

# State of the Art in Debris-Flow Research: The Role of Dendrochronology

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## 1 Introduction

Debris flows and their volcanic counterparts lahars are one of the most destructive mass movement process worldwide, being responsible for hundreds of death every year and leading to horrific multi-thousand death tolls every decade or so. Consequently, debris flows have been the focus on intensive research with hundreds of papers appearing annually on various aspects of debris flow research. For most researchers and practitioners it is difficult to keep abreast of all advances in debris flow research and to extract the most relevant publications. Several dedicated conferences have been held whose sole focus is debris flows. In 2005 a book on debris flows and related processes was published (Jakob and Hungr 2005) to offer a more systematic review of the state-of-the-art. The book was published in 2005 and thus reflects mostly knowledge up to 2003 or 2004. With that it is outdated in some fields. It is clearly impossible to replace the 2005 book and provide a comprehensive review of all significant advances in debris flow science in the space of this chapter. The author has therefore attempted to provide a short summary and highlight outstanding questions and how they can be addressed, at least in part, by application of dendrochronology.

This chapter begins with a definition of debris flows and their formation to avoid confusion in nomenclature and application in practice. It then summarizes the present state of debris flow science for select topics, the present research needs and the application of dendrochronology in helping to advance the science.

### 1.1 What are Debris Flows?

Debris flows are now a well-defined landslide process and nomenclature ambiguity ought to be a matter of the past. In the past, different definitions have been offered by various workers. The present author prefers a hybrid of definition by Hungr

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et al. (2005) and Iverson (2009) which defines debris flows as “a flow of saturated non-plastic mineral and sometime organic debris in a steep channel that include some 50–70% solid grains by volume, can attain flow velocities in excess of 10 m/s and can range between 10 and 109 m<sup>3</sup> in volume. Mud flows can be contrasted by higher water content and a plasticity index of >5%.” While this definition is preferred and used by the author of this chapter, in this book the term debris flow is also used for events with sediment concentration below those of true debris flows that are usually referred to as hyperconcentrated floods.

## 2 A Brief Summary of the State of Debris Flow Science

### 2.1 *Debris Flow Mechanics*

Debris flow mechanics are very complex, and detailed research on this topic has been conducted for over 20 years. An adequate understanding of debris flow mechanics is required to create single and multi-dimensional models that simulate debris flow motion. While it is not necessary to recreate the exact physical perturbations during the flow and deposition phases of a debris flow, an equivalent fluid needs to be formulated that behaves similar to observed debris flows and can adequately replicate runout behaviour. Accordingly, debris flow modelling has been subject to intensive research and scrutiny over the past ten years. Identification of an appropriate debris flow rheology is key to the modelling and prediction of debris flow characteristics and behaviour, which has led to a vigorous debate on the most appropriate rheological formula. Contrasting the single-rheology focus are field observations demonstrating that a single rheology is unable to completely describe debris flow behaviour. Field observations and flume experiments suggest that rheologies vary temporally, spatially and exhibit feedbacks that depend on evolving debris flow dynamics. Therefore, a single rheologic model is unattainable because non-hydrostatic forces cannot exist in steady states. More advanced models such as the Coulomb mixture theory strive to account for unsteady flow behaviour. In addition, very few workers (i.e. McDougall and Hungr 2004) have attempted to include entrainment of debris into their model regimes. Debris flow fans are understood as depositional landforms and model output is limited to fan deposition (i.e. Tekka et al. 2007), even though entrainment on debris-flow fans has been observed numerous times (see Section 2.2).

Several single and multi-dimensional debris flow runout models have been developed (MacArthur and Schamber 1986; Takahashi and Nakagawa 1989; O’Brien et al. 1993; Hungr 1995; Chen and Lee 2000; Iverson and Denlinger 2001; McDougall and Hungr 2004; Pudasaini and Wang 2005; Rickenmann et al. 2006).

One of the most prolific researchers focusing on debris flow mechanics is Dr. Iverson of the US Geological Survey. He recently provided a new depth-averaged model of debris-flow motion that is able to characterize the evolution of flow velocity,

depth, solid and fluid volume fractions and pore-fluid pressure simultaneously (Iverson 2009). This model advances beyond traditional two-phase debris-flow models that typically lack evolution of solid and fluid volume fractions and their interaction with flow dynamics. A potential downfall of the model, as admitted by Iverson, is the lack of representation of grain size segregation, which is responsible for coarse debris flow fronts, inverse grading and levees.

While progress in deciphering the “true” mechanics of debris flows is desirable and required to be translated into modelling software, it is the present author’s opinion that no model will be able to fully account for random and often chaotic flow characteristics that may stem from multiphase flow with organic debris over complex terrain. This includes coarser debris lobes stalling, then being overrun by hyperconcentrated flow surges, log jams on fans leading to unpredictable avulsions, as well as spatial and temporal variability in scour within the fan reaches. For the experienced field worker, this may come as a relief as expert knowledge and judgment will always have a place in detailed debris flow hazard and risk assessments despite any future advances in debris flow physics and numerical modelling.

## ***2.2 Scour in Colluvial Channels/Fans***

Debris flow scour is one of the least understood facets in debris flow science. Debris flow scour affects the total volumes of debris flows produced, particularly if most of the material is entrained on colluvial cones or alluvial fans. Scour is also of crucial importance in the design of crossings of linear infrastructure that require burial (i.e. water/gas/oil/concentrate pipelines/fiber optics). A puncture or rupture of a mine concentrate pipeline, for example, due to debris flow scour at the pipeline crossing could result in direct economic losses of several million dollars per day plus secondary effects such as environmental losses due to pollution of heavy metal enriched concentrate. Finally, environmental pollution and contamination of water ways could result in lawsuits, retraction of mining rights and reputation loss that could amount to hundreds of millions of indirect losses. Such events provide an unacceptable risk to the owners and must be prevented at considerable expense.

Debris flow bed mobilization is likely a consequence of a combination of factors namely the transfer of momentum through solid collisions, friction and fluid thrust, often combined with reduction of effective strength of substrate due to pore pressure changes and/or strain softening (Hutchinson and Bhandari 1971; Sassa 1985). Theoretical approaches to bed stability predictions (Hung et al. 2005) have not yielded satisfactory results for practical applications. This may be attributed to a lack of understanding of shear strength variability along a channel, the effects of vegetation on channel bank cohesion and the variability of pore pressures along the channel before and during the passage of the debris flow. Debris-flow scour is thus a multi-variate problem that may only be resolved through detailed monitoring along high frequency debris flow channels and large scale flume experiments. Empirical relationships can be established that may then form the basis for mathematical formulation.

Dendrochronology may aid this science by providing some data on the depth of scour that can be expected along colluvial channel sections. Many conifers are capable to form adventitious roots if they are inundated, and thus allow the dating of inundation events but also the reconstruction of scour events. Longitudinal averaging of expected scour depth may then be used in combination with channel geometry consideration to predict potential scour. It should be pointed out, however, that this method may be prone to large error if geomorphic thresholds for catastrophic material entrainment are exceeded that are not part of the reconstructed time series. There are several such events documented in the literature and have been noted by consulting experience by the author. For example, a large alluvial fan complex in the southern Coast Mountains of British Columbia suddenly produced a debris flow in the order of 50,000 m<sup>3</sup> through fan channel entrainment only (Jakob et al. 1997). There had not been any such precedents in the 80 years prior that could be documented by air photo interpretation and dendrochronology.

### 2.3 *Frequency-Magnitude Relationships*

As one of the three (together with varve chronology and sclerochronology) annual dating methods, dendrochronology plays a crucial part in reconstructing debris flow activity in the past. This can be accomplished for single debris flow fans (i.e. Stoffel 2010, this volume; Bollschweiler et al. 2010, this volume), or on a regional scale (i.e. Strunk 1995; Jakob 1996; May and Gresswell 2004). This is important to answer questions of landform evolution and especially to develop reliable frequency-magnitude (F-M) relationships of debris flows that form the basis for quantitative risk assessments (QRAs).

Several countries are now calling for landslide QRAs for their existing or new developments. The development of reliable F-M relationships requires a significant effort. This book provides an example where 2,246 tree ring series were analysed from 1,102 old-growth trees (Stoffel 2010, this volume), although recent work (Stoffel and Bollschweiler 2009) has suggested that a much smaller subset of data may provide results that are still usable for frequency-magnitude relationships. Frequency estimates can and should be extended and completed from other data sources such as interviews with locals, newspaper searches, air photograph interpretation, lake sediment analysis, vegetation succession (i.e. Bollschweiler et al. 2010, this volume), lichenometry (Wilkerson and Schmid 2010, this volume) and radiometric dating (i.e. Jakob and Weatherly 2005). Dendrochronology offers the advantage of being precise and allowing a more or less continuous record over a few hundred years if performed by qualified personnel.

Dendrochronology can also support the reconstruction of debris flow volume and peak discharge. Volumes can be deciphered by mapping trees affected by the same event that may provide at least areas affected particularly for fans in densely vegetated areas that preserve the spatial pattern of debris flow inundation (Bollschweiler et al. 2007). Areas are related to volumes and can thus be used as a

volume surrogate if subsurface investigations cannot be conducted due to budget limitation, land ownership or lack of access for heavy machinery. Peak discharge can be back-calculated if tree scars along bedrock controlled sections are dated, the cross-section measured and the flow velocities calculated from empirical equations (Jakob 2005). If risk assessments need to exceed the dating range for dendrochronology because, for example, the development has a risk potential that requires modelling of several thousand year return period events, radiometric methods (standard radiocarbon and AMS dating) will need to extend the dendrochronologic record.

## ***2.4 Debris Flow Forecasting and Warning Systems***

There is an astounding body of work that has been completed on this subject. Most workers have followed Caine's (1980) approach by plotting rainfall duration against intensity for a large range of durations and plotting those events that have led to landslides or debris flows (i.e. Guzzetti et al. 2008). While this approach is a reasonable first step in identifying debris flow-producing storms, it is unsuited as a warning tool in most applications because exceedence of the lower threshold envelope would result in too many warnings to be taken seriously by residents. This calls for more sophisticated approaches that integrate antecedent conditions (e.g. Chleborad et al. 2008) or use statistical techniques to distinguish storm characteristics from storms that have produced landslides from those that have not (Jakob and Weatherly 2003; Cannon et al. 2008; Jakob 2009). Watershed conditions are typically too complex for a system based entirely on rainfall characteristics to ever yield a 100% success rate.

Unfortunately, there is little scope for dendrochronology in this field other than providing dates (years) for debris flows, which with careful analysis may be attributable to a given storm. Once verified this storm date can then be used to obtain the required hydroclimatic data.

## ***2.5 Debris Flows and Wildfire***

Devastating forest fires in the southwestern US and Europe in past few years have sparked a surge in research on the impacts of wildfires on debris flows. Debris flows are among the most hazardous consequences of rainfall on recently burned hillslopes (Cannon and Gartner 2005; Cannon et al. 2010). Removal of vegetation and impacts to soil by wildfire can change the hydrologic response to rainfall, often resulting in increased runoff and significant sediment movement (i.e. Shakesby and Doerr 2006, DeBano 2000). Most debris flows that occur in the first few years after a fire are generated through a process of progressive bulking of runoff with material eroded primarily from channels (Meyer and Wells 1997; Cannon et al. 2001; Santi et al. 2008). An abundance of fine particles from loose, burned soil, dry-ravel deposits,

and fine ash mantling the surface make burned areas particularly susceptible to this process; fine particle entrainment is thought to increase flow transport capacity and shear stress, permitting mobilization of coarser channel sediments (Gabet and Sternberg 2008). Rainfall intensity-duration conditions that trigger fire-related debris flows are significantly lower than those described for the generation of debris flows in unburned settings, and debris flows are often triggered in response to as little rainfall as that that falls in 2 year-recurrence interval storms (Cannon et al. 2008). Over longer time periods decreased rates of evapotranspiration caused by vegetation mortality and decay of root structure may result in the increased soil moisture and loss of soil cohesion necessary for failure of discrete landslide masses in burned areas (i.e. Jackson and Roering 2009).

While progress is being made in understanding the debris flow response of burned watersheds, there are still some significant gaps in our knowledge. For example, long-term (>100 years) frequency-magnitude relationships in basins with wildfire driven changes in sediment supply characteristics are still rare. Furthermore, there are only few reliable recharge relationships established from repeat channel surveys that would quantify the non-linear increase in available sediment after a wildfire.

Tree ring information, including fire scar and germination dates and age-structure data, are routinely used to establish regional and local fire histories (e.g., Covington and Moore 1994; Allen et al. 2002). Integration of data from these studies with those from alluvial fan stratigraphies that include post-fire events can be used to gain insight into the potential regional impacts of changing climates (e.g., Pierce and Meyer 2008; Pierce et al. 2004), and of basin-scale effects of the extent and severity of past fires on the geomorphic response (i.e. Bigio et al. 2005; Frechette and Meyer 2007).

## ***2.6 Debris Flow Mitigation***

Debris flow mitigation has a very long history in various mountainous regions on Earth. In particular in Austria and Japan, debris flow mitigation has advanced to a sophisticated science that addresses a range of components from source area stabilization over various intermittent channel measures to large engineered structures at the basin outlet. While rigid steel and reinforced concrete structures still prevail, there is an increasing use of dynamic debris flow defenses that allow deformation and thus absorption of kinetic energy such a debris flow nets and geo-synthetic reinforced soils (GRS). The advantage of these structures is usually lower cost than rigid systems.

The desire to construct mitigation at low cost requires a good understanding of frequency-magnitude relationships as well as debris flow intensities. Furthermore, particularly in areas frequented by tourists, large unsightly concrete structures are not always supported by local communities and may either need to be hidden from sight or replaced by more aesthetically pleasing structures.

Appropriate debris flow mitigation is based on a thorough understanding of the debris flow hazard including most of the topics included in this Chapter.

Dendrochronology can also help in the design of mitigation measures by identification of the most active fan sector and likely flow or avulsion paths. For example, Bollschweiler et al. (2010, this volume) were able to reconstruct recent activity of Grosse Graben in Switzerland and thus identify the most likely avulsion locations. It should be remembered, however, that over large (typically century) time scales, old fan surfaces can be reactivated due to episodic build up of the fan surface in recently active sectors. Accordingly, a differentiation needs to be made in the mitigation philosophy if risk reduction is aimed for decades or centuries to come. This kind of dendrochronologic investigation will also help an early recognition of shifts in fan activity and thus allow for early planning to reduce risk for fan sectors that have been unaffected for long time periods.

## 2.7 *Debris Flows and Climate Change*

Landslide response to climate change is a higher order effect of global warming that leads to higher atmospheric moisture content, which in turn will lead to higher rainfall amounts and intensities in some regions. However, the hydrologic response of debris flows to climate is complex (Jakob and Lambert 2009) and cannot be condensed to a statement that equates more rain with more or larger debris flows. Antecedent moisture conditions are an important variable in priming hillslopes to landslide susceptibility. Drier and longer summers in some areas will shift antecedent moisture thresholds later into the rainy season. Warmer temperatures may increase the elevation of significant snow accumulation that may increase both the time during which debris flows are likely (a thinning snowpack loses its capability to absorb rain) and it may lead to debris flows initiating at higher elevation. More annual rainfall may in some regions translate in more rain days, while in others, short-term rainfall intensity will be augmented. Long-term changes in the type and spatial distribution of vegetation will need to be accounted for as it changes the canopy intercept, evapotranspiration rates and perhaps even the root distribution and thus root cohesion, which affect hillslope stability in forested terrain.

Dendrochronology may help in identifying the effects of climate change through high resolution studies of debris flow frequencies (Stoffel and Beniston 2006; Strunk 1995), particularly in transport-limited watersheds where the exceedence of a given hydroclimatic threshold is very likely to trigger debris flows. An increase of debris flow frequency in those basins (in absence of human interference) may indicate that the combination of hydroclimatic parameters required to trigger a debris flow may have shifted. The related science of dendroclimatology can be used to monitor changes in moisture and/or temperature regime.

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