



A size classification for debris flows

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Abstract

A 10-fold classification for debris flow size is proposed based on total volume, peak discharge and area inundated by debris. Size classes can be used for regional overview studies where detailed site investigations are either unnecessary, too costly or where the highest hazard and risk creeks need to be identified for further study. They are also useful to compare the regional impact between affected areas and the effects of rainstorms, and they allow lay-people to obtain an understanding of debris flow magnitude and consequences. Finally, different size classes allow the estimation of travel times to points of interest based on empirically derived equations. It is proposed that agencies concerned with debris flows should establish a documentation of debris flow size according to this classification, which serves as a data base for hazard and risk planning.

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1. Introduction

Existing classifications for landslides are based on process, morphology, geometry, movement type and rate, type of material and activity (Varnes, 1978; Cruden and Varnes, 1996; Hungr et al., 2001). Size classifications are rarely used for landslide characterization because they provide too little information on other, often more important, morphologic or process characteristics of a landslide. This paper argues that for debris flows a classification that incorporates

different size characteristics could be used in regional studies along infrastructure corridors because it addresses variables that are part of a hazard evaluation. A mandatory debris-flow size classification is proposed as part of provincial and federal landslide inventory initiatives, because these data will yield information where detailed hazard assessments are required. This suggestion is motivated by the common practice of simply removing debris flow deposits by contractors whose scope of work does not include the documentation of debris flow size. The purpose of their work is to re-establish traffic, electricity or oil and gas flow, or to decrease hazard to landowners. The local government or utility provider responsible for the clean-up

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rarely maintains an inventory of size variables, or event dates (there are some exceptions, for example, for rockfall). Several European countries have also begun to establish a systematic and coordinated documentation of mountain disasters, which will aid future research and cost-effective disaster mitigation (Huebel et al., 2002).

The general neglect of recording debris flow size contrasts to routine collection of stream flow and precipitation data by most governments. Collection of these data is often limited to scientists or engineers who volunteer their time to further investigate a debris flow event, or are involved as expert witness if legal action ensues. This occurs some time after an event has taken place and debris flow size data are usually of lesser quality.

This paper discusses some size classifications for slope hazards and the reason why a separate classification is warranted for debris flows. The new size classification is introduced by explaining the choice of variables and defining the individual classes. An application of the system is presented for the analysis of a road through debris-flow-prone terrain followed by a discussion of the classification system with regard to size dependency for different return periods.

2. Previous work on slope hazard size classifications

A landslide size classification based on volume was proposed by Fell (1994) (Table 1). Volume, however, is of minor relevancy when pipeline, railway or highway crossings are considered in a hazard or risk analysis. Furthermore, the size ranges appear to be arbitrary and could be simplified by a classification system based on powers of 10.

Table 1
Size classification for landslides (Fell, 1994)

Size class	Size description	Volume (m ³)
1	Extremely small	<500
2	Very small	500–5000
3	Small	5000–50,000
4	Medium	50,000–250,000
5	Medium–large	250,000–1,000,000
6	Very large	1,000,000–5,000,000
7	Extremely large	>5,000,000

Table 2

Size classification for snow avalanches (McClung and Schaerer, 1981)

Size class	Typical mass (Mg)	Path length (m)	Impact pressures (kPa)	Potential consequences
1	<10	10	1	Relatively harmless to people
2	10 ²	100	10	Could bury, injure or kill a person
3	10 ³	1000	100	Could bury a car, destroy a small building or break a few trees
4	10 ⁴	2000	500	Could destroy a large railway car or truck, several buildings or a forest with an area up to four hectares (4000 m ²)
5	10 ⁵	3000	1000	Largest avalanches known could destroy a large village or a forest of 40 ha

Pierson (1998) included a size classification to differentiate travel times of wet volcanic mass flows by discharge because of a positive correlation between velocity and debris flow magnitude. He differentiated between moderate (10² to 10³ m³/s), large (10³ to 10⁴ m³/s), very large (10⁴ to 10⁶ m³/s) and extremely large (>10⁶ m³/s) volcanic debris flows.

A well-documented size classification system exists for snow avalanches, which has been applied for over 30 years (de Quervain et al., 1973). European approaches focused on relative size classes such as proposed by Föhn (1975). A more quantitative system was proposed by Föhn et al. (1977) with a three-fold classification of ‘small’, ‘medium’ and ‘large’ based on avalanche runout area. The main criticism is that some important variables are not included and the insufficient number of classes to differentiate between events (McClung and Schaerer, 1981).

In 1977, the Canadian Avalanche Committee adopted a modified size classification system originally introduced by the USDA (1961) to estimate the potential destruction in the middle of the avalanche path at terminal velocity. This system identifies hazard potential of differently sized events and thus provides input to scientific studies, hazard and risk analyses or mitigation design. Table 2 lists the factors used in the size classification for avalanches.

3. Debris-flow size classification

The basic requirement of a size classification of debris flows is that at least some variables included are easily obtainable, are meaningful for assessing hazard and risk, and can be used for evaluating the need for passive or active debris flow mitigation. As demonstrated by Pierson (1998), they are also useful in predicting travel times for debris flows and may thus allow timely evacuation or closure of transportation corridors. The variables proposed in this paper include total debris volume, peak discharge and area inundated, and a description of potential consequences (Fig. 1). While measures of size may be difficult to conceive for the lay-person, descriptions of potential impact are easily understood. The system proposed in this paper does not include descriptive size classes such as “small”, “medium” and “large” as these descriptors are very vague, and can only obtain objectivity if used in connection with numbers. The adoption of other size classifications, for example the existing one for snow avalanches, is not appropriate due to significant differences in their use. These differences pertain to the physical properties of the materials, the number of classes, the types of meaningful variables chosen and the need to

differentiate between volcanic and other muddy debris flows and bouldery debris flows. Debris flows also span a much wider range of volumes due to the much greater volume of available materials, especially from Quaternary volcanoes. Volcanic debris flows from Mount Rainier, for example, have reached volumes of up to $3 \times 10^9 \text{ m}^3$ (Scott et al., 1995). This much wider size range justifies the introduction of additional classes.

3.1. Parameters used in the size classification

The use of debris flow volume (V) only in describing the size of a debris flow may be insufficient to allow its use for hazard and risk assessments. For these studies it is important to determine the peak discharge (Q) and the area that will likely be inundated by debris (B).

Debris volume is a variable used for the design of debris basins or debris barriers whose purposes are to halt the debris flow before reaching an area of high potential consequences. Debris volume also affects runout distance and area covered by a debris flow and is needed as an input parameter in existing runout models (O'Brien and Julien, 1989; Hungr, 1995; Iverson et al., 1998; Iverson and Denlinger, 2001).

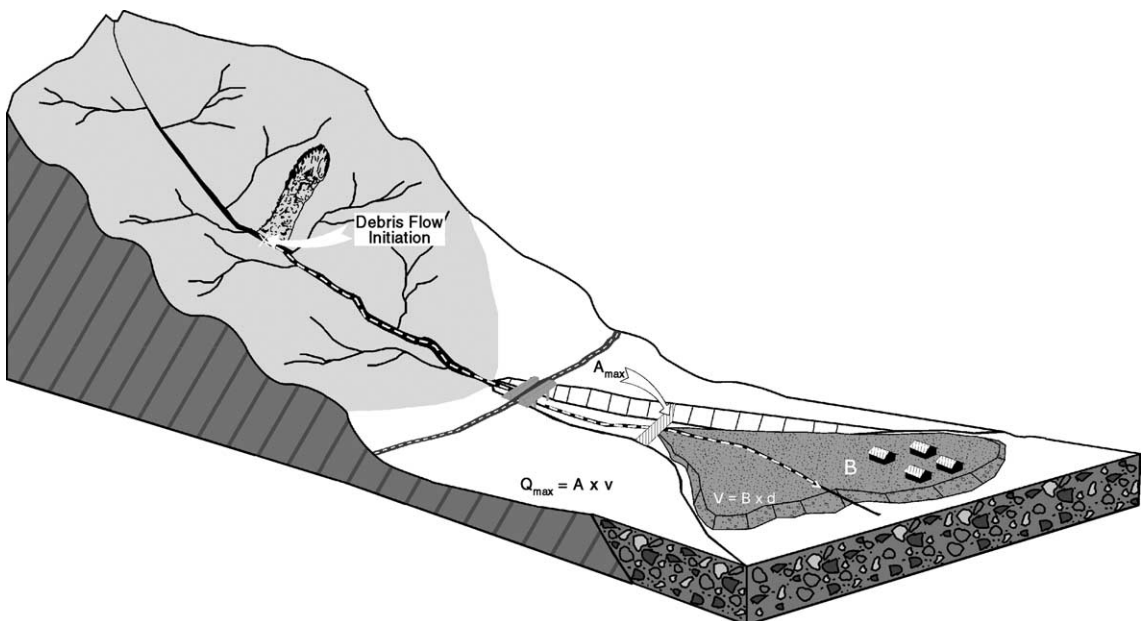


Fig. 1. Conceptual sketch showing the variables on which the debris-flow size classification is based.

Therefore, volume directly affects debris flow hazard or intensity maps and ultimately derivative land-use maps, which makes it a more appropriate measure than mass. Debris-flow volume is defined as the total volume of debris transported beyond a point of interest (usually the apex of a creek fan on which development occurs). It should be noted, however, that deposit thickness is often very difficult to determine.

Peak discharge is an input variable for the design of bridges, culverts, pipeline crossings and channelization works as it determines the cross-section area needed to pass the design flow. Discharge is also needed as an input parameter for models that require a hydrograph as an input variable (O'Brien, 2001). Peak discharge is defined as the product of the largest cross-section in a reach of interest and the highest estimated or measured flow velocity of the flow passing this cross-section. Flow cross-section can easily be measured, while velocity estimates can be achieved by a number of methods discussed by Jakob (2005). Peak discharge has been correlated with total debris volume for different types of debris flows (Costa, 1988; Mizuyama et al., 1992; Bovis and Jakob, 1999; Jitousono et al., 1996; Rickenmann, 1999). The formulae developed by these authors provide a range of possible peak discharges for muddy or volcanic and bouldery debris flows associated with the respective volume. The wide range of debris flow discharge can at least be partially explained by the frictional resistance of coarse boulder fronts, which can slow debris flows to velocities significantly less than without those boulder fronts. The highest and lowest discharge values from the equations in Table 3 were used to define the discharge classes in Table 4. Using the size classification summarized in Table 4, debris flow volume can then be estimated from peak discharge or peak discharge can be determined from volume.

Finally, area inundated is included because it provides a measure of debris flow mobility and potential consequences. For example, a developer requires inundation area information for the zonation of a resort in a valley or on a fan, while an engineering company requires B to design efficient deflection berms for potential debris flows. Area inundated was again separated in bouldery debris flows and muddy (mostly volcanic) debris flows because the latter will

Table 3

Correlations between peak discharge (Q_p) And total volume (V)

Formula	Author
$Q_p=0.135V^{0.78}$ (bouldery debris flows)	Mizuyama et al. (1992)
$Q_p=0.019V^{0.79}$ (muddy debris flows)	Mizuyama et al. (1992)
$Q_p=0.006V^{0.83}$ (volcanic debris flows)	Jitousono et al. (1996)
$Q_p=0.04V^{0.90}$ (bouldery debris flows)	Bovis and Jakob (1999)
$Q_p=0.003V^{1.01}$ (volcanic debris flows)	Bovis and Jakob (1999)
$Q_p=0.001V^{0.87}$ (volcanic debris flows)	Jitousono et al. (1996)
$Q_p=0.1V^{0.83}$ (bouldery debris flows)	Rickenmann (1999)

Caution should be exercised for the differentiation between granular debris flows and muddy debris flows for size classes exceeding 10,000 m³ in volume (Class 4 and 5). Work by Rickenmann (1999) has demonstrated that regression lines for some muddy flows and granular flows can converge at these higher classes. Locally derived relationships between volume, peak discharge and area inundated may be used for an improved assignment of debris flow size into the correct classes.

spread over larger areas due to their higher mobility. Areas inundated, B_v , by volcanic debris flows were calculated by using the relationship:

$$B_v = 200V^{2/3} \text{ (Iverson et al., 1998)} \quad (1)$$

where V equals the debris flow volume, and:

$$B_b = 20V^{2/3} \text{ (Griswold, 2004)} \quad (2)$$

for bouldery debris flows. Path length, which is defined as the total travel distance from the initiation of the debris flow to its farthest runout, is not used due to its poor correlation with debris-flow volume. Similarly, runout distance, defined as the total distance of debris flow deposition, is not included in the size classification because many debris-flow channels end in higher order streams, which truncate the debris flow thus providing an underestimation of runout. In addition, debris flow runout is often assessed very subjectively because some workers define runout as the limit of fine sediment deposition, while others use the extent of coarse debris.

3.2. Size definitions

This section describes and justifies the size classes that have been used in this classification. It is necessary to point out that volume estimates reflect the total volume transported beyond a point of interest (usually the fan apex). The peak discharge is considered near the fan apex and the area inundated

Table 4
Size classification for debris flows

Size class	V , range (m ³)	Q_b , range (m ³ /s)	Q_v , range (m ³ /s)	B_b (m ²)	B_v (m ²)	Potential consequences
1	<10 ²	<5	<1	<4×10 ²	<4×10 ³	Very localized damage, known to have killed forestry workers in small gullies, damage small buildings
2	10 ² –10 ³	5–30	1–3	4×10 ² –2×10 ³	4×10 ³ –2×10 ⁴	Could bury cars, destroy a small wooden building, break trees, block culverts, derail trains
3	10 ³ –10 ⁴	30–200	3–30	2×10 ³ –9×10 ³	2×10 ⁴ –9×10 ⁴	Could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines
4	10 ⁴ –10 ⁵	200–1500	30–300	9×10 ³ –4×10 ⁴	9×10 ⁴ –4×10 ⁵	Could destroy parts of villages, destroy sections of infrastructure corridors, bridges, could block creeks
5	10 ⁵ –10 ⁶	1500–12,000	300–3×10 ³	4×10 ⁴ –2×10 ⁵	4×10 ⁵ –2×10 ⁶	Could destroy parts of towns, destroy forests of 2 km ² in area, block creeks and small rivers
6	10 ⁵ –10 ⁶	N/A	3×10 ³ –3×10 ⁴	>2×10 ⁵	2×10 ⁶ –3×10 ⁷	Could destroy towns, obliterate valleys or fans up to several tens of km ² in size, dam rivers
7	10 ⁶ –10 ⁷	N/A	3×10 ⁴ –3×10 ⁵	N/A	3×10 ⁷ –3×10 ⁸	Could destroy parts of cities, obliterate valleys or fans up to several tens of km ² in size, dam large rivers
8	10 ⁷ –10 ⁸	N/A	3×10 ⁵ –3×10 ⁶	N/A	3×10 ⁸ –3×10 ⁹	Could destroy cities, inundate large valleys up to 100 km ² in size, dam large rivers
9	10 ⁸ –10 ⁹	N/A	3×10 ⁶ –3×10 ⁷	N/A	3×10 ⁹ –3×10 ¹⁰	Vast and complete destruction over hundreds of km ²
10	>10 ⁹	N/A	3×10 ⁷ –3×10 ⁸	N/A	>3×10 ¹⁰	Vast and complete destruction over hundreds of km ²

V is the total volume, Q_b and Q_v are the peak discharge for bouldery and volcanic debris flows, respectively, B_b and B_v are the area inundated by bouldery and volcanic debris flows. N/A signifies that bouldery debris flows of this magnitude have not been observed. The constant in Eq. (2) was rounded so that B by non-volcanic debris flows is 10 times smaller than that of volcanic debris flows.

refers to the debris flow fan. For Class 6 to 10 volcanic debris flows where entire floodplain or mountain forelands are inundated, the three size categories refer to the maximum volume transported beyond the initiation area, the peak discharge anywhere along the transport zone, and the total area inundated downstream of the initiation area. The description of potential consequences is based on an extensive review of the debris flow literature, specifically the proceedings of the Conference on Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment (Chen, 1997; Wiczeorek and Naeser, 2000; Rickenmann and Chen, 2003).

Class 1 debris flows (10 to 10² m³ volume) occur in small channels or gullies and usually entrain little material as they flow downhill. They may be triggered in-channel or by a small debris slide or perhaps rock fall. Sediment supply limitations, insufficient water or rapid drainage in coarse and highly permeable colluvial deposits and low gradient encourage early deposition. These types of debris flows can be found in small gullies in hilly or mountainous terrain (Fig. 2). Debris flows with up to 100 m³ volume, discharge of up to 5 m³/s and up to 4000 m² of inundated area (Table 4), can cause significant damage if structures

are located near the fan apex where the debris flow is still traveling fast and carrying large boulders. There is no class smaller than Class 1 because debris flows with volumes under 10 m³ are usually of limited practical interest.

Class 2 debris flows (10² to 10³ m³) occur on small creeks that are often, but not necessarily, supply-limited. Debris flows in supply limited basins require a significant recharge period prior to each debris flow event and exhibit a lower frequency of debris flow activity. In contrast, supply-unlimited basins are controlled primarily by hydroclimatic events, since the supply of easily mobilized sediment is rarely a limiting condition for debris flow occurrence (Fig. 2). With a peak discharge of up to 30 m³/s, Class 2 debris flows can destroy small brick or wooden buildings over an area of up to 20,000 m² in the runout zone. Very heavy rainfall events can cause hundreds or thousands of Class 2 and Class 3 debris flows in a large region that may coalesce into higher class events (e.g. Lopez et al., 2003; Jan and Chen, 2005). Class 1 and 2 are rarely described in the scientific literature because case studies focus on spectacular or destructive events with few exceptions (Johnson and Warburton, 2003).

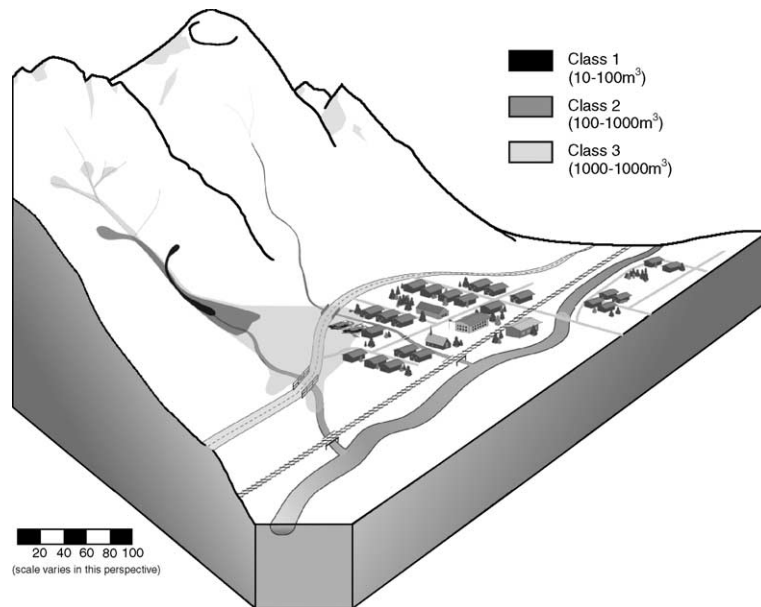


Fig. 2. Conceptual sketch for debris flows of size Class 1 to 3.

Class 3 ($V=10^3$ to 10^4 m³) encompasses a very typical size range that produces debris flows at decadal return periods in non-volcanic, supply-limited watersheds or at higher return periods for supply-unlimited channels (Fig. 2). These flows have high destructive potential with peak discharges of up to 200 m³/s and 90,000 m² area inundated. These flows are not easily recognized as a hazard because their return period in small (<5 km²) watersheds may span decades and ‘silent witnesses’ such as boulder lobes, impact scars on trees, or trim lines along channels of past debris flow activity are eroded or overgrown (Hungri et al., 1984). Examples of Class 3 debris flows include the 5000 m³ San Rocco debris flow and the 7000 m³ Bertogna debris flows in Italy (Bianco and Franzi, 2003).

Class 4 debris flows (10^4 to 10^5 m³) may occur on the same creeks as on Class 3 creeks but at return periods of hundreds of years for supply-limited watersheds (Jakob and Bovis, 1996; Bovis and Jakob, 1999), and they are seldom recognized as a significant hazard by individuals other than debris flow experts (Fig. 3). For many supply-limited watersheds of up to 5 km² size, the upper limit of Class 4 is the maximum size that can be achieved even during very long (thousands of years) return periods. An example of an

upper Class 4 bouldery debris flow with a total volume of 92,000 m³ and a peak discharge of approximately 1000 m³/s is the Hummingbird Creek debris flow in southern British Columbia (Jakob et al., 2000).

Class 5 debris flows (10^5 to 10^6 m³) originate mostly from volcanoes (but do not need to be syneruptive) or from areas with abundant sediment sources such as the Jiangjia ravine in southern China (Cui et al., 2005). Volcanic debris flows with a high clay content and a poorly developed or non-existent bouldery front that increases flow resistance are significantly more mobile than bouldery debris flows with a sandy-matrix. These characteristics of volcanic debris flows result in excessive runout distance that can convey the hazard from the source area to distant developed areas (Fig. 3). An example of a Class 5 event is the Drift River debris flow with a peak discharge of 2500 m³/s 19 km downstream of the source at Redoubt Volcano that occurred on March 9, 1990 (Dorava and Meyer, 1994). Bouldery debris flows of this magnitude are very rare, and physical evidence of older events can often only be interpreted by analyzing sedimentological evidence in trenches or natural exposures in the runout area. Because of their high volume, discharge of up to 12,000 m³/s and

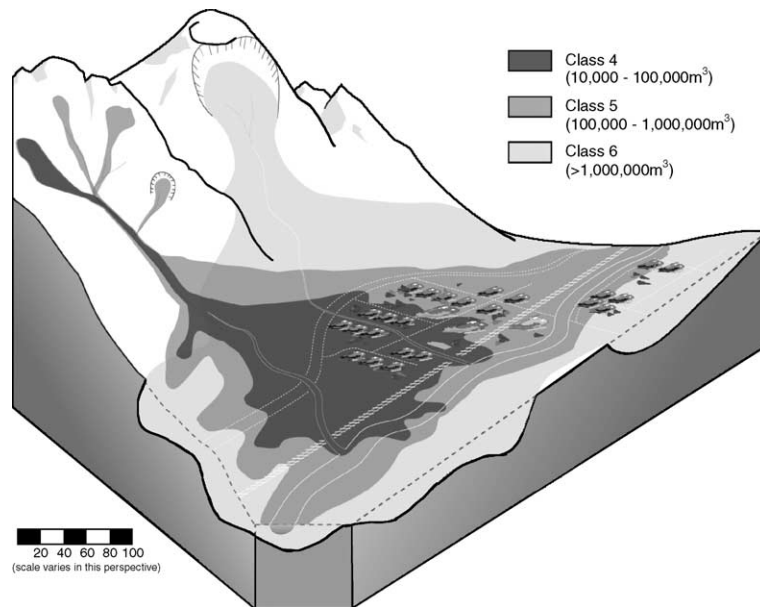


Fig. 3. Conceptual sketch for debris flows of size Class 4 to 6.

inundation of up to 2 km², Class 5 debris flows pose a tremendous risk to infrastructure and populations in their paths (Fig. 3).

Class 6 debris flows range from 10⁶ m³ to 10⁷ m³ in volume with a peak discharge of up to 30,000 m³/s and can inundate an area of up to 30 km². Class 6 debris-flows are usually triggered at volcanoes by edifice flank or sector collapses, eruption-triggered snowmelt or subglacial melting or lake outbreaks (Fig. 3). Class 6 debris flows are responsible for several tens of thousands of lost lives in the past 100 years worldwide (e.g. Wolf, 1878; Murai, 1960; Plafker and Ericksen, 1978; Pierson et al., 1990; Mothes, 1992). Class 6 is also the largest size classification given for bouldery debris flows as larger flows are known only from volcanoes. Four additional classes are introduced for the larger volcanic events that differ from the classes applied by Pierson (1998).

The 1998 Casita debris flow in Nicaragua serves as an example for a Class 7 debris flow with a volume of 1.8 × 10⁶ m³ (Scott, 2000). Well-studied examples of Class 8 events are the 1980 South Fork Toutle River debris flow with a volume of 1.3 × 10⁷ m³ and a peak discharge of 68,000 m³/s at Mt. St. Helens (Fairchild, 1985), and the debris flow at Huascarán, Peru ($V=1.3 \times 10^7$ m³) in 1962, and again in 1970 ($V=5$

to 10 × 10⁷ m³) (Plafker and Ericksen, 1978). Class 9 debris flows include the 4000 years BP event at Mt. Meager, British Columbia with an estimated volume of 1–2 × 10⁸ m³ (Friele and Clague, 2004) and the North Fork Toutle River debris flow ($V=1.4 \times 10^8$ m³, $Q=7200$ m³/s) at Mt. St. Helens (Fairchild, 1985). Examples of Class 10 debris flows include the Osceola Mudflow with 3–4 km³ volume and the Electron Mudflow (0.25 km³ volume) at Mount Rainier (Vallance and Scott, 1997). Without sufficient warning, debris flows of Class 7 to 10 could cause thousands to hundreds of thousands of fatalities and regional-scale destruction with long-term socio-economic consequences (Scott et al., 2001).

3.3. Application

This section addresses how the size classification could be used for a hazard assessment along a new road, railway or pipeline through debris flow-prone terrain.

The first step in such study would likely be a detailed air photograph interpretation along the highway alignment to identify debris-flow-prone creeks. Depending on the photo scale used, photogrammetry can aid in determining channel length (including

debris-flow-prone tributaries), and channel width. Spot checks in the field allow a rough estimate of yield rate (amount of material stored per meter channel length), and average depth of shallow debris-flow triggering landslides. Area measurements of landslide scars that triggered debris flows can also be accomplished using photogrammetric methods. In many areas and different climate zones the depth of shallow landslides does not differ significantly, which implies that volumetric estimates of the initiating failure can be attempted. Yield rate can be extrapolated over the channel length and summed with expected point source volumes to yield an estimate of debris flow volume. Using this method it is not possible to assign specific return periods for the volume thus determined, which would only be possible by detailed field investigations. This point is further discussed in Section 4. However, the application of the same methods to all watersheds

provides a comparable standard without the necessity of considering return periods. Recognizing that there will always be measurement error, a size classification based on order-of-magnitude estimates will smooth out any large discrepancies that may occur between practitioners.

Having estimated a total debris flow volume, Table 4 provides information on the expected range of peak discharge and total area inundated. Air photograph interpretation can usually identify the deposition zone of debris flows (typically downstream of the fan apex), and an approximation can be made as to the location of the area that would likely be debris covered. These data can then be used to rank debris-flow-prone watersheds by their hazard potential, to realign the road to avoid the highest hazard areas and to determine the magnitude of expenditures for debris flow mitigation measures where the hazard can not be avoided.

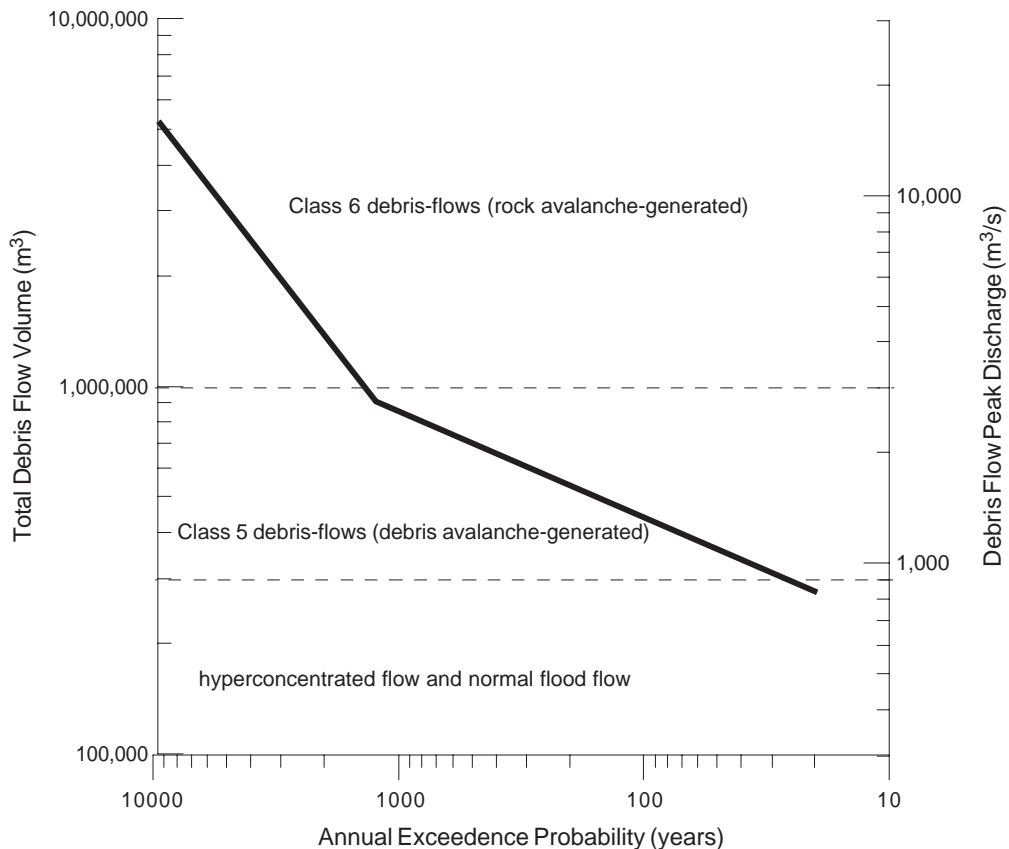


Fig. 4. Size classification for debris flows of a single stream (Cheekye River). Particularly for volcanic debris flows a wide spectrum of sizes can be observed, while supply-limited watersheds are likely to produce debris flows in only one or two size ranges.

For existing roads, data on past debris flows should be included in the size class estimates. The local government authority responsible for clean-up or restoration after debris flows should request the collection of debris flow size data immediately after an event has occurred. These data could be stored in a web-based database. The classification as proposed in this paper could aid this process because it does not necessarily require specialists to estimate sizes. This is even more important since, in most cases, the reopening of a transportation route is of highest priority, and experts are only sought if damage to people or essential infrastructure has occurred. By the time the expert arrives at the site, however, much of the physical evidence has been removed by the clean-up operations.

4. Discussion

Debris flows of different size classes may occur in the same watershed, usually increasing in size with longer return periods. In particular, channels draining large Quaternary volcanic complexes can produce debris-flows over a wide class range. For example, the Mount Garibaldi volcanic complex near the southern B.C. town of Squamish produces Class 4 and 5 debris flows on a decadal time scale and Class 6 debris flows on a millenium time scale (Fig. 4) (Friele and Clague, *in press*). Similarly, at Mount Rainier, debris flows of Class 5 occur almost annually, Class 6 on a century time scale, and Class 7 to 9 on a millenium time scale (Vallance, *pers. comm.*, 2003). The classification of debris-flow size, therefore, should not be interpreted as indicating that a certain class (that of the last reported event) cannot be exceeded. This can only be resolved if a frequency–magnitude relationship is constructed from a detailed reconstruction of past events. Such analysis needed for hazard quantification and delineation may entail separate analyses for debris flows of similar origin. Fig. 4 shows a frequency–magnitude curve for Cheekye River, which likely includes debris flows from volcanic rock avalanches that transform into debris flows (Class 6), and smaller debris flows generated by transformation of small debris slides or debris avalanches (Class 4 and 5) (Friele and Clague, *in press*).

5. Conclusions

A 10-fold classification system for debris flows is proposed based on debris-flow volume, peak discharge and area inundated by debris. A distinction is made between less mobile bouldery debris flows and highly mobile volcanic and other muddy debris flows. This system will be useful for regional debris-flow studies such as those conducted to evaluate the effects of a landslide-triggering storm or for hazard overview studies along infrastructure corridors. It is suggested that this classification be used routinely whenever a debris-flow has been recorded and that size information be entered in a publicly accessible database. These data would be very useful in detailed hazard assessments that require the construction of frequency–magnitude relationships of debris-flows, and it would help to prioritize mitigation work along highways, railways or pipeline corridors to protect infrastructure from damage.

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