Debris flows constitute a serious geologic hazard to communities in many parts of the world. Pyroclastic flows and debris flows are loosely consolidated and easily erodible material that makes volcanoes especially susceptible to large scale and destructive debris flow events called lahars. At the Republic of the Philippines’ most active volcano, Mt. Mayon, rainfall of sufficient intensity and duration mobilizes volcanic material into lahars. 138 rain lahars were documented during the 5-years following the 1984 eruption (Rodolfo and Arguden, 1991). Interestingly, the most destructive debris flow events have occurred during periods of volcanic repose and not directly related to eruptions. For example, the 1875 lahar, which caused 1,500 fatalities, was 5-years after a major eruption (Ramos-Villarta et al., 1985). Additionally, the delivery of intense rainfall over a short duration, 466 min in 12 hours, by typhoon Reming (Durian) initiated extensive lahars that resulted in the loss of life of some 1,266 people in November of 2006 – nearly 6 years after an explosive eruption, which produced pyroclastic flows.

Debris flows consist of disperse volcanic materials in suspension, reworking of pre-existing volcanic materials, and hydraulic fractionation leading to the formation of lahars. Lahars are a mixture of both solid and fluid components and are most often generated by high-intensity rainfall (Guzzetti et al., 2003). During rainfall events, water entrains volcanic materials, mobilizing and transporting the material downstream as a debris flow (Huppert and Sparks, 1983). Lahars are composed of volcanic materials, clastic debris, and juvenile ash (Guzzetti et al., 2003). Lahars can exceed 20 m in height, move faster than 10 m/s, and can travel up to 10 km from the source of the event (Guzzetti et al., 2003).

The transition from hyperconcentrated stream flow to debris flow on volcanoes is influenced by the ability of the flow to build up - incorporate more material. In turn, this requires more runoff to mobilize the debris, which is controlled by intensity-duration of rainfall and infiltration (Vallance, 2000). With this in mind we compared the rain- fall/runoff relations superimposing volcanic activity and during periods of repose at Mayon. We also characterized the infiltration characteristics of the Mayon substrates and compared them to volumes of debris flows in each drainage area (Figure 1). Additionally, we measured the effects of fine ash on infiltration to observe how major eruptions alter the soil moisture content.

The rainfall-runoff characteristics, influenced by changes in infiltration by inflows of new material during eruptions, control the probability and extent of debris flow activity. Lahars are much more likely to be destructive during periods of repose (>3 years after an explosive eruption), but the resulting event has a higher probability of being disastrous once the threshold is reached – usually restricted to extreme rainfall events. Lahars that exceed the threshold are highly erosive and can travel substantial distances. Lahars associated with Mayon are a serious threat due to the high frequency of lahars and the proximity to communities.

Infiltration rates were shown to be different between substrates, including those with a single volcanic watershed (Figure 3). Old lahars exhibit lower infiltration rates and higher amounts of fines compared to new lahars - likely because of vegetation growth and bioturbation. Mayon has two different pyroclastic flow deposits - one bomb rich and the other containing mainly small to medium lapilli clasts; these two deposits exhibit very different infiltration rates. PF Lithic and PF Lithic (2) are representative of two distinctly different eruptive events spaced seventeen years apart but exhibit nearly the same infiltration characteristics. Typhoons fall-rich, rich with coarse lapilli, had surprisingly similar infiltration characteristics to the bomb rich pyroclastic flow material. The presence of a simulated ash layer alters infiltration rates – significantly reducing average and final infiltration. However, its effects on initial infiltration is varied - likely due to lack of initial moisture content.

Infiltration rate and intensity-duration of rainfall explains variation in lahar activity:

**Mt. Mayon, Philippines**

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**BACKGROUND**

Debris flows constitute a serious geologic hazard to communities in many parts of the world. Pyroclastic flows and debris flows are loosely consolidated and easily erodible material that makes volcanoes especially susceptible to large scale and destructive debris flow events called lahars. At the Republic of the Philippines’ most active volcano, Mt. Mayon, rainfall of sufficient intensity and duration mobilizes volcanic material into lahars. 138 rain lahars were documented during the 5-years following the 1984 eruption (Rodolfo and Arguden, 1991). Interestingly, the most destructive debris flow events have occurred during periods of volcanic repose and not directly related to eruptions. For example, the 1875 lahar, which caused 1,500 fatalities, was 5-years after a major eruption (Ramos-Villarta et al., 1985). Additionally, the delivery of intense rainfall over a short duration, 466 min in 12 hours, by typhoon Reming (Durian) initiated extensive lahars that resulted in the loss of life of some 1,266 people in November of 2006 – nearly 6 years after an explosive eruption, which produced pyroclastic flows.

**METHODS**

Two tipping bucket rain gauges equipped with data loggers were deployed in order to create a intensity-duration rainfall time-series during quiescent periods on Mayon. The results were compared to the interval time-series created for debris and hyperconcentrated flows following the 1984 Mayon eruption (Rodolfo and Arguden, 1993) (Figure 2). The steady state infiltration capacities of Mayon’s substrates were determined using a double-infiltration ponding method (Figure 3). Sieve analysis was performed according to ASTM C-136. Sieved fines (< .1 mm) from pyroclastic flow material were used to simulate a fresh ash layer for approximately half of the infiltration tests.

**RESULTS (INFILTRATION)**

The new power relation rainfall threshold for debris flow initiation, $i_{p}=46.10^{-13}\text{mm/hr}$ (2006-2008), is much higher in comparison to the threshold created after the 1984 eruption, $i_{p}=27.3D^{0.56}$ and the global threshold, $i_{p}=4.829D^{0.66}$ (Rodolfo and Arguden, 1991). Furthermore, rainfall events reaching the new threshold line do not result in hyperconcentrated flows. Figure 3 illustrates the dynamic changes to lahar initiation related to volcanic activity. From the equation a minimum of $35\text{mm}/\text{hr}$ rainfall intensity at a minimum duration of 6 hours is needed to result in debris flow activity. During its most intense phase typhoon Reming resulted in 46 mm/hr over a 6 hour period. The results indicate that the probability of an intense rainfall event to occur that will trigger a debris flow is lowered, but once the threshold is reached the severity and extent may be much greater (Figure 2).

**RESULTS (INFILTRATION)**

Infiltration rates were shown to be different between substrates, including those with a single volcanic watershed (Figure 3). Old lahars exhibit lower infiltration rates and higher amounts of fines compared to new lahars - likely because of vegetation growth and bioturbation. Mayon has two different pyroclastic flow deposits - one bomb rich and the other containing mainly small to medium lapilli clasts; these two deposits exhibit very different infiltration rates. PF Lithic and PF Lithic (2) are representative of two distinctly different eruptive events spaced seventeen years apart but exhibit nearly the same infiltration characteristics. Typhoon fall-rich, rich with coarse lapilli, had surprisingly similar infiltration characteristics to the bomb rich pyroclastic flow material. The presence of a simulated ash layer alters infiltration rates – significantly reducing average and final infiltration. However, its effects on initial infiltration is varied - likely due to lack of initial moisture content.

**DISCUSSION AND CONCLUSIONS**

The Mayon debris flow event of 2006 was a scenario that could happen at many volcanic locations. The resulting devastation was a sober reminder that extensive and devastating lahars, can happen many years after and sometimes unrelated to volcanic activity. Results showed that rainfall of greater intensity and duration is needed to trigger debris flows during periods of repose (>3 years after an explosive eruption), but the resulting event has a higher probability of being disastrous once the threshold is reached – usually restricted to extreme rainfall events. The rainfall-runoff characteristics, influenced by changes in infiltration by inflows of new material during eruptions, control the probability and extent of debris flows. Additionally, volcanic substrates, new and old, have varied infiltration rates, which also impacts storm water surface runoff and debris flow initiation in individual drainage. However, current rainfall-runoff simulations do not take into account changes in infiltration rate. The correlation between surface runoff, surface drainage and infiltration from this research illustrates the importance of including this parameter in future models and mitigation strategies.

**LITERATURE CITED**


Reming lahar in Padang village, Philippines (Photos by Jarod Maggio).

Figure 5:
