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Rain-triggered lahar susceptibility using a shallow landslide and surface erosion model

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ABSTRACT

Lahars are mass flows containing variable concentrations of water and volcanic debris that can cause catastrophic impacts to life, livelihoods and infrastructure downstream from their volcanic origin. Accurate and quantitative information on lahar hazards are essential for reducing the impact of these events. Lahar hazard assessments often focus on the use of numeric or empirical models to describe flow behaviour and inundation areas, which rely on historic lahar events and expert elicitation to define model inputs. This results in qualitative or semi-quantitative estimates of hazard that do not account for the mechanics of lahar initiation or, in the case of rain-triggered lahars, the dependence of rainfall intensity and duration on initiation. Here we develop a method for calculating rain-triggered lahar susceptibility, defined as the occurrence probability of a particular lahar initial volume at a specific location. The model relies on terrain and deposit characteristics and a probabilistic measure of rainfall in the form of rainfall intensity-frequency-duration relationships. Results for a case study of the October 28, 1995 lahar at Mangatoetoenui stream, Ruapehu Volcano, New Zealand, indicate lahar volume is controlled by a characteristic timescale, relating the deposit depth H to the hydraulic diffusivity D_0 in the ratio H^2/D_0. The timescale describes the transmission of positive pore pressures within the deposit, leading to shallow failure. As a consequence of this timescale, rainfall duration is the most important factor determining initial lahar sediment volume. Rainfall intensity plays a minor role, controlling the volume of water in the lahar mixture. This observation is consistent with power-law relationships used to determine lahar triggering rainfall thresholds. The rain-triggered lahar susceptibility approach developed here is anticipated to improve probabilistic lahar hazard assessments by providing quantitative, reproducible estimates of initial lahar volumes.

1. Introduction

Lahars are a class of volcanic mass flows containing a mixture of water and volcaniclastic debris that form as a consequence of the presence of four controlling factors: (1) water; (2) easily entrained debris; (3) steep slopes and; (4) a triggering mechanism (Vallance, 2000). This definition of lahar encompasses a wide range of flow volumes and behaviours. For example, four categories of lahar (snow-slurry, large dilute lahars, smaller concentrated lahars and lahars generated from remobilised tephra) were observed during and immediately following the 1995 Ruapehu eruptive sequence (Cronin et al., 1997). Syneruptive lahars are generated from overflow or expulsion of water following eruptions within the Crater Lake, while secondary lahars (i.e. lahars not caused directly from an eruption as defined in Blong (1984) and Sigurdsson (2000)) result from the remobilisation of tephra triggered by snowmelt or heavy rainfall. The sediment concentration, flow behaviour, bulking (incorporation of sediment) and volume of these lahars vary depending on the triggering mechanism, debris availability and lithology, all of which can cause differing hazard outcomes. The interactions between and difficulty in quantifying these quasi-static spatial (e.g. terrain, material properties) and temporal (e.g. rainfall, snow depth, eruption frequency) controlling factors makes lahar hazard complex to determine.

Here we refer to hazard as a probabilistic measure expressing the likelihood of a specific event (e.g. lahar of a certain size and type at a specific location) occurring within a reference period. For hazard assessment, the reference period is typically a single year with hazard metrics (e.g. run-out, arrival time or velocity) expressed using an annual exceedance probability (AEP) (van Westen et al., 2006). This expression of hazard is commonly used in other volcanic hazard assessments (e.g. Bonadonna et al., 2005; Magill and Blong, 2005; Jenkins et al., 2012; Calder et al., 2015; Thompson et al., 2015), landslide hazard (e.g. Varnes, 1984; van Westen et al., 2006) and flood hazard (e.g. Merz et al., 2007). The complexity in quantifying mass flow hazards is not unique to lahars, landslide hazard and risk assessment also suffers from difficulties in the quantification and interaction between initiation mechanisms, flow types and environmental parameters. These issues

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are comprehensively discussed and analysed in the context of landslides by van Westen et al. (2006).

Qualitative, semi-quantitative and purely quantitative estimates of lahar hazard have previously been obtained through the use of three main inputs: environmental factors (e.g. terrain, material properties), triggering factors (e.g. rainfall, snowmelt, eruption) and historic records (Calder et al., 2015). Qualitative estimates of lahar hazard (e.g. Waitt et al., 1995; Wolfe and Pierson, 1995; Bacon et al., 1997; Sherrod et al., 1997; Hoblitt et al., 1998) are often conducted where limited information is available. These commonly utilise expert opinion to identify the origin and likely paths of lahar inundation based on historical and geological information. Inundation paths are typically assumed to follow drainage channels with lahar magnitude based on estimates of probable maximum volume. Since these estimates are subject to broad assumptions and rely on sparse historical data, there is considerable uncertainty in the resulting hazard footprints. As a consequence of this uncertainty, the resultant qualitative hazard maps are most often used for communication or initial estimates of hazard.

Semi-quantitative methods that display a relative or indicative hazard are common as they strike a balance between accounting for uncertainty due to limited information and the need to provide some indication of probability. Carranza and Castro (2006) developed a method to determine distal lahar hazard given limited baseline information. A weight of evidence approach was used to determine distal lahar inundation zones at Pinatubo volcano prior to the 1991 eruption. The lahar source zone was estimated by an energy cone (H/L ratio) (Sheridan, 1979) and the distal lahar inundation zone was determined based on four factors: (1) proximity to the source zone, (2) proximity to a drainage line, (3) elevation, and (4) terrain gradient. Although these purely statistical methods are useful for predicting hazard zones with little historical or geological information, they have several drawbacks. For example, the mechanics of initiation are neglected, changes in environmental conditions are usually not accounted for, and an assumption that all events occur under the same conditions is made (van Westen et al., 2006), which is not entirely valid for lahars, as highlighted in Cronin et al. (1997). Furthermore, causal relationships such as those outlined in Carranza and Castro (2006) are generalised and simplified to only consider metrics that are easily calculated on digital elevation models (van Westen et al., 2006; Frattini et al., 2009).

Non-statistical, semi-quantitative estimates are often elicited from outputs of computational lahar models (e.g. Scott et al., 1997; Scott et al., 2001; Aguilera et al., 2004; Robinson and Clynne, 2012; Amigo, 2013; Darnell et al., 2013; Thouret et al., 2013; Pistolesi et al., 2014). These lahar models range in complexity, from empirical solutions (e.g. Iverson et al., 1998; Pierson, 1998) and simplified numerical models (e.g. Fagents and Baloga, 2005), to more complex single-phase (e.g. O'Brien et al., 1993) or two fluid (e.g. Pitman and Le, 2005; Pudasaini, 2012; Iverson and George, 2014) two-dimensional models with the possibility to incorporate downstream sediment entrainment and deposition (e.g. Fagents and Baloga, 2006). As deterministic models, these methods have been used to describe the behaviour and outcomes of specific lahar events (e.g. Carrivick et al., 2010; Procter et al., 2010; Córdoba et al., 2015); however, probabilistic hazard assessment requires that these outcomes are attached to a recurrence probability. Several authors (Scott et al., 1997; Scott et al., 2001; Aguilera et al., 2004; Robinson and Clynne, 2012; Amigo, 2013; Thouret et al., 2013) determine this recurrence probability through providing probabilistic initial conditions of lahar volume and source location to the computational model. In all these cases, volumes were determined from geological and geomorphological evidence, previous historical events, observations of lahars at similar volcanoes and expert opinion. A qualitative estimate of probability (e.g. high to low or most likely to least likely) was then used when determining and mapping the hazard footprints from lahar models. However, these qualitative and semi-quantitative measures of hazard are relative indications only and can be open to interpretation by end users (Calder et al., 2015).

Typically, the previously discussed qualitative and semi-quantitative hazard estimates rely on geologic and historic records to prescribe lahar volume, type and frequency. This is an important limitation on hazard estimates as historic data is often incomplete (Coles and Sparks, 2006; Deligne et al., 2010; Mead and Magill, 2014) and can be irrelevant under different environmental conditions (e.g. land usage) or when topography changes (Volentik et al., 2009), which is often the case in volcanic settings. In order to provide a fully quantitative measure of lahar hazard, such as in the form of an AEP, the spatial and temporal probability of lahar initiation by size, type and location needs to be directly quantified in terms of the antecedent conditions. This spatial and temporal probability of initiation is termed susceptibility (van Westen et al., 2006). Here we define lahar susceptibility as the probability of a lahar with a specific initial volume of water and sediment occurring over a certain duration (annually) and area given a triggering mechanism. This definition encompasses both spatial and temporal probabilities, which can then be combined with lahar inundation models to determine the specific hazard.

Lahar susceptibility, or its contributing products of lahar initiation regions, types and volumes have previously been identified using deterministic methods. Frattini et al. (2004) used an infinite slope stability model to identify areas of instability in pyroclastic soils during the May 1998 landslide events in Sarno, Italy. Areas of instability identified by the model correlated well with landslide triggering times and areas. Volentik et al. (2009) identified potential rain-triggered lahar source regions through coupling a tephra fallout model to an infinite slope stability model and applying a tephra runoff relationship. Using the infinite slope stability approach, the total volume of tephra within the failure zone (1.7×10^7 m^3) was used to estimate runout distance using the empirical relationship between volume and planimetric area of Iverson et al. (1998). A correlation between tephra thickness and decreased infiltration was used to estimate the volume of hyperconcentrated lahars based on the increased runoff. A similar infinite slope stability approach was used by Galderisi et al. (2013) to identify zones of instability following tephra fall at Vulcano Island. These zones of instability were used to guide the selection of potential initiation locations and volumes for subsequent lahar simulation. However, these approaches only identified the spatial component of lahar susceptibility by specifying initial lahar volumes and did not provide information on the temporal aspect of lahar susceptibility by specifying a likelihood or recurrence interval.

The temporal aspect of lahar susceptibility has been more extensively studied, particularly for rain-triggered lahars. Rainfall intensity and duration (I-D) thresholds for lahar initiation have been developed for various volcanoes through coupling lahar acoustic flow monitor (AFM) observations with rain gauge data (e.g. Tuñgol and Regalado, 1996; Lavigne et al., 2000; Lavigne and Thouret, 2003; Barclay et al., 2006; Capra et al., 2010; Jones et al., 2015). While rainfall intensity is a good indicator of rain-triggered lahar initiation, AFM data can only provide a semi-quantitative estimate of the magnitude and type of lahar if combined with direct observation (Jones et al., 2015). As these methods are based on recent occurrences of lahars, they become less valid as environmental and terrain conditions change, as was the case at Pinatubo volcano where intensity-duration thresholds varied constantly as sediment was transported downstream (van Westen and Daag, 2005; Gran et al., 2011). Frattini et al. (2009) compared rainfall triggering thresholds calculated using physically based (deterministic) and statistical approaches. Statistical models were found to be effective on large datasets, requiring minimal inputs in comparison to the physically based approaches. Although the physically based approaches are sensitive to uncertainties in input data, Frattini et al. (2009) suggested these methods can be adapted to determine the degree of severity (i.e. susceptibility) through calculation of unstable area. The utility of identifying susceptible areas was demonstrated in Gomes et al. (2008), who determined debris flow hazard through a combination of a susceptibility model and an empirical model to determine subsequent inundation