Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **30**, 1663–1674 (2005)
Published online in Wiley InterScience (www.interscience.wiley.com). **DOI:** 10.1002/esp.1225

Analysing the relation between rainfall characteristics and lahar activity at Mount Pinatubo, Philippines

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Received 12 January 2004;
Revised 4 December 2004;
Accepted 31 January 2005

Abstract

The eruption of Mount Pinatubo in June 1991 altered the conditions of the surrounding river catchments. Pyroclastic flows and tephra fall were deposited over extensive areas, stripping off the forest cover and burying drainage divides. These recent deposits are very loosely consolidated and generally consist of sand-sized particles, which commonly mobilize into lahars in response to rainfall of a certain magnitude. Several devastating lahar occurrences have buried settlements covering tens to several hundred square kilometres in a single event. Correlation of storm rainfall intensities and durations with lahar activity as recorded by acoustic flow monitors is used to investigate trends in the initiation conditions for lahar activity. This research confirms that the relationships of rainfall intensity and duration with lahar initiation threshold values are not linear but rather approximate a power relation. Different relations were found for lahar initiation in different years, from 1991 to 1997, as a result of the dynamic changes in hydrologic and geomorphic conditions of the affected catchments. Data from acoustic flow monitors are used to distinguish debris flow and hyperconcentrated flow activity from that of muddy water. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: lahar; pyroclastic flows; Mount Pinatubo; debris flow; rainfall threshold

Introduction

After the June 1991 eruption of Mount Pinatubo in the Philippines, approximately 6 km^3 of loose volcanic sediments (pyroclastic flows) were deposited on the upper slopes around the volcano (Scott *et al*., 1996) The deposition of this large volume of material resulted in significant changes in the physical attributes of the affected areas, such as topography, infiltration capacity, catchment size, and the availability of erodible material. With the altered conditions of the slopes, even small amounts of rainfall could trigger lahars. Depending on the rainfall intensity and duration, lahar flows could be single short events or flows that last for several hours or even days.

The runoff or channel flow associated with the lahars differs considerably from normal to muddy stream flow in the sense that it consists of more than 20 per cent sediments. Lahars are rapidly flowing mixtures of rock debris and water other than a normal stream flow (Smith and Fritz, 1989). The rheological characteristics of lahar flows can be categorized into debris flows and hyperconcentrated flow based on the ratio of sediment to water content measured in volume percentage or weight percentage (Pierson and Costa, 1987). Hyperconcentrated flows have a sediment to water ratio between 20 to 60 per cent in volume and 40 to 80 per cent in weight. Debris flows are considered to have greater volumetric and weight ratios than hyperconcentrated flows. Their flow is so dense that it produces vibrations in the channel that can be recorded on seismographs and acoustic flow sensors. These lahars caused significant channel bank erosion and deposition in the lower settlements more than 50 km downstream.

In order to give significant warning to low-lying villages, it is important to investigate the relation between rainfall intensity and magnitude conditions with the occurrence of lahar flow events. The final goal would be to derive rainfall threshold values that can give insight into the different responses from varying catchment conditions. Likewise by studying the magnitude of the recorded vibrations brought by the flow, the types of phenomena generated can be determined, as debris flows and hyperconcentrated flow will have different speeds and behaviour than muddy stream flow.

Objective

The objective of this work is to study the relation between lahar initiation and rainfall intensity/duration in order to derive threshold conditions for lahar activity that can be used as the basis of a warning system. Numerous lahar events immediately after the 1991 eruption indicate that there are several different catchment conditions that affect the triggering conditions through time. Most lahars at Mount Pinatubo are triggered by rainfall that most frequently occurs during the rainy months from June to November. Other triggering mechanisms for lahars include lake breakout and landslides caused by secondary explosion on still-hot pyroclastic flow deposits. The latter events were not considered in the analysis. Studying the rainfall–lahar trends for each year is necessary because the catchment conditions are very dynamic over time. Stream piracy and extremely high erosion rates characterize these changes. The rheology of lahars, i.e. debris flow to hyperconcentrated flow, is evaluated from the installed flow sensors.

Study Area

In total eight major catchment areas were affected by the 15–16 June 1991 pyroclastic flows around Mount Pinatubo. This study focuses on the two contiguous catchments that are located on the east side of the volcano, namely, Pasig and Sacobia (Figure 1). These two catchments were heavily monitored during the lahar crisis because these contain highly populated and developed areas in the downstream part, which could be affected by lahars generated from these

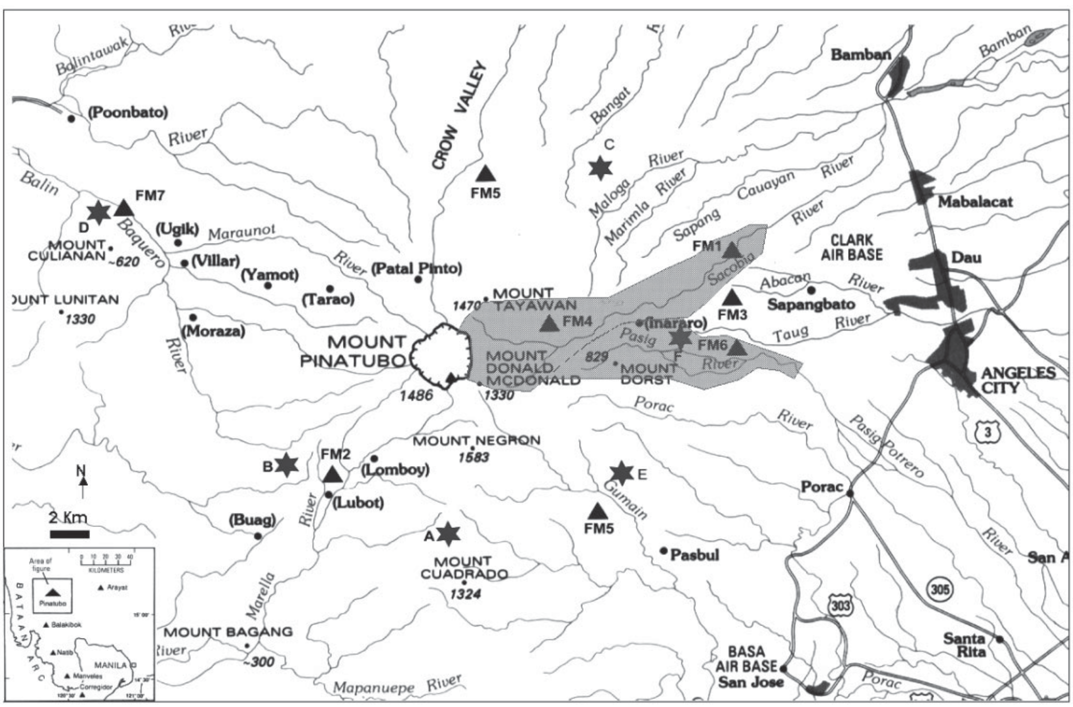

Figure 1. Overview of the Mount Pinatubo area, with the location of the Pasig and Sacobia catchments (shaded area), the installed rain gauges (shown as stars) and the flow sensors (triangles). For this study data were used from rain gauges A, C, E and F, and flow sensors FM1 and FM6. Flow sensor FM4 was not used due to large changes in channel location. Flow sensor FM3 was not used because it was located along a channel that did not experience lahars after the first year following the 1991 eruption, due to stream piracy in the upper catchment.

upper catchments. The two catchments together have a total upper area of 57 km^2, and were covered by a total volume of 1·15 km^3 of pyroclastic flow deposits in 1991 (Scott *et al*., 1996). There was a significant change in the catchment area in October 1993 due to the occurrence of large-scale landslides triggered by secondary explosions in the thick and hot pyroclastic-flow deposits which resulted in substantial impacts in the rainfall–lahar response and lahar delivery (Daag, 2003).

Methods

To study relationships between rainfall and the initiation of lahar flows, a network of telemetered rain gauges and flow sensors was installed on the different upper catchments (Figure 1). The rain gauges use a tipping bucket to measure rainfall. For every 1 mm of rainfall, the bucket tips and an electronic signal is telemetrically sent in real time. The flow sensor uses a rugged Mark L10-AR geophone that measures vertical ground accelerations or vibrations, with recorded units of $cm/s \times 10^{-6}$ or acoustic flow units (AFU). During a lahar flow, the sensor records three frequency bands simultaneously: broad band (10–300 Hz), low band (10–100 Hz) and high band (100–300 Hz) (Hadley and Lahusen, 1993). The sensors were used in Redoubt Volcano in 1990 and Merapi Volcano in 1994 (Hadley and Lahusen, 1991; Lavigne *et al*., 2000). Electronic data from both the rain gauges and flow sensors are received by the central computer at the volcano observatory located 20 km east of Mount Pinatubo crater. Rainfall data are transmitted either every 30 min or every 10 tips during heavy rainfall. The flow sensor data are transmitted once every 30 min on normal mode or every minute when a signal has passed a certain preset threshold (e.g. 10 AFU).

A total of six rain gauges were installed at locations around the pyroclastic-flow deposit to characterize conditions in the different catchments, and are mostly located on the upper slopes accessible only via helicopters (see Figure 1). Eight flow sensors were installed in the middle reaches of the catchments along active lahar channels. The sites were several kilometres upstream of the nearest settlements in order to enable early detection of lahar flows so that a warning could be issued with sufficient lead-time. Sites were chosen to be as close as possible to the lahar channel but safe enough not to be affected by erosion (Bautista *et al*., 1991; Marcial *et al*., 1996).

In order to determine rainfall conditions that are required to trigger lahars, we correlated rainfall data with flow sensor data. Both instruments must work in tandem in order to validate the timing of rainfall and the lahar-flow events. To validate the occurrences of lahars, the flow sensors are calibrated while observing active lahars in the field. Different lahar channels will have different calibration factors. The fundamental variations in actual flow versus recorded flow from the sensors are associated with the distance of the sensor to the active flow. In the field set-up, every sensor is located at a different distance from the channel since the installation is dependent on the topography (required for line of sight for data transmission). Variation also exists in flows where the distance of active lahars to the sensor changes through time as a result of channel migration.

It has been generally known that, depending on the rheology of lahars, the recorded vibration signals differ. From the three bands recorded, it has been noted that lahar signals are concentrated in the low bands (10–100 Hz). For this reason most of the instrumental lahar monitoring has used this band (Tuñgol and Regalado, 1996; Arboleda and Martinez, 1996; Lavigne *et al*., 2000). The reason for the concentration of lahar information in the low bands is that lahars carry large amounts of sediment and boulders that produce significant vibrations along their passage. Lahars such as debris flows and hyperconcentrated flows are better registered in the low bands, whereas normal to muddy stream flows give higher signals in the high bands (100–300 Hz). With this set-up, we can classify the flows as either debris flow and hyperconcentrated flow or as muddy to normal streamflow.

In selecting triggered lahar events, only the low bands were given emphasis, and in order to get the approximate rheology of the flow, the corresponding high band signals were also correlated. A record from a flow sensor was classified as lahar when it had recorded at least 100 AFU and was sustained for at least 15 min. Below this threshold signal, the flow could be very low and very diluted. Events should be triggered within 5 to 200 min at the start of the rainfall (Figure 2).

All of the data recorded between 1991 and 1997 from the two catchments were analysed, resulting in about 450 events that exceeded the threshold conditions by analysing either rainfall only or events detected by flow sensors. However, not all events have paired records, i.e. with rain gauge together with flow sensor data. This is caused by data gaps due to extreme difficulty in the maintenance of the instruments. Also serious problems were encountered in the transmission of the data to the central computer due to interference with other radio signals, which produced unsystematic data errors that had to be filtered out. After filtering all the data, there are 286 events that have records in tandem. A typical example of an event is shown in Figure 3. Some problems were encountered with the saturation of the signal in the low frequency band, during large debris flows; however, these did not influence the final result.

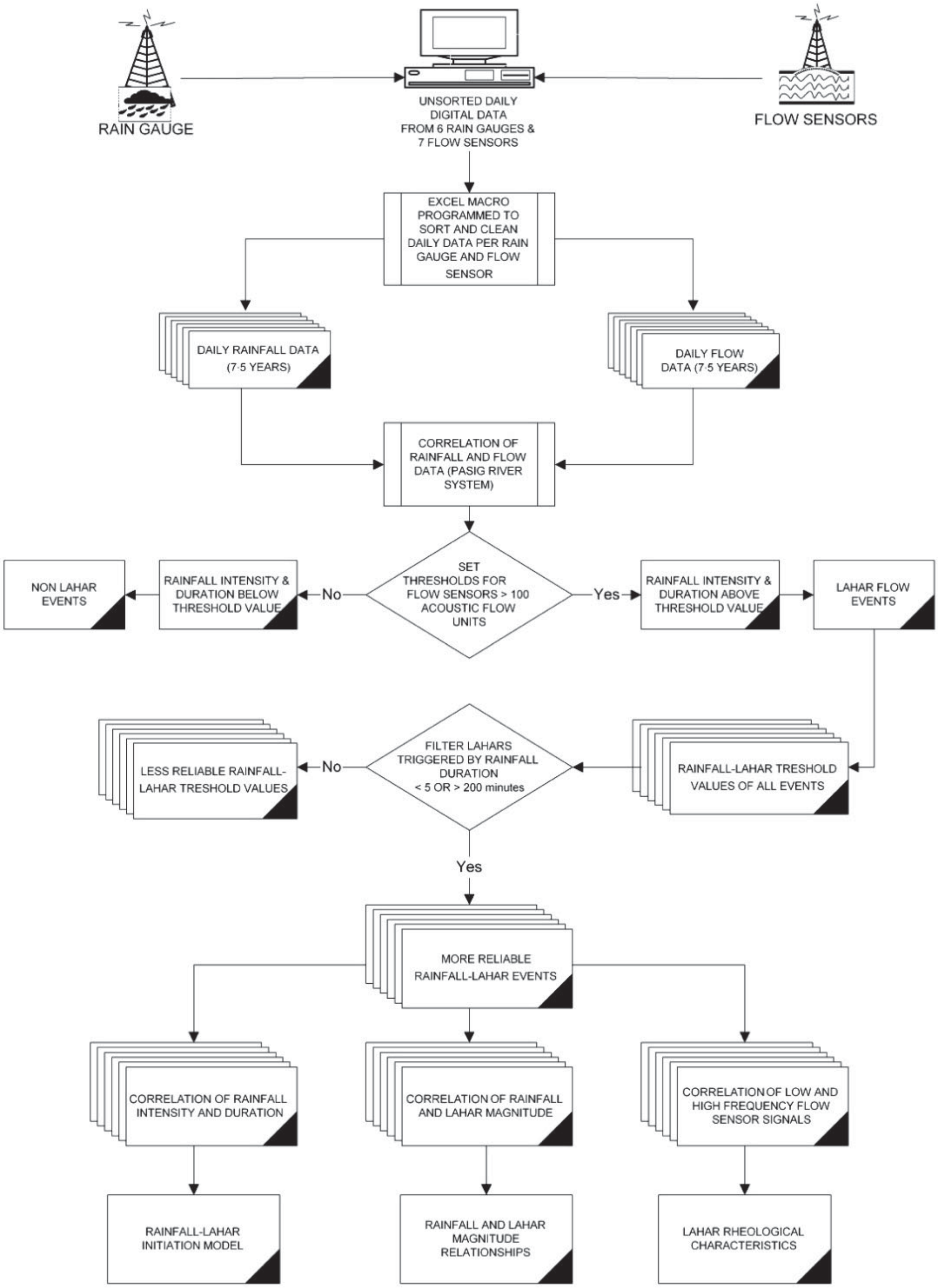

Figure 2. Summary of the procedure for using automated rain gauge and flow sensor data in analysing lahar-triggering rainfall relations.

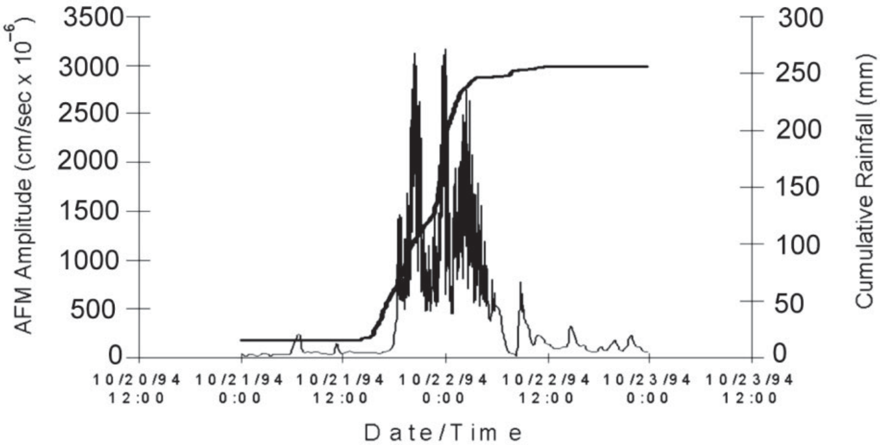

Figure 3. Rainfall characteristic of a strong typhoon (Typhoon Katring, on 21 and 22 October 1994). Total rainfall was 250 mm lasting for 22 hours. Lahar activity continued for almost 24 hours.

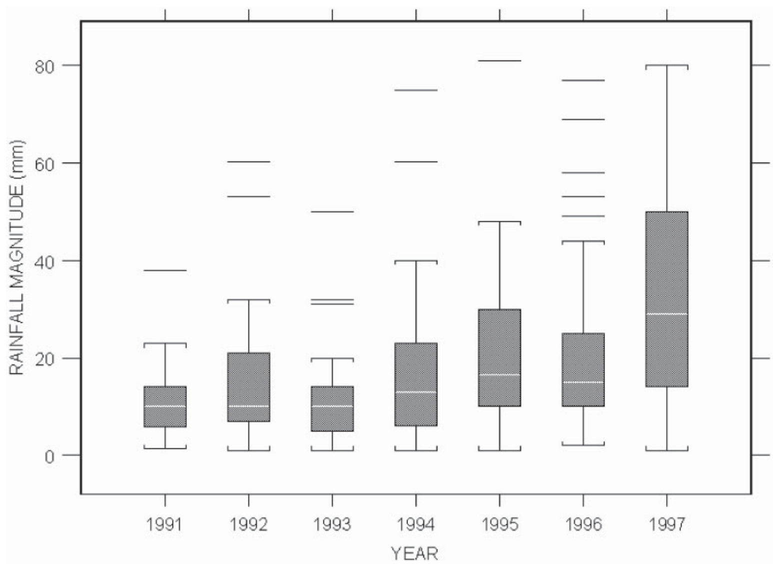

Figure 4. Box plot diagram of different lahar-triggering rainfall magnitudes.

Results and Analyses

Rainfall magnitude using box plot

One way to analyse the various rainfall–lahar relations is to summarize the data and plot the values in mean, median, quartiles and ranges, and these can be represented in a box plot (Figure 4). Figure 4 shows the summaries calculated from the minimum amount of rainfall that triggered lahars. The length of the box describes the inter-quartile range (IQR). The white line inside the boxes indicates the median value. The whiskers depict the data range and are projected at 1·5 distance from the IQR. The offset bars show extreme values, which may suggest outliers or just extreme values that can occur naturally under the influence of other factors. The graph shows different spreads for different years and to some extent with larger variations of IQRs. Most of the median values are skewed to the lower end of the box, with average values of 13 mm of rainfall magnitude for all data. The median is a better indication of the average values since it is not heavily affected by extreme values (outliers). From Figure 4 it can be concluded that the median values and the spread of the lahar-triggering rainfall amounts vary each year. This can be explained by the

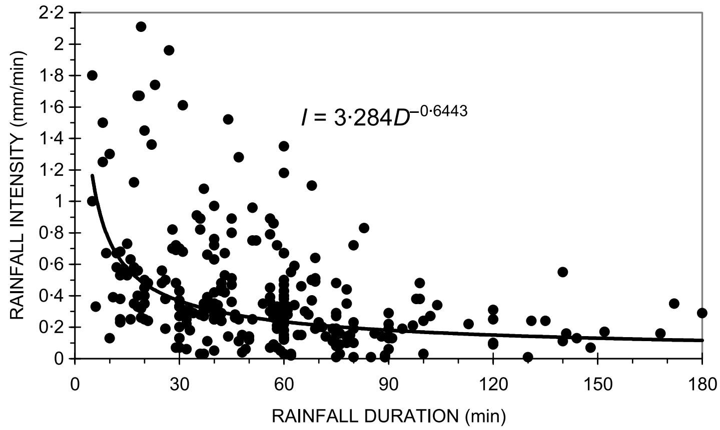

Figure 5. Plot of rainfall intensities (I) and durations (D) for lahar-triggering rainstorms over a seven-year period (1991–1997). Heavy line shows power relationship for the data ($r^2 = 0{\cdot}18$).

significant change in the physical conditions of the watershed due to extensive erosion and, more importantly, to the stream piracy events (Daag, 2003).

Rainfall intensity–duration trends for lahar-triggering storms

On many volcanoes, it has been demonstrated that storm rainfall intensity and duration are the main factors in lahar generation (Lavigne *et al.*, 2000). It has been reported that the relationships of rainfall intensity and duration with lahar initiation are not linear (Rodolfo and Aruguden, 1991; Arboleda and Martinez, 1996; Tuñgol and Regalado, 1996; Lavigne *et al.*, 2000), but rather approximate a power relation of the form:

$$I = cD^{-b}$$

where I = rainfall intensity, D = rainfall duration and c and b are constants.

For the Mount Pinatubo data, the storm rainfall intensities and durations that led to lahar events and that have paired correlations, are plotted in one graph (Figure 5) and a regression curve was fitted. The relationship between rainfall intensity and duration can be defined by:

$$I = 3{\cdot}284D^{-0{\cdot}663}$$

This relationship is an approximation of the threshold rainfall intensity and duration that can initiate lahars. From this equation, a minimum of 0·33 mm/min rainfall intensity with a minimum duration of 30 min or 0·22 mm/min in 1 h would lead to lahar activity. The relationship is not very significant ($r^2 = 0{\cdot}18$) and cannot be used as the straightforward basis of a lahar warning system, as lahars are triggered under a wide variety of rainfall conditions (Figure 5). Unfortunately, due to the problems mentioned earlier with the telemetric system, no complete record could be obtained that would have allowed evaluation of the relation between rainfall events that did cause lahars and those that did not, or would have taken into account the effect of antecedent rainfall.

Variation in rainfall–lahar triggering conditions by year

Yearly records were reviewed in order to determine the changes in rainfall–lahar triggering trends that have occurred as a result of changes in catchment conditions over time. Figure 6 shows the regression lines plotted for the yearly records. The individual regression lines show the time in minutes and the required rainfall intensity to trigger lahars. In some years, there are fewer data points, particularly in 1991 and 1997. The 1991 data set started in October 1991, which is almost at the end of the rainy season. Although the instruments were installed in early August, there were only a few records before October. In the period from 1992 to 1996, more lahars were generated. In 1997, although the instruments were in good condition, fewer lahars were generated, even with relatively stronger rainfall. In 1998, most of the recorded events are muddy stream flows with a sediment concentration of less than 20 per cent by volume.

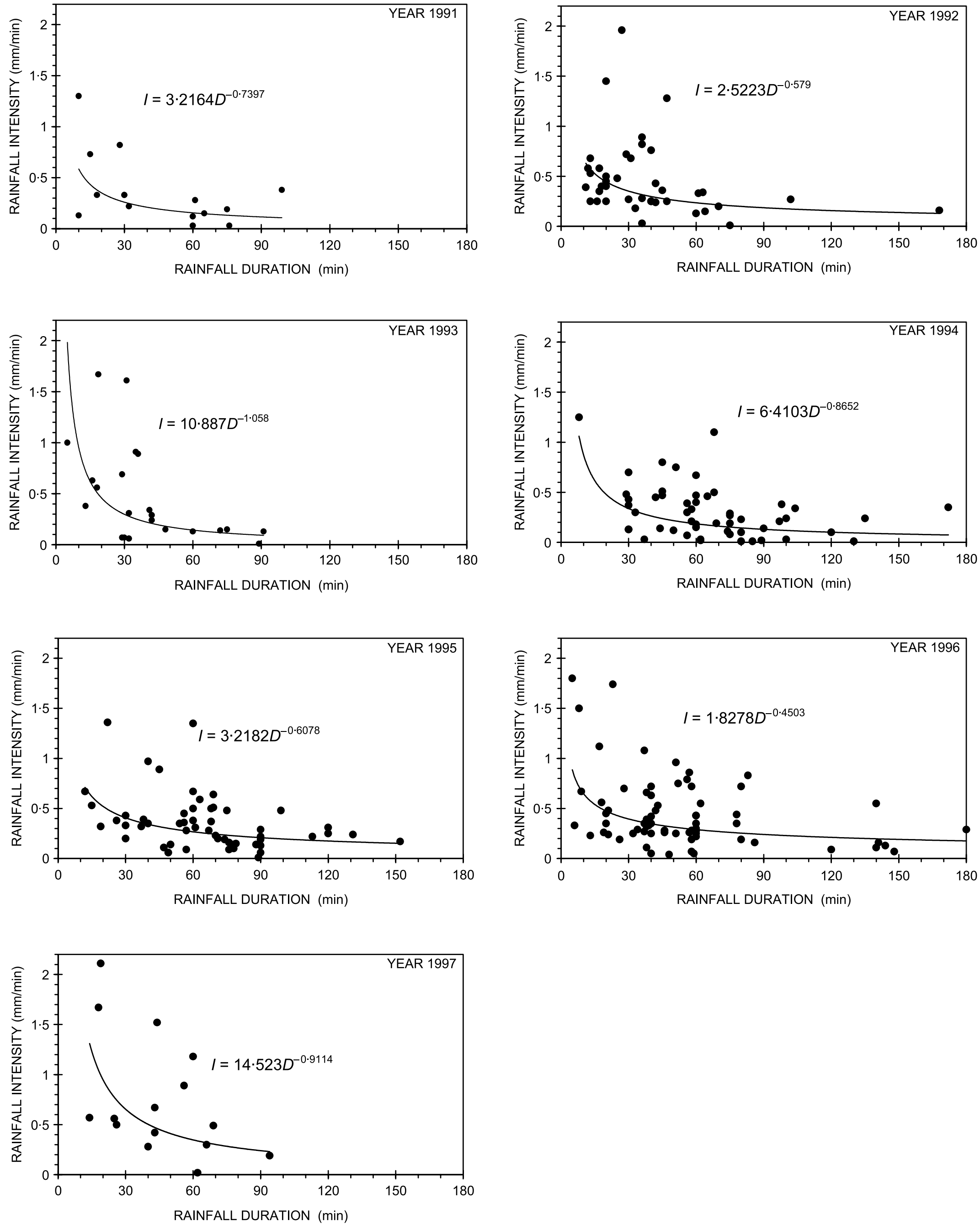

Figure 6. Plots of rainfall intensities (*I*) and rainfall durations (*D*) that triggered lahars for each year between 1991 and 1997.

Yearly forecast of lahars

Although the fits were not so good (with r^2 values between 0·18 and 0·35) an attempt was made to use the equations presented in Figure 6 to generate general threshold levels of rainfall intensity and duration that would be required to trigger lahars. The results are displayed in Figure 7. The graph plots the threshold values in different rainfall durations, i.e. 15, 30, 45, 60 and 90 minutes. From this figure it can be deduced that the threshold amounts vary through time. It is logical to expect that the threshold value will increase each year because the volume of source materials in the

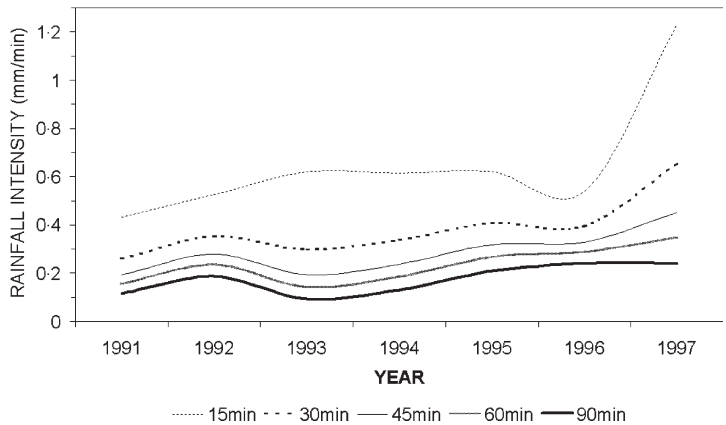

Figure 7. Changes in peak lahar-triggering rainfall intensities over time. The thresholds differ each year as a result of geomorphic changes in the catchments. Higher thresholds are required over time as the catchment stabilizes.

catchment is constantly decreasing, mainly as a result of erosion. However, in the Pasig catchment, the physical conditions changed significantly each year, causing the triggering thresholds to show variable trends. It can be observed from the graphs that in 1991 lower rainfall intensities and duration were needed to trigger lahars. This condition is to be expected since erodible source sediments were abundant and a dense gulley network was formed which made erosion quite efficient.

The 1992 values show that a higher rainfall threshold was required to trigger lahars. The relative increase in threshold values is in the order of 25 to 35 per cent for a rainfall duration of 30 to 60 minutes. In 1993 there was a major transition in the Pasig–Sacobia catchment owing to the secondary explosion of 6 October, which caused the capture of 20 km^2 of the upper Sacobia catchment by the Pasig River (Daag, 2003). This resulted in substantially reduced lahar magnitudes in the Sacobia River and a remarkably increased lahar hazard in the Pasig River. This major change is not clearly reflected in the calculated threshold values for 1993 since the event occurred almost at the end of the rainy season. The 1993 graph shows an increase in threshold values for shorter rainfall duration only (5 to 30 min). From 1994 to 1997, there is a slight progressive increase in threshold levels as the catchment progressively 'recovers' and sediment entrainment becomes less effective. This can be a function of depleting source sediments and valley widening. Wide U-shaped valley floors are less susceptible to lateral erosion during small flows. The only effective way to erode is during large flows when lateral erosion and undercutting play a major role. Thus, this requires a higher rainfall magnitude before lateral erosion begins.

Differentiation between debris flow and stream flow using acoustic flow sensors

The acoustic flow monitoring (AFM) system not only provides information related to the timing of lahar events, but can also provide useful information on the lahar type. The difference between the strength of the low and high band acoustic signals can give a general estimation of the sediment concentration in the flow (Hadley and Lahusen, 1993; Lavigne and Thouret, 2003; Lavigne *et al*., 2000). At Merapi, moderately sized lahar events have signals of about 500 AFU. During bigger flows, debris flows can have a signal of about 1100 AFU while hyperconcentrated flows yield a signal of 350 AFU. The difference between low and high band signals can be five-fold for debris flows. Diluted lahars show little difference in the low and high band signal (Lavigne *et al*., 2000).

At Pinatubo, several observations of active lahars were carried out in the field, which were correlated with the corresponding flow sensor data. Most of these observations were done along the Sacobia and Pasig lahar channels. Depending on the type of flow, either one of the signals dominates. Debris flows produce more low frequency signals, hence the low band signal dominates when this type of flow occurs. On the other hand, during diluted hyperconcentrated flows to muddy stream flows, the high frequency band records higher values than the low band. In order to establish the relationships between the two band signals with the types of lahar flow, a simple direct subtraction of the two band signals was made. Since low band signals are dominant during several lahar events, we use the low band signal as a minuend and the high band as a subtrahend. In this regard, positive high values are expected for debris flow events. For example, 1500 AFU (low band) minus 100 AFU (high band) will give a difference of 1400 AFU. This example is considered as debris flow, since low band values are dominant. The larger the AFU difference, the more sediment

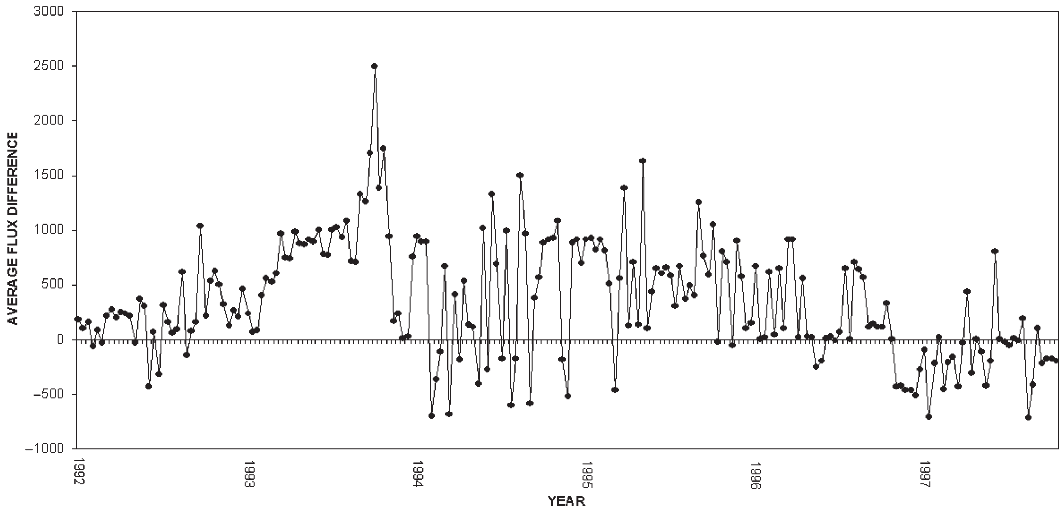

Figure 8. Lahar events (small dots) showing the acoustic flow signal difference (low frequency band minus high band) for the period of seven years. Events above the zero line are low-band-dominated signals, while events with negative values are dominated by high band signals. Points with a value above +100 are considered debris or hyperconcentrated flows, while events below −100 are muddy to watery flows.

concentration the debris flow or hyperconcentrated flow will have. On the other hand, during diluted hyperconcentrated flow to muddy stream flow, the values of the high frequency band are greater than those of the low band. For example, 100 AFU (low band) minus 500 AFU (high band) will give negative 400 AFU.

At Mount Pinatubo, high-density debris flows can have a difference of 2500 AFU between low and high band signals, while for muddy stream flows the difference can be −500. A debris flow discharge of 200 m^3/s can have an acoustic signal of 1200 AFU, and a flow with a discharge of 500 m^3/s about 2000 AFU. It has proven to be difficult to use the data to differentiate between debris flows and hyperconcentrated flows, because in a single lahar event it is common to observe changes from debris flow to hyperconcentrated flow and vice versa, as proven by numerous direct observations of lahars (Daag, 2003).

Figure 8 illustrates the average difference in the acoustic signals of several lahar events plotted chronologically for seven years. Each dot represents the average difference between low and high band signals of one single event. It can be deduced that during the initial years of lahars the events generated were mostly debris flows or hyperconcentrated flows. In the initial years, from 1991 and up to the stream capture incidents (October 1993), the average flux difference is not very high, in the order of 300 to 400. Most of these lahars are considered events of moderate size.

After the capture in October 1993, subsequent lahars were remarkably large, in terms not only of magnitude but also of difference in low and high band signals, indicating that most lahars were massive debris flows. Most of the observed large flows (debris and hyperconcentrated flows) have associated acoustic flow values with large discrepancies between the low and high band signals. The difference is in the order of at least 300 AFU and even greater for larger flows. In 1997, lahar flows were more diluted, resulting in high-band-dominated signals.

Lahar discharge measurements

Data from the acoustic flow sensors were correlated with observed lahars. Most observations were done in the initial years (1991 and 1992) at Sacobia and on some occasions at Pasig. Some events were fully observed, from the front right up to the tail of the flow. These flows were generally small events lasting only a few hours. It is hard to document the full event of large flows because they may last for a day or even more.

Field calculation of active lahar discharge has a number of inherent uncertainties. A great uncertainty lies in the measurement of the flow depth of relatively large flows. Lahars are very erosive, thus the streambed profile can change significantly during flows, resulting in some uncertainty in the measurement of discharge. During relatively small flows, there may be some measurable objects that could lead to a better estimation. These are the dunes and anti-dunes of flow and the presence of rolling boulders. In general, since the estimation of discharge is mostly visual, subjectivity plays a role.

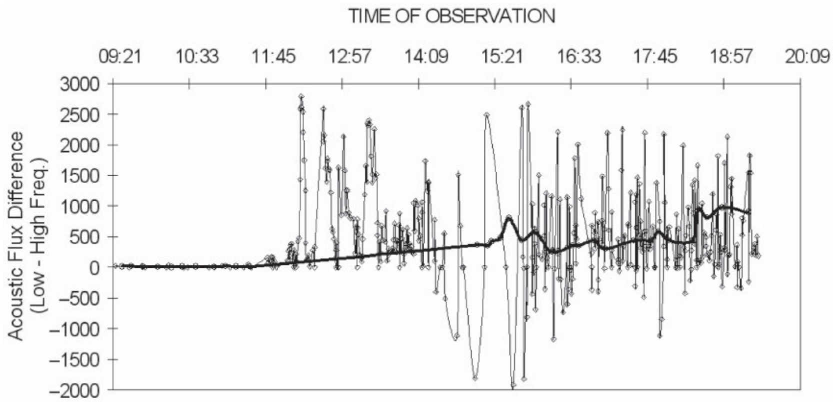

Figure 9. Record of acoustic flow difference (low minus high band signal strength shown by dots) and corresponding lahar discharge (thick line) at the Pasig channel on 29 August 1992. A flow signal difference below 100 is considered as threshold to differentiate muddy stream flow from diluted hyperconcentrated flow.

Since 1997 lahar activity has greatly diminished, mainly due to the depletion of source materials. Heavy rainfall during a typhoon in September 1998 only produced muddy stream flow with a maximum 25 per cent sediment volumetric ratio. Despite the strong rainfall, no debris or hyperconcentrated flows were observed.

Hayes (1999) correlated discharge (m^3/s) with acoustic flow monitoring values (AFM units in $cm/s \times 10^{-6}$) of low band signals. These flows generally range from muddy stream flow to small flow lahars at Pasig River in 1997 and 1998. A correlation equation of $Q = 0{\cdot}34$ AFM with $r = 0{\cdot}85$ was obtained. The flow observations were mostly for discharges below 20 m^3/s. An acoustic reading of 100 units roughly corresponds to a discharge of 35 m^3/s. Tuñgol and Regalado (1996) correlated the debris flows and hyperconcentrated flows at the Sacobia channel with the AFM values in July and August 1992. They obtained the relationship $Q = 0{\cdot}24$ AFM with a correlation coefficient of $r = 0{\cdot}76$. Lahar discharge ranged from tens to 600 m^3/s. The relationship tends to be exponential for higher flow sensor amplitude (>2000) and high discharge.

Figure 9 displays the lahar discharge and the corresponding acoustic flow sensor differences (low − high frequency band signals) observed at the Pasig channel during a 12-hour period on 29 August 1992. Although there are some gaps in the discharge estimation, the lahar was observed from the start of the initial flow at 11:45 hours to the period of normal stream flow with a discharge of no more than 10 m^3/s and acoustic signals of less than 100 units. Acoustic signals above 300 have at least 250 m^3/s discharge and these are lahars (debris to hyperconcentrated flows). The rheology of flow changed from lahar (from 12:00 to 14:30 hours) to transitional muddy stream flow (14:30 to 16:00 hours) and back again to lahar (mostly hot debris flow, as observed in the field).

Acoustic flow data will give an estimate of the type of flow that can be expected in the channel even without direct observation in the field. Estimating the lahar discharge purely by correlating the acoustic flow signals can result in a very rough but useful estimate of the flow.

Discussion and Conclusions

The major advantage of the telemetry system is that it can record data continuously from many field stations in real time, which is vital for lahar warning. Data are received in digital format and can be used directly to issue lahar warnings to the downstreams settlements, to evaluate the relation between rainfall characteristics and lahar initiation time, magnitude and duration, and to estimate the type of lahar flow. However, some data gaps were inevitable when some instruments ceased operation or when transmitted data were badly affected by radio noise. The drawback of this set-up is that the instruments are difficult to maintain because the sites are only accessible by helicopter. Moreover, flow sensors are positioned near the active lahar channels to maximize the signal produced by vibrations during lahar flows. In some cases channel erosion can endanger the instruments; if instruments are lost or have to be relocated, it is difficult to compare the data with previous records.

The presence of high mountains (up to 1583 m a.s.l.) significantly affects the rainfall variation over the Mount Pinatubo area, leading to some localized convection cells with intense rainfall that is sometimes not recorded by the rainfall network. Therefore lahar occurrences might be recorded with very low triggering rainfall values measured in the rain gauges. In the opposite case, extremely high rainfall values may be concentrated in the area of the rain gauge itself, whereas no lahar is recorded by the flow sensors.

Rainfall events that triggered lahars in the period from 1991 to 1997 were presented using box plots as shown in Figure 4 and the results suggest that strong variations of rainfall magnitude have triggered lahars. The lahar-triggering rainfall amounts varied significantly from year to year as a result of changing morphological conditions in the catchments.

Rainfall intensity and duration data for a large number of lahar events were used to evaluate the trends in the rainfall–lahar relationship. Unfortunately, due to the problems with the telemetric system, no continuous records could be obtained, and therefore it has not been possible to compare rainfall characteristics for lahar events with those of non-lahar events, in order to be able to develop a rainfall threshold that could be used as the basis for lahar warning. The relationships that were found were of a power function, and the average threshold for the seven-year data was represented by the equation $I = 3{\cdot}284D^{-0{\cdot}663}$ (I = rainfall intensity and D = rainfall duration). However, this regression has a very low correlation coefficient, and cannot be used as an actual warning tool. Furthermore the relation is changing constantly, due both to depletion of the source sediments and to sudden local changes in the affected catchments caused by large landslides or secondary explosion. The analysis did show that the rainfall amounts in Mount Pinatubo that can trigger lahars are significantly lower than those reported for the Mayon and Merapi volcanoes.

From the flow sensor data recorded in three different frequencies it was possible to extract a number of relations. The magnitude and the duration of lahar flows in 1992 for the Sacobia River can be estimated (Tuñgol and Regalado, 1996; Hayes, 1999; Hayes *et al*., 2002). The established equations can be site- or channel-specific since the distance of the sensor to the active lahar channel can influence the sensitivity of the sensor and likewise the channel configuration can change after major lahar events. The data from the three frequencies of the flow sensors can also be used to differentiate between lahars (debris flows or hyperconcentrated flows) and muddy stream flows. Debris flows produce low frequency vibrations while muddy stream flows generate high frequency ones. An average flux difference of 100 AFU is typical for debris flows and hyperconcentrated flows while a difference of −100 AFU is typical for muddy stream flows. The seven-year acoustic flow data suggest that debris flows were most prominent in the period from 1991 to early 1996, whereas after this period the lahars evolved into more diluted flows. The flow sensor data also allowed determination of the relative timing of the stream capture event of Pasig and Sacobia in October 1993, resulting in a sudden shift of lahar flow magnitude from the Sacobia to the Pasig river.

The installed rain gauges and flow sensors were an important tool in lahar warning. The flow sensors gave about 30 to 60 min lead-time before the lahars were detected at the first visual lahar watch point. It was then about an hour or more before they reached the community downstream. These systems were successful in issuing warnings of lahars and have been extensively used in the Pinatubo area.

Acknowledgements

The authors would like to thank the International Institute for Geo-Information Science and Earth Observation (ITC) in Enschede, The Netherlands, and the Philippine Institute of Volcanology and Seismology for funding support. The telemetered rain gauges and flow sensors were developed by the United States Geological Survey (USGS) at Cascades Volcano Observatory. They were deployed in cooperation with the Volcano Crisis Assistance Team (VCAT) of the USGS, aiming to help monitor volcanic crises in the world. Helicopter support to maintain the remote instruments was provided by the Philippine and US Air Force. The authors thank Frank Lavigne for critically reviewing the text.

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