Debris flows constitute a major natural hazard in mountainous regions. The main elements required for a practical hazard assessment include the following steps: (i) estimation of potential initiation zones and sediment sources, (ii) establishment of a relation between the magnitude and frequency of expected future debris-flow events, and (iii) assessment of the flow behavior and delineation of areas potentially endangered by flowing debris. A general overview is presented of the main triggering conditions and initiation mechanisms for debris-flow formation. A brief summary is given of methods to establish a magnitude-frequency relation and to estimate the total volume of sediments transported to the fan during so-called “design” events. To assess the runout distance of debris flows and potentially affected areas, either simple empirical approaches or more physically based numerical simulation models may be used. An example application for a Swiss debris fan illustrates the variability of the results when using three different debris-flow simulation models, even though all three models were first calibrated based on the observed deposition areas of a past event.

**Key words:** debris flow, hazard assessment, engineering practice

### 1. INTRODUCTION

Debris flows represent an important natural hazard process in mountain areas. Steep streams, which are prone to debris-flow occurrence, are termed “torrents” in European Alpine countries. Apart from mitigation measures against snow avalanches occurring on steep slopes and against flooding hazards in mountain river valleys, for a long time so-called torrent control works formed an important task for the mountain population. Such protection measures have a long tradition in European mountain areas and aim at reducing potential damage arising from hydrologically driven channel processes in torrents, such as fluvial bedload transport and debris flows. Some of the earliest reports on debris-flow occurrence and/or on torrent control works were prepared in European Alpine countries [Duile, 1826; Surell, 1841; Culmann, 1864; Demontcez, 1894; Bonney, 1902; Stiny, 1910] and in the United States of America [Blackwelder, 1928].

It is generally acknowledged that debris flows constitute a complex process, and a representative mechanical description depends on the material composition of the solid-fluid mixture [e.g., Takahashi, 1978; Costa, 1984; Coussot, 1997; Iverson, 1997]. It is therefore essential to obtain field measurements during a debris-flow event, to better understand and quantify the range of key parameters characterizing debris-flow initiation, propagation and deposition. First systematic field observations of moving debris flows were made in the 1960s in China [Li et al., 1983], and in the 1970s in Japan [Okuda et al., 1980] and in the former Soviet Union [Khégai et al., 1992].

It appears that relatively few more comprehensive compilations summarize practical methods for debris-flow hazard assessment [e.g., Hungr et al., 1984; PWRI, 1988; Meunier, 1991; VanDine, 1996; Jakob, 2005; Rimböck et al., 2013; Rickenmann, 2014; 2016; Corominas et al., 2014], despite their importance for the engineering practice. This paper aims to provide an overview over the most important steps required for debris-flow hazard assessment, and it summarizes some research studies which could support this challenging task.
2. MAIN ELEMENTS FOR DEBRIS-FLOW HAZARD ASSESSMENT

To improve the management of natural hazards, standardized procedures and regulations have been introduced for example in Europe during the last two decades [e.g., Hübl et al., 2002; Petrascheck and Kienholz, 2003; Greminger, 2003; Fuchs et al., 2008; Hürlimann et al., 2008]. According to these regulations, hazard danger levels have to be determined for potentially affected areas such as a fan. These hazard danger levels are a function of process intensity and probability of occurrence. Process intensities for debris flows and floods are typically defined as a function of flow velocity and flow depth, which vary spatially and which depend on the magnitude (or peak discharge) of the process [Hürlimann et al., 2008]. This implies that the expected magnitude or volume of a debris-flow event (the so-called “design event”) and the expected frequency of occurrence (or return period) are key parameters in the hazard and risk assessment of debris flows. The sediment volume or the sediment-water volume of a debris-flow event or of a single surge is typically taken as a measure of the magnitude [Jakob, 2005].

In assessing the potential hazard of debris flows, therefore basically two aspects have to be described: (a) debris-flow occurrence, and (b) characteristics of the flow process. Fig. 1 shows the main elements to be considered and their interrelationship. An overview of several methods used in the assessment of debris flow parameters is given in Table 1 (see Appendix), together with remarks about the required input and some limitations of these methods.

In general, a spectrum of possible debris-flow volumes can be expected to occur with different probabilities; large geophysical events that pose great hazards occur less frequently than smaller events. With regard to debris-flow occurrence, the main factors to be evaluated include the identification of starting zones, of critical (rainfall) conditions for debris-flow triggering, of sediment sources to be mobilized and entrained (defining the event magnitude), and of the event frequency.

Concerning the flow process, the main aspects to be described are the initiation mechanisms, the propagation of the debris flow surges in the channel (including sediment entrainment), and the deposition process on the fan. Soil mechanical aspects are important at the initial and final phase of the process (i.e., initiation and deposition), when the flow velocities are low and the sediment concentration is often relatively high. With regard to the propagation phase of debris flows, the modelling of erosion along the flow path is still very poorly understood and difficult to quantify. The movement of the debris-flow mixture depends primarily on the sediment (or water) concentration and on the composition of the solid material (grain size distribution and lithology), thus leading to different types of debris flows.

3. DEBRIS FLOW INITIATION AND EROSION ALONG THE FLOW PATH

In many mountain regions of the world, debris flows are triggered by rainfall events. As water supply is a necessary requirement for debris-flow occurrence, snowmelt may also enhance event triggering apart from intense or prolonged rainfall activity. A particular triggering situation is associated with glacial lake outburst floods, which have resulted in some of the largest and most disastrous debris-flow events since they may involve large runoff volumes and shear stresses, and they typically occur in steep channels with abundant morainic material [e.g., Haeberli, 1983].

Often occurring during a rainstorm event, the two main types of debris-flow initiation are shallow slope instabilities and substantial erosion of sediments along a steep channel bed [Costa, 1984; Takahashi, 2000]. During the same rainstorm event, both shallow landslides and increased channel runoff may occur, and both processes may eventually trigger debris flows (Fig. 2). Shallow landslides may transform into hillside debris flows, enter a headwater channel and continue as a channelized debris flow, or the landslide mass may temporarily be deposited in the channel, blocking sediment and water supply from upstream and finally resulting in debris-flow triggering through a failure of this solid-water mixture [Takahashi, 2000; Kean et al., 2013]. Debris-flow initiation by channel bed mobilization requires a minimum shear stress or
discharge to destabilize part of the stored bed sediment en masse [Berti and Simoni, 2005; Kean et al., 2013].

Numerous debris flows occurred during the summer 1987 in the Swiss Alps, and based on related field investigations Rickenmann and Zimmermann [1993] found that the slope at the initiation zone of channel-triggered debris flows decreased with increasing upstream catchment area, whereas hillslope-triggered debris flows showed a much narrower range of slopes at the initiation zone (Fig. 3). This observation suggests that the local hydrogeologic conditions during the triggering of shallow landslides are more important than concentrated water supply from upstream (by subsurface or surface runoff).

In terms of possible event frequency and hazard assessment, it would be useful if critical rainfall conditions can be defined to determine thresholds for the occurrence of the above-mentioned two triggering types of debris flows. Numerous studies were made to estimate critical rainfall conditions for the initiation of shallow landslides (and hillslope debris flows), most often defined in terms of critical mean rainfall intensity as a function of rainfall duration (ID-threshold) [e.g., Godt et al., 2006; Guzetti et al., 2008]. Although such rather simple approaches were used in engineering practice, several factors may not be sufficiently accounted for, such as for example a more accurate quantification of antecedent rainfall conditions, subsurface hydraulic conditions and soil stability [e.g., Glade et al., 2000; Baum et al., 2010].

Concerning channel-bed debris flow initiation, a few studies were made recently based on flume experiments [Gregoretti, 2000; Tognacca et al., 2000] and on field observations [Berti and Simoni, 2005; Gregoretti and Dalla Fontana, 2008; Kean et al., 2013]. Similarly as for the initiation of shallow landslides and hillslope debris flows, ID-thresholds of critical rainfall conditions were developed [Berti and Simoni, 2005; Gregoretti and Dalla Fontana, 2007; Coe et al., 2008]. Kean et al. [2013] developed a one-dimensional morphodynamic model to describe the formation of channel-bed debris flows surges based on coupled equations for water flow, bed load transport, slope stability, and mass flow.

Once a debris flow has formed in a channel, more solid material and water may be entrained along the flow path. This process can lead to a substantial bulking of a debris flow surge, resulting in a significant increase of material transported down to the fan. There are only limited flume and field measurements on channel bed erosion and subsequent bulking of the flow [e.g., Rickenmann et al., 2003; Papa et al., 2004; Berger et al., 2011; McCoy et al., 2012]. Theoretical models for debris-flow entrainment were developed and discussed in some studies [Hungor et al., 2005; Fagents and Baloga, 2006; Iverson, 2012; McCoy et al., 2012]. However, in engineering applications of debris flow modelling, typically the material entrainment is user defined for example by specifying a spatially distributed maximum erosion depth or erosion velocity [Hungor and McDougall, 2009; McDougall and Hungor, 2005; Hungor, 1995].

4. FREQUENCY AND MAGNITUDE ESTIMATION

Semi-quantitative methods to estimate the
likelihood of debris flow occurrence in a particular
torrent catchment were proposed in Austria
[Aulitzky, 1980], in Japan [Nakamura, 1980], in
Canada [VanDine, 1985], and in Switzerland
[Rickenmann, 1995]. In these evaluations, factors
such as previous debris-flow traces, sediment
sources and erodibility, channel slopes, infiltration
capacity and others are weighted and combined to
arrive at an index value which represents a
combined degree of probability and event
magnitude of a possible debris flow.

Although the relationship between the magnitude
and the frequency of a debris-flow event is essential
for any hazard or risk analysis, it is often difficult to
assess. The magnitude of a debris flow event forms
an input or basis for simple empirical relations to
estimate important flow parameters [Rickenmann,
1999] or for numerical models simulating flow
propagation and deposition (see section 5 below). In
a simplified view, debris-flow occurrence and
magnitude ultimately determine flow behavior (see
also Fig. 1).

If a sufficiently long record of debris-flow
observations were available (as may be the case for
discharge measurements in rivers), then a
magnitude-frequency relation for debris-flow events
could be determined with extreme value statistics.
However, long-term monitoring data in headwater
catchments are typically rare. In inhabited mountain
areas historic documents often form an important
source of information on past debris-flow activity.
Descriptions of associated damage or areas affected
by a particular event may help to estimate an
associated magnitude [Zimmermann et al., 1997].
Such information plays an important role in
debris-flow hazard assessment for example in
Switzerland and in Austria.

Other methods to determine debris-flow frequency
(and to some extent also magnitude) include
dendrochronology [e.g., Schneuwly-Bollscheider et al., 2013] and lichenometry [Innes,
2006]. Radiocarbon dating may be applied where
natural exposures or test trench sediments provide
organic materials for dating [Chiverrell and Jakob,
2011]. Mapping of dated events along with
determination of the thickness of the respective
deposits can yield magnitude estimations. Even if a
comparatively large set of historical data on past
debris-flow occurrence is available, the estimation
of magnitude-frequency relation with statistical
methods may not be straightforward [Jakob, 2012;
Nolde and Joe, 2013].

Apart from these backward-oriented methods
[Petrascheck and Kienholz, 2003], potential future
sediment delivery processes may in principle be
modeled for entire headwater catchments, for
example based on rainfall scenarios and slope
stability analyses [e.g., Montgomery and Dietrich,
1994; Baum et al., 2010; von Ruette et al., 2013].
However, in applying such models in practical
hazard assessment, one of the main challenges is
that the characteristics of the soil and subsurface
layers are often heterogeneous and unknown.

A common practice in event-magnitude
estimation of debris flows is based on plausible
ranges of debris stored in the channel, which are
estimated for example from historical flow volumes,
and to calculate sediment bulking along the main
channels [Hung et al., 1984; VanDine, 1985;
Williams and Lowe, 1990; Marchi and D’Agostino,
2004; Jakob, 2005]. Detailed channel yield rates
(erosion cross-sectional area per meter channel
length potentially eroded) may be estimated through
field investigations, along with an estimation of
additional sediment input from landslides, for an
assumed return period of a triggering rainstorm
event [Kienholz et al., 2010]. A limitation of this
approach is that the volume estimate refers to the
time of the investigation. For example, in a
supply-limited catchment the sequence and
magnitude of future events may deplete the amount
of erodible sediment available at a later point in
time, possibly invalidating a previous (high)
estimate of a future rare event.

5. FLOW MODELLING AND RUNOUT
PREDICTION ON THE FAN

Runout prediction methods for debris flows may
be based on empirical-statistical or dynamical
methods [Rickenmann, 2005]. Empirical equations
for the total travel distance (the entire horizontal
path length) of debris flows were proposed by
Corominas [1996], Rickenmann [1999], Legros
[2002], Toyos et al. [2008], and Prochaska et al.
[2008]. In most of these approaches the runout
length is essentially a function of the volume and
angle of reach or the longitudinal profile of the
expected flow path. In other empirical methods to
estimate the total travel distance, a sediment budget
along the flow path was established [Cannon, 1993;
Fannin and Wise, 2001].

To delineate potentially endangered areas in more
detail, the runout pattern or the surface area of
potential debris-flow deposits on the cone should be
known. A mass-point-model, originally developed
for snow avalanches, was also used in a dynamical
runout model for debris flows and it requires an
empirical calibration of two parameters [Ricken-
mann, 2005]. A simple topography-based empirical
approach to model the depositional areas based on total flow volume was first developed by Iverson et al. [1998] primarily for lahars. Subsequently, more observations on debris flows were used to test or modify this approach in studies by Crosta and Agliardi [2003], Berti and Simoni [2007], Oramas Dorta et al. [2007], Griswold and Iverson [2008], and Scheidt and Rickenmann [2010]. Many studies using empirical approaches underline the importance of debris-flow volume on the prediction of total travel distance or depositional area on the fan [Rickenmann, 2005].

In principle the most accurate description of the depositional process of debris flows is provided by hydraulic simulation continuum models. An important element of many proposed models is an appropriate formulation for the constitutive behavior of debris flows. Model concepts were first developed for “mud flows” [e.g., Johnson, 1984; Costa, 1984] and for “stony debris flows” [Takahashi, 1978; 1991]. These two categories basically distinguish between flows with a considerable proportion of fine material and flows where the coarser particles dominate the rheologic behavior, respectively. According to a classification by Takahashi [2000], the turbulent flow regime is a third basic regime for debris flows for cases where turbulent stresses dominate the flow behavior. This third regime may also be considered as a transitional regime between fluvial bedload transport and fully developed debris flows [Rickenmann, 2012].

The more fine-grained mud flows are often described as a Newtonian laminar fluid or as a Bingham fluid; a somewhat more general form is the Coulomb viscous model [Johnson, 1984] or the Herschel-Bulkley model [Coussot, 1997]. For coarse-grained debris flows it has been suggested that grain collisions dominate the flow behavior, and Takahashi [1978] further developed the dilatant or inertial grain shearing model based on ideas of Bagnold [1954]. After Takahashi [2000] the Reynolds number is used to distinguish between the turbulent and viscous regime, and the ratio of flow depth to particle size (h/D) to distinguish between the turbulent and grain-inertia regime. There is empirical evidence that for values (h/D) greater than about 25 the flow is not in the grain-inertia regime [Julien, 1997]. This suggests for many natural debris flows with both mean grain size and solid concentration decreasing behind the front that the flow should be either turbulent or viscous in these rear regions.

Several modifications and refinements have been proposed with regard to these three basic flow regimes. For example, rheologic investigations of debris-flow slurries suggest that the Herschel-Bulkley model should be preferred over the Bingham model, because the former is more general and can better describe the fluid behavior particularly at low shear rates [Coussot, 1997; Ancey and Jorrot, 2001]. A simple version of combining all three basic flow regimes suggested by Takahashi [2000] is the so-called quadratic rheologic model of Julien and Lan [1991] and O’Brien et al. [1993]. This model combines viscous and yield stress with a third stress term, which includes a quadratic dependence on velocity gradient along with a lumped coefficient that accounts not only for dispersive but also for turbulent stresses. Iverson and Denlinger [Iverson and Denlinger, 2001; Denlinger and Iverson, 2001] proposed a different approach concerning the essential equations controlling debris-flow behavior. They developed a two-phase simulation model where debris flows are assumed to have a behavior between one-phase granular flow and a viscous flood. The model considers an evolution of apparent constitutive behavior in response to the changing pore-fluid pressure.

In many numerical simulation models for debris flows, the solid-fluid mixture is considered as a quasi-homogeneous fluid. A number of models are partly or fully based on a rheologic formulation for a Bingham or viscoplastic fluid [Choi and Garcia, 1993; Laigle and Coussot, 1997; Fraccarollo and Papa, 2000; Imran et al., 2001; Malet et al., 2004]. Only in some model applications exact values of the rheologic parameters were known [e.g., Laigle and Coussot, 1997; Imran et al., 2001; Malet et al., 2004]. In several applications to natural debris flows, the pure Bingham model was modified by adding a friction term accounting for channel roughness and turbulence [O’Brien et al., 1993; Han and Wang, 1996; Jin and Fread, 1999].

The commercially available Flo-2D simulation model [O’Brien et al., 1993] has possibly been most widely applied to natural debris flows or compared with other models [e.g., Chuang et al., 2000; Sosio et al., 2007; Armento et al., 2008; Bertolo and Bottino 2008; Marchi et al., 2010]. In some of these applications the Bingham model parameters were inferred from the measured rheology of samples of the fine material slurry. However, generally the sediment concentration in the real debris flows may be very variable. A further assumption has to be made regarding the pseudo-Manning coefficient. This value is often adjusted to optimize agreement between simulated and observed flow behavior. The associated friction term may dominate the flow behavior at higher velocities in several cases.
A number of other debris-flow simulation models was applied in case studies and compared to real debris flows, such as RAMMS [Christen et al., 2010; 2012], DAN-3D [McDougall and Hungr, 2004; 2005], FlatModel [Medina et al., 2008], MassMov2D [Beguería et al., 2009], RASH-3D [Pirulli and Sorbino, 2008], and TRENT-2D [Armanini et al., 2009]. Typically, appropriate values for the rheologic or friction parameters were assumed or back-estimated from field observations [Hungr, 1995; Rickenmann and Koch, 1997; Ayotte and Hungr, 2000; Revellino et al., 2004; Nafe et al., 2006; Rickenmann et al., 2006; Tecca et al., 2007; Hungr, 2008; Hürlimann et al., 2008; Pirulli, 2010].

An example application of three different models to a potential future event on a fan in Switzerland illustrates the considerable variability of the obtained results. The debris-flow simulations were used to determine hazard intensity maps, with intensity classes depending on flow velocity and flow depth according to the procedure of Rickenmann given in Hürlimann et al. [2008], for the case of the Milibach fan in canton of Valais, Switzerland (Fig. 4). All three models were first calibrated with the observed deposits of an event with a total volume of 10'000 m³ that had occurred in November 2002. They were then applied with the same model parameters to a possible future event with a total volume of 24'000 m³, consisting of three debris-flow surges with a volume of 8'000 m³ per surge.

It was found in many studies to model debris-flow deposition on the fan that, once the flow has overtopped the channel, the runout pattern was determined to a large degree by the fan topography. Therefore, an accurate digital elevation model of the potential depositional area is an important requirement for debris-flow hazard assessment on a fan.

6. CONCLUSIONS

With regard to debris-flow occurrence, the main factors to be evaluated include the identification of starting zones, critical (rainfall) conditions for the triggering, sediment sources, the potential event magnitude, and the event frequency. A major challenge in debris-flow hazard assessment is to establish a magnitude-frequency relation. Occurrence of debris flows may be relatively rare in many headwater catchments, and thus there may be only few historically documented events. Nevertheless a catalogue of past events is often an important basis for the hazard assessment. The magnitude of an estimated “design” event is typically assessed based both on information about past events and on geomorphological investigations in the catchment.

It is recognized that the flow behavior is very complex. A difficulty related to selecting an appropriate simulation model is the large variability of material compositions and water contents. Rigorous criteria are largely lacking to distinguish
between appropriate flow regimes for the spectrum of debris flows which can be expected in a given catchment. Since most simulation models require some calibration of the parameters, a major drawback in view of engineering applications is that most of these models have not been tested rigorously against field events. Nevertheless it appears that some general characteristics of debris flows needed for the hazard assessment may be reasonably well simulated with rather simple modeling approaches if a prior calibration of the model parameters is possible.

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Corominas, J. (1996): The angle of reach as a mobility index for


APPENDIX

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<td>model parameters often require calibration with field observations; lacking criteria for applicability of different flow types</td>
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