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Debris-flow hazard assessments – a practitioner's view

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Abstract

Substantial advances have been made in various aspects of debris-flow hazard and risk assessments over the past decade. These include sophisticated ways to date previous events, runout models including multi-phase flows and debris entrainment options, and applications of extreme value statistics to assemble frequency-magnitude analyses. Finally, quantitative risk management (QRM) has emerged as the most rational and defensible method to assess debris-flow risk and optimize mitigation efforts. Pertinent questions, of course, have remained the same: How often, how big, how fast, how deep, how intense, how far and how bad? Similarly, while major life loss attributable to debris flows can often, but not always, be avoided in developed nations, debris flows remain one of the principal geophysical killers in mountainous terrains. Substantial differences persist between nations in hazard or risk management. Some rely on a design magnitude associated with a specific return period, others use relationships between intensity and frequency, and some allow for, but do not mandate, in-depth quantitative risk assessments. The range in return periods considered in hazard and risk assessments varies over two orders of magnitude from 1:100 to 1:10,000. In many nations, access to funding and lack of at least regional prioritization provides the biggest obstacles to widespread safeguarding against debris flows. Two factors conspire to challenge future generations of debris flow researchers, practitioners and decision makers: Population growth and climate change. The former will invariably invite continued development in debris-flow prone areas, especially fans, floodplains and terraces subject to lahars or landslide/moraine dam/glacial outburst floods which, at times, assume debris-flow characteristics. As far as debris flows are concerned, climate change is manifesting itself increasingly by augmenting hydroclimatic extremes, especially a several-fold increase in the frequency of short-duration high-intensity rainfall that may soon exceed historical precedents. While researchers will undoubtedly finesse future remote sensing, dating and runout techniques and models and bring some of those to a degree of maturity, the practitioners will need to focus on translating those advances into practical cost-efficient tools and closely collaborate with clients to integrate those tools into meaningful long-term debris-flow risk management. Future debris flow disasters will not occur due to a lack of quantitative methods, but likely due to the lack of recognition, wilful ignorance of debris-flow hazards, lack of enforcement of risk management policies, or simply a lack of means to mitigate against known debris flow risks.

Keywords: debris flow; debris flood; hazard assessment; risk assessment;

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1. Introduction

Adding some 70 million humans to Earth every year leaves a mark not only on ever-expanding urban centers and their suburban fringes as well as development of wildland interface, but a proportion of that growth will spill directly into mountainous terrain. Mountains consist of peaks and valleys, plateaus and ridges, ice-clad or bone-dry, covered with dense vegetation and entirely arid. Irrespective of their individual geomorphological or hydrological setting, water, however much or little there may be, drains from zero order barely noticeable depressions to higher order streams until those debouche onto floodplains or peneplains at the piedmont. If sufficiently steep and if loose, erodible sediment is available for transport, debris flows will form whenever sufficient rainfall exceeds some hydroclimatic threshold. With these defining criteria there are likely millions of debris-flow prone streams worldwide. Traditionally,

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people have built homes and infrastructures on fans because in mountainous terrain these can be the areas with the shallowest gradients. The threat of debris flow may be recognized, but there can be a perception that riverine floods are the more damaging event because observable bank full flows may occur frequently and major overtopping of the flow channel at higher return periods may have been witnessed. Debris flows, in contrast, may occur at return periods of century scale, and thus outside the typical memory of residents or infrastructure owners. The longer the periods between events, the less obvious the signs of past destruction and geomorphic change. On top of that, the human trait of delusional thinking that such events are anomalous has led to continued urbanization of fans and cones in areas with high relief. None of this is new, and nations such as Japan, European countries adjoining the Alps, countries straddling the North and South American cordilleras, and other nations have developed systems to map, analyze and assess hazard and risk, and mitigate to the standard of the day. Hundreds of thousands of mitigation works have been constructed worldwide, ranging from make-shift log-crib structures, or masonry dams built entirely by hand to impressive mega-structures constructed with concrete capable of holding millions of cubic meters of sediment.

This contribution is not meant as an exhaustive review of debris-flow hazard assessments of which hundreds have been reported in the literature. Summaries of hazard assessments have been provided elsewhere (Jakob, 2005; Rickenmann, 2016; Chae et al., 2017). Rather, a few cases are highlighted to demonstrate the debris-flow risk assessments that have had a demonstrable effect of reducing risk to populations living amongst debris-flow hazards.

There is a bewildering plethora of papers that are being generated by the scientific community every year. An attempt was made in 2005 by Jakob and Hungr to summarize the state of knowledge through an edit volume of debris flows and related phenomena. Now, 13 years later, this volume hardly does justice to the key advances. This paper cannot address all significant new findings due to lack of space and the admission by this author of not being able to keep up with all relevant advances in debris flow science. Hence, personal bias is unavoidable.

2. Hazard Assessments

Debris-flow hazard assessments form the backbone of any plans to mitigate, if accompanied by a risk assessment or not. In simple speak, if the hazard assessment is faulty, so will be the risk assessment and, ultimately, the mitigation design to reduce hazard or risk. Of course, this can go both ways: An overestimated hazard will lead to an overestimated risk, which by extension results in overdesign of the mitigation works and the associated burden on funding agencies and/or the tax payer.

What does a thorough hazard assessment entail? The list is long but is separated, by and large, by two principal aspects: 1) assessment of the frequency and magnitude of events, and 2) assessment of the intensity of the respective debris-flow scenario. Breakthroughs have been made in the assessment of frequency analyses with the refinement of, for example, dendrochronological methods (Ballesteros-Canovas et al., 2015) and radiocarbon dating methods (Chiverrell and Jakob, 2013; Sewell et al., 2015). Magnitude analyses have been greatly enhanced and refined through empirical methods (e.g. Gartner et al., 2014) and numerical modeling that may allow event magnitudes to be reasonably estimated from known source area volumes and user-specified and/or theoretical entrainment rates (e.g. McDougall and Hungr, 2005; Iverson, 2012). Both methods can and ought to be used complimentarily to decipher the “true” frequency-magnitude relationships. Unfortunately, it is literally impossible to characterize every known event, however, the statistical science has produced methods that are suited for a magnitude-limited truncation of datasets. Peak over threshold (POT) analyses can be applied to this problem set and statistical distributions such as the Generalized Pareto Distribution (GPD) are fit for application where fragmentary data exist but where one can be reasonably confident to have captured the biggest events (Jakob et al., 2017).

The degree of sophistication that is being applied to such hazard assessments differs widely from nation to nation, but also within nations with poorly developed or missing guidelines, and is strongly dependent on the practitioner’s background knowledge and that of his or her team. Many such assessments are conducted by consulting firms who may have to write competitive proposals. If all or most methods available to the practitioners are proposed, the costs of such studies may become non-competitive and a lower bid may win the job. This competitive process may put pressure on firms to win jobs with the lowest reasonable effort possible. But what does that mean and is it truly a problem?

Spectacular failures of debris-flow mitigation works are rarely reported in the scientific literature, presumably for reasons of embarrassment or potential ensuing legal action. Particularly in more litigative societies, legal action seems almost predictable and a thorough forensic analysis of a debris-flow mitigation system failure can be obscured through confidentiality clauses. This is lamentable, as the greatest advances in debris-flow mitigation may derive from an analysis of past failures. In this sense, it is worthwhile to examine a few notable failure modes which have recently been summarized by Moase (2018).

2.1. Regional debris-flow studies

Most districts, states, provinces or even nations have limited funds for geohazard mitigation. This necessitates the allocation of existing funds to those sites with the highest risk potential. In reality, funds for studies and mitigation often get allocated because of particularly damaging events that result in focused public, media and political attention. Those sites, however, may not necessarily be the ones with highest risk. High risk sites are those that occur frequently and with a high economic or life loss potential. Only in the most affluent societies with long histories of debris-flow hazard recognition, quantification and management is it possible to systematically evaluate hazards and risks and prioritize mitigation accordingly (Sturzenegger et al., 2019, this volume, Kang and Lee, 2018). Even if possible, detailed fan and watershed studies for entire nations such as Switzerland, Austria or Japan take a very long time and hazard potential changes with land use, extreme events such as major landslides or volcanic eruptions and direct or indirect consequences of climate change. Therefore, it is advisable to devise methods in which debris-flow susceptibility can be adequately approximated and be readily compared to each other. Hazard frequencies can be assessed in classes with class boundaries being systematically defined and air photograph analysis allowing class designation. Debris-flow magnitude can be gleaned from regional debris-flow susceptibility models such as the empirically based Flow-R software. Flow-R model ("Flow-R" refers to "Flow path assessment of gravitational hazards at a Regional scale") was developed by Horton et al. (2008, 2013). It allows identification, at a preliminary level of detail, of potential debris flow or debris flood hazard and modeling of their runout susceptibility over large study areas. Unlike other numerical models suitable to simulate debris flows such as RAMMS, FLO-2D, DAN-3D and D-Claw, which may require substantial computer runtimes, depending on the model grid size and modelling domain, Flow-R runs very quickly and can be run on numerous debris-flow susceptible creeks at the same time. Sturzenegger et al. (2019, this volume), demonstrate the use of the model for a debris-flow risk-based prioritization study in British Columbia. Once magnitude and frequency have been approximated many creeks, the consequences can be evaluated either for fixed assets (homes, industries, linear infrastructure), or people in transit (on roads, by rail). An example of such regional prioritization has been provided by Holm et al. (2016, 2017). In this sense, debris-flow hazards and risks may not be estimated with any precision and susceptibility maps should not be interpreted as hazard maps. The importance lies in a systematic, replicable and transparent comparison of risks by using the same methodology for all sites investigated. Such prioritization studies cannot replace detailed fan hazard and risk assessments that would form the basis for mitigation design.

Future advances in this science could include a linkage between regional frequency-magnitude analysis and susceptibility models. This would allow a higher granularity in regional studies that have design frequency caps. Such added granularity would glean more confidence in risk quantifications as, often, the highest risk locations are those where debris-flow impact leads to life loss at the lowest return period (highest frequency).

2.2. Dating past debris-flow events

In terms of dating past debris-flow events, practitioners have a substantial variety of methods at their fingertips, and environmental conditions and budget are the key constraints. One of the most deeply researched methods that is also one of the most useful is dendrochronology (Stoffel and Bollschweiler, 2008; Stoffel, 2010; Stoffel et al., 2010; Schneuwy-Bollschweiler et al., 2012; Ballesteros-Canovas et al., 2015). Some key refinements are still outstanding, such as estimating the individual deposit volumes and intra-seasonal dating precision (Stoffel, pers. comm., 2018). Dendrochronological investigations are also used increasingly to identify possible climate change signals (van den Heuvel et al., 2016). Obviously, one does need trees on the fan or along the channel, and preferably old ones to obtain a reasonable record. Relative dating methods such as lichenometry (Innes, 1983; Andre, 1990, Rapp and Nyberg, 1981; Bull, 2018) provide a decent approximation, but without calibration of the lichen growth curve, translation into areas affected by debris flows and their respective date hampers establishment of detailed frequency-magnitude relationships. Radiocarbon dating (i.e. Chiverell and Jakob, 2013) remains a profoundly successful method and can be used not only to date debris flows, but by measuring the thickness of dated deposits allows approximations of debris-flow volumes.

2.3. Debris-flow magnitude analysis

Empirical relationships between flow volumes and inundated areas are highly useful (e.g. Griswold and Iverson, 2008), though local coefficients need to be established rather than blindly adopting reported ones, as was found in several of the author's and his colleagues unpublished studies. More work is needed here to differentiate hybrid events between coarse granular and fine-grained highly mobile events.

One aspect that is still rather challenging is to establish frequency-magnitude methods on a regional scale. For example, pipelines or other above-ground or buried linear infrastructure are still being built worldwide, some of which cross mountainous terrain. Oil and gas pipeline owners have a particularly low tolerance to pipeline rupture. Moreover, they wish to know the chance of pipeline impact for a range of return periods; in other words, a frequency-magnitude analysis is needed for tens if not hundreds of fans that their pipeline may cross. Detailed dendrogeomorphic studies, radiocarbon dating or even detailed mapping of previous deposits is very time and cost intensive and typically is not funded. Jakob et al. (2016) provided a simple, yet effective method to estimate frequency-magnitude relationships (Figure 1). However, this method is not particularly applicable if a high degree of precision is warranted. Using a series of well-researched debris-flow frequency-magnitude relationships, Jakob et al. (2016) were able to show that fan area or fan volume can well predict these relationships with quantifiable error. The underlying rationale is that the fan, unless truncated by a higher order stream, or obfuscated by a rapidly aggrading floodplain, reflects the sum of all fan-forming events. This method is particularly helpful in areas with late Pleistocene glaciation which means that the fan area or volume integrates all debris-flow events that occurred since deglaciation.

Fan areas, are very simple to measure in Google Earth or from orthorectified air photographs. However, caveats must be identified, such as abnormally large fans for their respective watersheds that may be attributable to previous large landslides that have now been overprinted by debris flows. In such cases, the method above may result in overly conservative results. Alternatively, river erosion at the toe of a fan may result in a fan area that is small in relation to the frequency-magnitude of debris flows in the upstream catchment.

The special case of debris-flow magnitude analysis in a post-fire setting has received much attention in the past 10 years and this paper can hardly do justice of the plethora of literature that has emerged. For the practitioner, general guidelines and simple applications are particularly useful, such as the recovery time for decreasing debris flow volumes to pre-fire situations (Santi and Morandi, 2013), or estimates of peak discharge in burned and unburned areas from bulked rational formulae and their limitations (Brunkal and Santi, 2017). Other highlights include probabilistic post-wildfire debris-flow modeling (Donovan and Santi, 2017) and studies on the timing of debris flows after fires (DeGraff, 2014; De Graff et al., 2015), which is key in triggering risk assessments, as debris flows may occur very quickly after fires are out (Kean et al., 2019).

Various statistical methods exist that help the practitioner with incomplete datasets that, in our science, are the rule rather than the exception. The application of simple magnitude-cumulative-frequency (MCF) methods or the GPD can lend credibility to the analysis and its extrapolation to annual probabilities outside the observed record. However, they come with a caveat, namely pronounced confidence bands. As has been shown by Jakob (2012), an honest reporting of such confidence bands may lead to a confidence loss with one's client or those potentially affected. The only remedy does remain expert judgement, which in itself is based on a thorough understanding of the entire debris flow system. Only a comprehension of potential point sources, entrainment rates, multiple debris-flow triggering mechanisms and runout behaviour will allow the practitioner or scholar to properly identify and quantify hazard zones.

2.4. Debris-flow scour and entrainment

On September 20, 2015 an anomalously erosive debris flow occurred on the fan of Neff Creek, north of Pemberton, British Columbia, Canada (Lau, 2017). The debris flow mobilized before reaching the fan apex. However, the total volume of the debris flow that was eventually deposited was 275,000 m^3 with 83,000 m^3 having been eroded from the fan. The discrepancy between these two volumes is due to the erosion of a small canyon-sized channel into the upper to mid alluvial fan, which at its maximum was 14 m lower than the original fan surface. Similar highly erosive debris flows have been observed in Switzerland (Scheuner et al., 2009; Frank et al., 2015) and elsewhere in British Columbia (Jakob et al., 1997; BGC Engineering Inc., 2018), but the causes for debris flow fans to "switch" between deposition and erosion are poorly understood and have only been recently researched (e.g. de Haas et al., 2017). Understanding when such highly erosive events occur on fans is crucial for practitioners tasked with specifying burial depth of pipelines or fiberoptic cables. In the case of Neff Creek, it is virtually certain, that even a professional with vast knowledge of debris-flow processes may have under-designed a buried crossing due to a severely underestimated scour depth on the fan. In addition, clients may exert some pressure on the practitioners not to be overly conservative with the recommended burial depth because costs of construction and maintenance increase substantially with increasing burial depth. Had a pipeline been built, it would have very likely resulted in a fracture and spill of whatever substance the pipeline had carried. It is such events that give us reason to pause and stimulate further research.

Buried linear infrastructure that passes through mountainous terrain will invariably cross alluvial fans and colluvial cones. While fans and cones are generally regarded as depositional landforms, observations of progressive and catastrophic scour on such landforms indicate that this view is too simplistic. Fan and cone scour has exposed, and in the worst case, severed buried linear infrastructure. Continued expansion of buried linear infrastructure motivates a more detailed examination of fan scour to predict scour depth and manage the risk of buried infrastructure failure. Recent papers are split between physical-mathematical treatments of the problem, in large part supported by full-scale flume experiments, and papers reliant on case study and empiricism.

Iverson et al. (2011) conducted large-scale experiments at the USGS's debris-flow flume in Oregon to examine debris entrainment in steep channels. They addressed the pertinent question: How can flows that entrain bed material travel faster and further than those that do not, given that momentum conservation implies flow retardation? Iverson et al. 2011) found that debris-flow mass and momentum grows simultaneously when rapid debris loading over a wet alluvial channel surface produces large positive pore pressures. These elevated pore pressure fields encourage bed sediment scour, lead to friction reduction and unleash a positive feedback through further momentum increase. The key question is when the feedback becomes negative either due to deposition, avulsions or an increasingly dry bed, perhaps due to fan surface infiltration.

Four years after these initial findings, Iverson and Ouyang (2015) reviewed various models and suggested that many existing models are not suitable to predict debris entrainment as they are incorrectly applying depth-integrated conservation principles. They show that erosion or deposition rates at the interface between layers must, in general, satisfy three "jump" conditions, which is rarely the case.

A novel approach to debris-flow scour was suggested by Kang and Chan (2017), who proposed a model that accounts for surface erosional effects through progressive scouring and shear failure on the channel surface. By considering simple geometry and particle configurations, the authors developed equations for progressive scouring and considered rolling and sliding motion. In Kang and Chan's model, a probability-density function (PDF) is used to calculate the entrainment rate. The authors compared the model to flume experiments and found that the entrainment rate can be calculated using a normal-distribution PDF. It will be interesting to observe if real debris flows and associated scour can be accurately simulated by the model.

The importance of debris entrainment has also been highlighted in a recent paper by Frank et al. (2015), who provide instructive examples from the Swiss Alps. Theule et al. (2015) developed a functional relationship from a stepwise regression model as an empirical fit for the prediction of channel erosion by debris flows with a critical slope threshold at 0.19. The authors interpreted this slope threshold as the transition between the transport-limited and supply limited regimes, associated with the upstream decreasing erodible bed thickness. Finally, Haas and Woerkom (2016) experimentally investigated the effects of debris-flow composition on the amount and spatial patterns of bed scour and erosion downstream of a transition from bedrock to channel colluvium. The debris flows entrained bed particles grain by grain and en masse, and the majority of entrainment was observed to occur during passage of the flow front. Interestingly, the authors found that scour depth is largest slightly downstream of the bedrock to colluvium transition, except for clay-rich debris flows. The authors also found that basal scour depth increases with channel slope, flow velocity, flow depth, discharge and shear stress. From a practitioner's point of view, this highlights that debris-flow fans with comparatively large watersheds, such as hanging valleys that result in high peak discharges, are particularly susceptible near their apices, where the transition from bedrock to colluvium occurs. This is very much in line with observed scour depths near fan apices and indicates that those locations should be avoided in the design of linear infrastructure.

Using experiments from a 1:30 scale model, Eaton et al. (2017) were able to demonstrate that channel degradation due to floods on alluvial fans is dominated by lateral channel migration rather than vertical incision. However, experiments were conducted on a modeled fan of 4.5% gradient, and many debris flow fans are substantially steeper. Hence, it remains to be determined if the findings from Eaton et al. (2017) can be applied to steeper fans.

3. Concluding Remarks

Debris-flow hazard and risk assessments have considerably improved from when the design of debris-flow mitigation works were largely based on a practitioner's gut feel or some experience-based guidelines. The wealth of methods, be they in dating past events, deciphering their magnitude, numerical models and measures of debris-flow intensities and vulnerabilities, has been bewildering and illuminating alike. Papers on one or another aspect of debris flows almost appear weekly, and only the most motivated may be staying abreast of absorbing this information tsunami. Rarely, however, can all or even several complimentary methods be applied to a specific problem. This is partially due to geographic constraints (i.e. dendrochronology is useless in treeless terrain, or radiocarbon dating is impossible in desert environments), and partially due to funding limitations in competitive bids for engineering/geoscientific studies.

Even in economically and socially advanced nations in Europe and North America, steep creek science has not advanced as rapidly as would have been desirable. A recent contribution (in German) by Rickenmann and Badoux (2018) identified deficits that are equally applicable to other nations: They include underfunding of process-based studies of mountain torrents, insufficient documentation of methods used for process characterization, missing transparency in debris-flow hazard assessments, and gaps in the systematic training of debris-flow specialists.

Only 10s of people (anecdotal data) die annually directly from debris flows in the US. However, indirect loss of life due to cutoff from health care, for example due to Hurricane Maria that affected Puerto Rico, can be much higher (Kishore et al., 2018). Globally, the total number of debris-flow-related deaths are more significant. Dowling and Santi (2014) estimated 77,779 fatalities have been recorded in academic publications, newspapers, and personal correspondence between 1950 and 2011, an average of approximately 1,250 fatalities per year.

While insignificant in terms of fatalities, the national economic costs are still substantial due to direct impact or infrastructure interruptions (Dowling and Santi, 2014; McCoy et al., 2016). Hence, complacency is certainly not warranted, nor morally justifiable. As with any science, it is valuable to occasionally take stock of the key accomplishments and ask the question: What else needs to be achieved until a science has matured to a degree where progress has slowed to a crawl or even stagnates, or where progress is largely academic with no direct or obvious connectivity to practical application?

One may argue that the quantitative methods available for debris-flow hazard quantification are approaching a level of maturity, as are the myriad of methods to mitigate hazard and associated risks. Clearly, refinements in numerical model capabilities, such as credible entrainment functions on channels and fans, are still necessary and welcome. There are potential pitfalls to widespread application of sophisticated debris-flow models by people with little modeling experience or a cursory understanding of the model being applied. Similarly, hazard intensity definition and mapping can still be homogenized and improved though existing tools that are well suited to deal with most, if not all, conditions adequately. National or regional databases are needed, as they allow a better statistical treatment of all components of hazard analysis. Setting tolerable risk thresholds will help to fine-tune and custom tailor mitigation measures while avoiding over-expenditure or underfunding. Finally, regional, or national-level debris flow risk prioritization is hugely helpful to allocate limited funding to the highest risk situations and to remove the arbitrariness of decisions on mitigation prioritization. None of the above will be useful unless a new generation of debris-flow experts is being trained in the science and art of debris-flow hazard and risk assessments. This needs to be complemented by the, formulation of detailed technical guidelines to homogenize approaches and enhancing research efforts including a systematic process documentation and its testing against existing methods.

Climate change is posing, and will continue to pose, a key challenge to institutions and practitioners alike, as the expected changes in climate and the associated higher order effects (glacial and permafrost changes, changes in wildfire activities, beetle infestations and associated tree mortality, all of which are known to influence debris-flow activity) in the ecosystems are becoming unprecedented in recent human history. While a fascinating global experiment, debris-flow researchers and practitioners will need to respond swiftly with amending their analytical arsenal in the attempt to predict and manage the effects of climate change as they pertain to debris-flow systems.

Despite all uncertainties clouding this science, future changes will require a new generation of experts who are knowledgeable in the ever-increasing subfields that feed into successful hazard and risk assessments. I hope that this contribution will inspire this debris-flow avant-garde and lead to ever more robust tools. It is also a call for funding agencies to provide academia with sufficient means to address pertinent outstanding questions so that science can be translated into practice with little delay. In conjunction with wise resource management and an acceptance of research-based decision making, there is reason for hope that debris flows may not become ubiquitous killer landslides. Future debris flow disasters will not occur due to imprecise science, rather due to the failure to fully recognize, nor quantify the debris-flow hazards and associated risks.

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