances downvalley in the range of a few tens of kilometres.

Sediment yields on volcanic slopes that are covered by fine-grained tephra commonly range from 10^4 to 10^5 m^3/km^2/yr (Major, 2000). Annual sediment yield at Merapi and Semeru are among this range. At Merapi, a volume of about 2.5 x 10^6 m^3 of pyroclastic-flow deposits were emplaced in the upper reaches of the Boyong, Bedog and Bebeng Rivers in 1994 (Figure 10.). Based on the volume of the lahar sediments that were trapped by the five new check dams during the first rain season following the 22 November 1994 eruption at Merapi, an annual rate of sediment yield of 1.5 x 10^5 m^3/km^2 was calculated in the Boyong river catchments (Lavigne et al., 2000a; Lavigne and Thouret, 2002; Lavigne, 2002; Figure 11). At Semeru, sediment discharges were assessed from direct measurements on the lahars in motion.

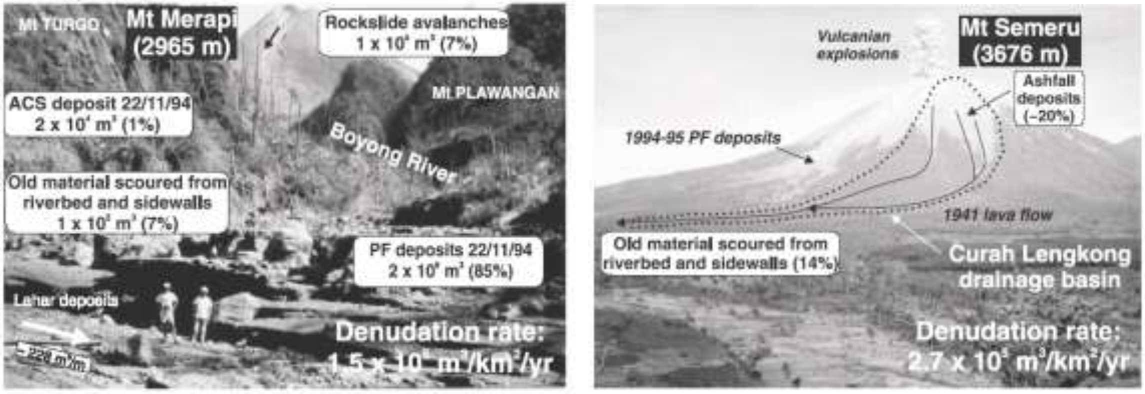

Figure 11. Visual representation of lahars sediment budget at Merapi and Semeru Volcanoes

In the Lengkong River, the rate of sediment yield in the year 2000 was estimated at 2.7 x 10^5 m^3/km^2. In both cases, the efficiency of the erosion does not result from a large volume of pyroclastic deposits following each eruption, but is a consequence of the yearly return period of the lahars. Daily vulcanian/strombolian explosions at Semeru provide a more continuous and voluminous sediment supply than dome avalanching at Merapi. But the magnitude of lahars decreases exponentially since the last effective eruption, and corresponding sediment yields decrease in a similar fashion. The decline of lahars is mainly caused by progressive loss of source pyroclastic debris, by the improvement in infiltration, and decrease in runoff on hillslopes previously mantled with tephra but rapidly covered with vegetation.

Sedimentary Facies

A wide range of facies may be generated from a single flow, which may transform downvalley from debris flow to hyperconcentrated flow. Non-cohesive debris flows (<5% clay/sand+silt+clay) and (or) grain flows commonly display such a trend. In contrast, mudflows and (or) cohesive debris flows (>5% clay/sand+ silt+clay) show no significant change downvalley (Scott, 1988; Scott and Vallance, 1997. A lahar deposit commonly forms one massive bed or a succession of stratified beds, either normally graded or inversely graded; toward the base, some beds show a thin, texturally fine-grained zone termed sole layer. Lahar deposits are poorly sorted, massive, and made up of clasts (chiefly of volcanic composition) that generally include a mud-poor matrix. At Merapi, textures are typically sandy gravel or gravely sand, because the source material is coarse block-and-ash debris from 'Merapi-type' pyroclastic flows. The debris flow deposits are commonly non cohesive, except in the Woro channel, due to the hydrothermal material source in the Woro solfatara field. Proportions of vitric, crystal, and lithic components of the lahar deposits help to discriminate the type of juvenile pyroclasts that feed the lahars and the amount of incorporated non-juvenile material. At Papandayan, West Java, lahar materials are usually cohesive and dominated by the silt and clay materials.

CONCLUSIONS

Lahars encompass debris flows, hyperconcentrated flows, and transitional flows. The triggering of secondary lahars depends firstly on rainfall intensity and secondly on the duration of rainfall and 'working rainfalls'. Lahars are usually characterized by one or two main pulses, but may have more events lasting 2 hours or more. Data of Real-time Seismic Amplitude Measurement and Acoustic Flow Monitoring systems were correlated with instantaneous flow velocities and discharges measured in the field at Merapi.

Average annual rate of sediment yield (1.5-2.7 x $10^5 m^3$/year) measured in the catchments of the Boyong River at Merapi and of the Lengkong River at Semeru is well above typical background on volcanic mountains. Sediment budget on active volcanoes are usually calculated from remote sensing or field data of yearly frequency, which do not take into account the geomorphic changes of the channel and of the unsteady transitional zone between two field surveys. Therefore, such methods are debatable because they tend to underestimate the erosion rates on active volcanoes.

Interpretation of massive and unsorted lahar deposits commonly ascribe the deposition regime to a freezing en masse process. However, recent laboratory experiments have highlighted that debris flows deposits may result from incremental deposition processes. Owing to abrupt initiation, flow instabilities, and particle segregation processes, lahars contrast with water floods in at least three ways: the flow behaviour is unsteady and non-uniform, the capacity of sediment transport is exceptional, and the effects on valley channels are severe. Recent advances in theory and experimentation show that a lahar moves as a surge or a series of surges, driven by gravity, by porosity fluctuation, and by pore fluid pressures, in accordance with the Coulomb grain flow model.

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