MORPHOMETRIC CONTROLS AND BASIN RESPONSE IN THE CASCADE MOUNTAINS

BY

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ABSTRACT. Morphometric variables associated with 36 debris torrent, 78 snow avalanche, 45 composite debris torrent and snow avalanche and 14 streamflow basins in the Cascade Mountains of southwestern British Columbia, Canada are examined. The results show significant statistical differences in top and bottom elevations, relief, channel length and gradient, basin area, fan gradient and area, and basin ruggedness between snow avalanche basins and the two basin types affected by debris torrents, reflecting the very different nature of these processes. Only top and bottom elevations and fan area differ significantly between debris torrent and debris torrent–snow avalanche basins, implying that the latter are probably debris torrent basins in origin. As many as six morphometric variables are significantly different between streamflow basins and the other basin types, allowing the former to be differentiated despite their small, steep character. Discriminant analysis indicates that bottom elevation and channel or path gradient are the best variables for classifying the four basin types by process. Generally strong correlations exist between basin area on the one hand and relief, channel length and channel gradient on the other in debris torrent, debris torrent–snow avalanche, and streamflow basins. Fan gradient and area are, however, weakly or modestly correlated with basin area or ruggedness. No such morphometric relations are present in snow avalanche basins. The results of this study also indicate that in debris torrent-prone basins the fan gradient and Melton's *R* have identifiable lower thresholds while basin area has an upper threshold, but use of these thresholds for identification of debris torrent hazard is complicated by overlapping thresholds for streamflow basins.

Introduction

Debris flows and snow avalanches are common mass movement processes in mountain environments. A variety of terms have been employed to describe debris flows (Innes 1983; Van Dine 1985), with "debris torrent" commonly used in southwestern British Columbia, Canada, to describe channelised flows distinguished by a lack of fine-grained fraction, particularly clay, and a large organic content (Slaymaker 1988; Kellerhals and Church 1990). In this paper the term debris torrent is employed even when referring to debris flows in other mountain regions. Where steep first- or second-order stream basins straddle the winter snowline, snow avalanches and debris torrents can frequently occur in the same location, complicating investigations of these processes in, for example, hazard evaluations. Studies of alluvial fans in the Canadian Rockies have attempted to identify morphometric criteria which can be employed in a preliminary differentiation of debris torrent and flash flood hazards (Desloges and Gardner 1984; Kostaschuk *et al.* 1986; Jackson 1987; Jackson *et al.* 1987). In the southern Coast Mountains of British Columbia, prediction of debris torrent frequency and magnitude has been performed on the basis of morphometric variables and measures of debris supply processes (Jakob 1996; Jakob and Bovis 1996). Similarly, morphometric criteria may provide a means of differentiating debris torrent and flood-prone basins from snow avalanche basins and those affected by both debris torrents and snow avalanches.

Morphometric analysis may also provide insights into the underlying processes (Church and Mark 1980). Yet despite the attention given to, for example, the elevational zonation of hydrologic–geomorphic processes in high mountains (e.g. Hastenrath 1971; Winiger 1981; Abele 1982; Caine 1984; Stablein 1984), debris torrents and snow avalanches have rarely been investigated from such a perspective. A number of earlier studies (Bull 1964, 1972, 1977; Denny 1965; Hooke 1968; Church and Mark 1980; Kostaschuk *et al.* 1986) have also explored the relation between the size of alluvial fans and their contributing basins in order to understand the mechanisms of fan construction.

The purpose of this paper is to describe the morphometric characteristics of small basins along highways in southwestern British Columbia, Can-

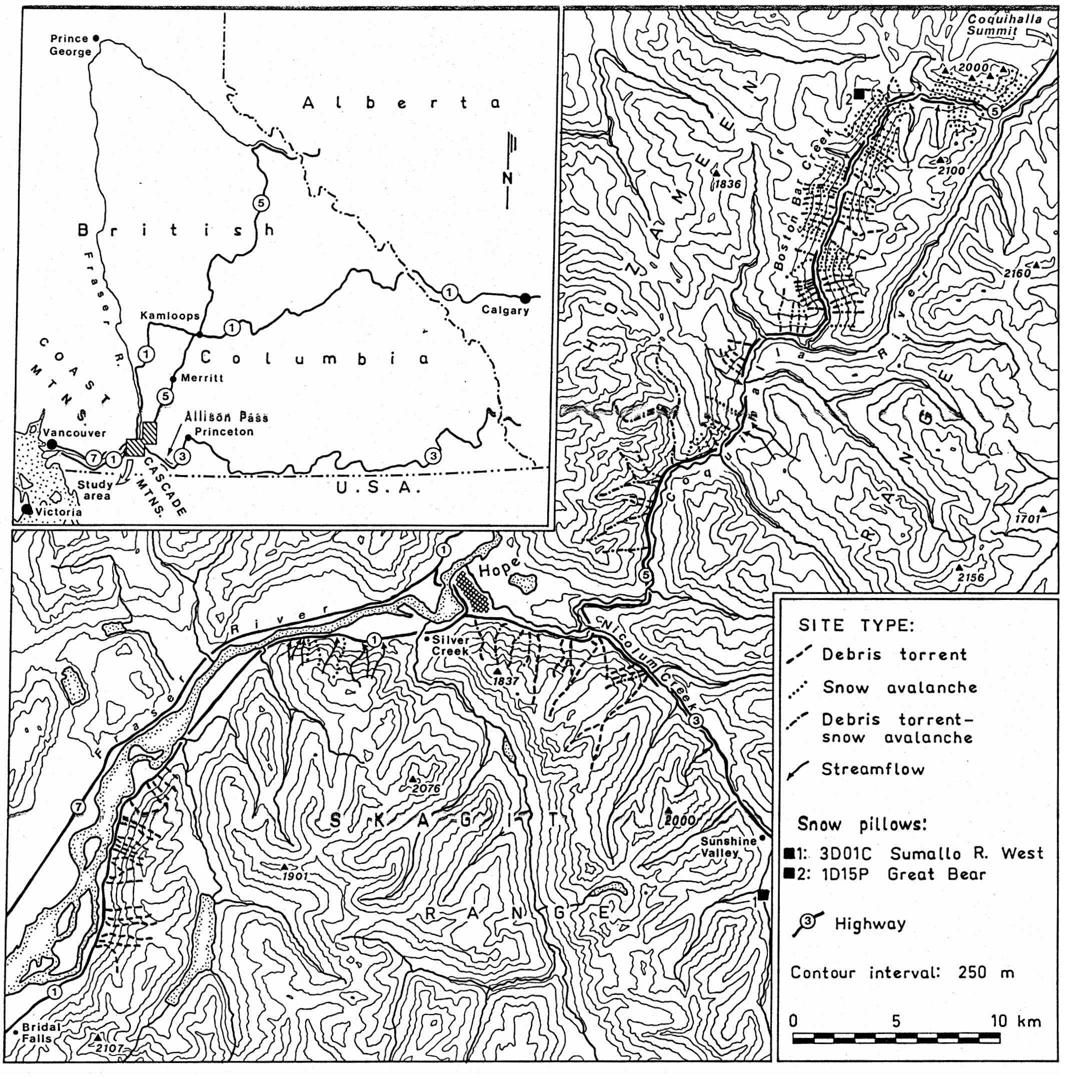

Fig. 1. Locations of debris torrent, snow avalanche, debris torrent–snow avalanche and streamflow basins in the study area.

ada, which generate debris torrents, snow avalanches and streamflow. The specific objectives are to: test for significant differences between the basin types and determine which of the morphometric variables can be employed to classify basins according to process; investigate relationships between morphometric variables at each type of basin; attempt to explain the results of the morphometric analyses on the basis of the underlying processes; explore the usefulness of selected morphometric characteristics for preliminary identification of debris torrent hazard.

Study area and data set

The study area is located in the Skagit and Hozameen Ranges on the west side of the Cascade Mountains in southwestern British Columbia (Fig. 1). These ranges consist of an axial core of gneiss and granitic rock flanked on the east and west by belts of folded and faulted, but not extensively metamorphosed, sedimentary and volcanic rocks of late-Palaeozoic to mid-Cretaceous age (Slaymaker *et al.* 1987). The basic structural pattern was established during intense deformation in mid-Cretaceous to early Tertiary time. Subsequent Pleistocene glaciations have greatly modified the physiography, especially through the action of valley and cirque glaciers which created U-shaped cross-sections and irregular longitudinal profiles in many valleys (Slaymaker *et al.* 1987). Many of the higher summits escaped being overridden by Pleistocene ice and thus being rounded, and as a result are today jagged.

The Cascade Mountains are a coastal mountain range and as a result mean annual precipitation decreases sharply from 1920 mm at Hope on the west side (40 m a.s.l.; Fig. 1) to 310 mm at Merritt on the east side (590 m a.s.l.; Fig. 1) 90 km away (Atmospheric Environment Service 1993). Orographic enhancement of precipitation is important, with higher slopes on the west side of the range receiving 2.5 times more precipitation than low-elevation stations near the coast (Hogg and Carr 1985). Seventy-three per cent of the annual precipitation falls during the October to March period, with the proportion falling as snow varying primarily with elevation; annual snowfall amounts to 170 cm at Hope while Allison Pass (1340 m a.s.l.; Fig. 1) receives 1430 cm (Atmospheric Environment Service 1980, 1993). Mid-winter thaws and rain-on-snow events are common at all but the highest elevations and as a result snowpack depths and water equivalents are also closely related to elevation. For example, four years of snow pillow data show a 1 April water equivalent of only 30 mm at the Sumallo River West station (790 m a.s.l.; Fig. 1) but 1610 mm at the Great Bear station (1660 m a.s.l.; Fig. 1) (BC Environment 1996). The regional timberline is situated at an elevation of 1550–1650 m a.s.l., with slopes below this being covered with dense coniferous forest except where logging has taken place.

Exceptionally steep slopes, relief of 1300 to 1700 m, and high intensity precipitation combine to produce a high level of debris torrent activity in the study area. Important sediment sources for debris torrents include veneers of Pleistocene glacial and Holocene colluvial deposits in the steep channels (Slaymaker *et al.* 1987), with the former more important at lower elevations. Most events are triggered by heavy rain in the late fall or winter in channels which are located completely or partially below the winter snowline. Debris torrents can occasionally be triggered by prolonged summer rain (Church and Miles 1987). With respect to such rainfall triggering, the rapid west to east changes in precipitation amount and type play an important role. Triggering of debris torrents by rockfall, often in conjunction with heavy rain, also appears to be relatively common in the study area with the implication that such events may run out onto slopes where normal debris torrents would not be expected to continue flowing (Slaymaker *et al.* 1987). Most snow avalanches in the study area are triggered by snowfall loading or rapid warming of an otherwise relatively stable snowpack. Occasionally snowpack instabilities can be generated by kinetic crystal growth during outbreaks of Arctic air from the interior of British Columbia (Bennetto 1988).

Data on morphometric variables, past events and potential for future events are available for debris torrent, snow avalanche and selected streamflow basins along three highways radiating out from Hope (Fig. 1): Hwy 1 adjacent to the Fraser River for a distance of 25 km southwest of Hope; Hwy 3 in the Nicolum Creek valley for a distance of 10 km southeast of Hope; and Hwy 5 in the valleys of the Coquihalla River and Boston Bar Creek for a distance of 34 km northeast of Hope. The individual sites are shown in Fig. 1. Debris torrent basins are small, steep and generally heavily forested basins, with an abundant supply of sediment available for debris torrents in or adjacent to channels. A small, steep and likewise heavily forested alluvial fan has usually been constructed at the mouth of debris torrent basins. Snow avalanche basins are situated at higher elevations although their runout and track zones, and in some cases even starting zones, are below the regional timberline. They include a wide variety of avalanche paths ranging from very small, minimally confined paths to large paths with well defined basins acting as starting zones. The avalanche paths are generally covered in dense brush although in the starting zones extensive areas of bare rock may be present. Basins with both debris torrent and snow avalanche potential usually possess characteristics of snow avalanche paths higher up and more closely resemble debris torrent channels in their lower reaches. Streamflow basins are small and as a result bear a superficial resemblance to debris torrent basins. Most generate only ephemeral or intermittent rather than perennial streamflow. Some possess a high to very high probability of debris floods but the formation of debris torrents is inhibited by lack of available sediment or the presence of sediment traps along the channel long profile. In this respect the role of sediment availability in debris torrent generation is explored extensively by Bovis and Dagg (1987), Jakob (1996) and Jakob and Bovis (1996).

Table 1. Categories of probability of debrish torrent occurrence employed in British Columbia.

Category	Description
4	**Very high probability of occurrence**: indicates that torrents of less than the design magnitude can occur frequently with high runoff conditions, and the design torrents should be assumed to occur within the short term. It is applied to creeks that have a history of more than one event involving greater than 500 m^3 or have physical characteristics that are comparable to these creeks.
3	**High probability of occurrence**: indicates that torrents of less than the design magnitude will occur less frequently than under category 4 but the design torrent should still be assumed to occur within the short term. It is applied to creeks that have a history of a single debris torrent. It is also applied to creeks that have no known history of events but possess several significant physical characteristics that are comparable to category 4 creeks.
2	**Moderately high probability of occurrence**: indicates that the design torrent should be assumed to occur during the life of a significant long-term structure (such as a bridge or house). It is applied to those creeks that have significant physical characteristics that fall well within the threshold where debris torrents are possible, although not in the range of category 4. To date these creeks have no recorded history of debris torrents, or have experienced events of uncertain origin.
1	**Low probability of occurrence**: indicates a low potential for the design torrent. It is applied to those creeks whose physical characteristics place them at or close to the threshold where debris torrents are possible. Although a significant debris torrent is possible during the life of a long-term structure, it would require an unusually high (and thus infrequent) runoff condition.
0	**No risk**: indicates that there is virtually no potential for large debris torrents to occur although small and local torrents may occur, and torrents of varying magnitudes may develop in upper reaches and tributaries. It is applied to channel reaches whose physical characteristics fall well below the threshold where debris torrents are possible.

From Thurber Consultants Ltd (1983)

Methods of analysis

Derivation of basin types and morphometric variables

The initial classifications of basin types are accomplished independently from the morphometric variables analysed in this study, being derived on the basis mostly of parameters associated with the processes themselves. Specifically, the presence or absence of debris torrent activity in each basin is determined on the basis of the probability of occurrence as assessed in Thurber Consultants Ltd (1985). This probability is rated according to a classification commonly used in the Canadian Cordillera (Table 1), and is evaluated using the following criteria: occurrence and volume of past events; basin area within the range associated with historic debris torrent activity; average and maximum stream gradients exceeding critical thresholds; presence of a fan that is abnormally large, or lobed or convex in shape; average fan gradient exceeding a critical threshold; availability of sediment for mobilisation by debris torrent; unstable channel banks which exceed 30% of the total stream length; logging along more than 10% of the stream's length (Van Dine 1985). While some of the criteria are morphometric the majority are not, thus avoiding the problem of the debris torrent probability rating being based exclusively on morphometric criteria. Summaries of detailed field surveys of channel conditions, sediment availability, historic debris torrents, and potential debris torrent initiation areas in Thurber Consultants Ltd (1985) confirm this. The identification of active or potential snow avalanche paths in the avalanche atlases is based on air photograph analysis and field checking of vegetative and other evidence of past avalanching, and observations of avalanche activity since 1973. These assessments of debris torrent and snow avalanche potential represent the state of the art in the Canadian Cordillera and a high level of confidence is placed in their accuracy.

For the purposes of this study, debris torrent basins are defined as those which either have demonstrated debris torrent activity (categories 3 and 4 in Table 1) or which have significant physical characteristics that fall within the threshold where debris torrents are possible (categories 1 and 2). The following basin types can then be classified: (a) debris torrent basins with no snow avalanche activity; (b) snow avalanche basins (active or potential) with no debris torrents; (c) composite debris torrent–snow avalanche basins; and (d) basins with no debris torrent or snow avalanche activity but where evidence of fan construction indicates streamflow. This classification scheme produces 36 debris torrent basins, 78 snow avalanche basins, 45 debris torrent–snow avalanche basins, and 14 streamflow basins.

The morphometric variables obtained for each of the basin types are shown in Table 2. Unless indicated otherwise they are obtained from Thurber Con-

Table 2. Description of morphometric variables.

Variable	Description
Top elevation	Highest point in the basin, measured from 1:25 000 or 1:5000 profiles or 1:1000 contour maps (debris torrent, debris torrent–snow avalanche and streamflow basins) or from 1:50 000 topographic maps (snow avalanche basins).
Bottom elevation	Lowest point on the alluvial fan (debris torrent, debris torrent–snow avalanche and streamflow basins) or runout zone (snow avalanche basins), measured as above.
Relief	Difference between the top and bottom elevations.
Channel or path length	Measured from 1:25 000 channel profiles (debris torrent, debris torrent–snow avalanche and streamflow basins) or calculated by the authors from the gradients and vertical falls of starting, track and runout zones in the avalanche atlases (snow avalanche basins). These are usually measured from 1:50 000 topographic maps although gradients are field surveyed whenever possible.
Channel or path gradient above the fan or runout	Average gradient of the channel or path above the fan or runout, measured from 1:25 000 or 1:5000 channel profiles or by field surveys (debris torrent, debris torrent–snow avalanche and streamflow basins) or calculated by the authors as the vertical fall-weighted average of the starting and track zone gradients in the avalanche atlases (snow avalanche basins). These are measured from 1:50 000 topographic maps or by field surveys.
Fan or runout gradient	Average gradient of the fan or runout, measured along the approximate axis of the fan from 1:5000 profiles or 1:25 000 enlargements of 1:50 000 topographic maps or by field surveys (debris torrent, debris torrent–snow avalanche and streamflow basins). The runout zone gradient is measured from 1:50 000 topographic maps or by field surveys in snow avalanche basins.
Basin area	Planimetric area of the basin, measured from 1:25 000 enlargements of 1:50 000 topographic maps (debris torrent, debris torrent–snow avalanche and streamflow basins) or measured by the authors from 1:25 000 enlargements of 1:50 000 maps in the avalanche atlases (snow avalanche basins).
Melton's ruggedness number (*R*) for the basin	An index of basin ruggedness (Melton 1965; Church and Mark 1980), calculated by the authors by: $R = H_b A_b^{-0.5}$ where H_b is the basin relief and A_b is the planimetric basin area. Both terms include the fan (or runout zone) whereas other studies have excluded the fan in the calculation of *R* (Kostaschuk *et al.* 1986; Jackson *et al.* 1987). Given the small proportion of H_b and A_b occupied by the fan (or runout) the difference in the value of *R* is negligible.
Fan area	Delineated from air photographs and transferred to 1:25 000 maps from which the area is measured; available for 35 debris torrent, 12 snow avalanche, 42 debris torrent–snow avalanche, and 14 streamflow basins. At the mouth of the snow avalanche basins a poorly developed fan or 'avalanche cone' (Luckman 1977) is present, probably constructed by some combination of snow avalanching and streamflow.

sultants Ltd (1985) or avalanche atlases of the BC Ministry of Transportation and Highways (1980a, b). In debris torrent–snow avalanche basins the values of morphometric variables provided by both Thurber Consultants Ltd (1985) and the avalanche atlases rarely disagree. Where they do, the value judged to be most accurately measured is employed.

Analysis of morphometric variables

Descriptive statistics for each of the morphometric variables shown in Table 2 are calculated using the basin type (debris torrent, snow avalanche, debris torrent–snow avalanche, streamflow) as the grouping variable. The significance of the between-groups differences in each variable is tested using Tukey-Kramer HSD pairwise comparisons, transforming variables with significant skewness by their natural logarithm first. The Tukey-Kramer test provides protection against the rapidly increasing probability of finding a significant difference by chance alone when the number of pairs being tested increases (SYSTAT 1992). Discriminant analysis is used to identify the variables which best classify debris torrent, snow avalanche and debris torrent–snow avalanche basins correctly. Streamflow basins are excluded because of the small sample. The discriminant analysis involves a stepwise procedure where the choice of variables for the discriminant functions is based on *F* values (SYSTAT 1992). All variables except fan area are employed in the discriminant analyses.

Pearson product-moment correlation is used to test the strength of relationships between morphometric variables at each type of basin. With the exception of the area of streamflow basins, logarith-

Table 3. Descriptive statistics for morphometric variables grouped by process type.

Variable	Basin type*	Mean	Minimum	Maximum	Standard deviation	Standard error of the mean	Skew-ness	Kurtosis†
Top elevation (m a.s.l.)	1	1009	325	1625	316	53	–0.31	–0.58
	2	1491	725	2010	287	33	–0.34	–0.07
	3	1315	790	1770	245	37	–0.24	–0.63
	4	1063	580	1380	265	71	–0.43	–1.08
Bottom elevation (m a.s.l.)	1	154	10	940	223	37	+1.80	+3.13
	2	867	40	1310	301	34	–0.77	+0.47
	3	532	100	940	223	33	–0.45	–0.87
	4	429	40	1190	440	118	+0.64	–1.14
Relief (m)	1	855	315	1360	308	51	–0.03	–1.24
	2	623	305	1170	162	18	+0.27	+0.39
	3	783	210	1565	270	42	+0.34	+0.89
	4	634	180	1200	321	86	+0.30	–0.99
Channel or path length (m)	1	2061	600	5650	1169	195	+1.45	+2.26
	2	1224	580	2500	330	37	+0.81	+1.66
	3	1785	550	4750	841	125	+1.48	+2.43
	4	2079	950	3040	607	162	–0.13	–0.79
Channel or path gradient‡ (degree)	1	30.9	12	43	7.9	1.3	–0.88	+0.20
	2	34.6	20	51	5.8	0.7	+0.86	+1.36
	3	28.9	12	36	5.7	0.9	–1.11	+0.87
	4	21.7	5	37	12.9	3.4	–0.10	–1.75
Fan or runout gradient (degree)	1	12.2	4	24	5.0	0.8	+0.45	–0.41
	2	16.5	0	29	5.1	0.6	–0.45	+0.67
	3	13.6	3	29	5.6	0.8	+0.61	+0.05
	4	12.7	2	30	8.5	2.3	+0.52	–0.86
Basin or path area (km^2)	1	1.34	0.05	10.90	2.26	0.38	+2.85	+8.05
	2	0.29	0.06	2.65	0.35	0.04	+4.79	+27.86
	3	1.28	0.04	19.20	3.01	0.45	+5.04	+26.52
	4	2.41	0.30	5.36	1.72	0.46	+0.27	–1.23
Fan area (km^2)	1§	0.080	0.005	0.298	0.080	0.013	+0.98	–0.01
	2§	0.036	0.002	0.210	0.057	0.016	+2.69	+5.91
	3§	0.035	0.003	0.420	0.072	0.011	+4.19	+18.61
	4§	0.068	0.012	0.240	0.064	0.017	+1.46	+1.72
Melton's *R*	1	1.12	0.38	1.77	0.37	0.06	–0.50	–0.48
	2	1.39	0.46	2.95	0.49	0.06	+0.48	+0.12
	3	1.07	0.23	1.89	0.38	0.06	+0.06	–0.82
	4	0.59	0.10	1.34	0.44	0.12	+0.31	–1.42

* 1, Debris torrent basins (n=36); 2, snow avalanche basins (n=78); 3, debris torrent–snow avalanche basins (n=45); 4, streamflow basins (n=14).
† 0, mesokurtic; +, leptokurtic; –, platykurtic.
‡ Above the fan or runout.
§ 1, n=35; 2, n=12; 3, n=42; 4, n=14.

mically transformed values of basin and fan areas are employed since the results show these variables to be significantly skewed and Pearson correlation assumes a normal distribution of data (SYSTAT 1992).

Results

The descriptive statistics for the untransformed morphometric variables are provided in Table 3 for comparison between the four basin types. Rankings for the mean values in Table 3, regardless of whether the differences between the means are statistically significant or not, are shown in Table 4. The statistically significant differences in mean values are described below. Table 3 shows that with the exception of basin area (debris torrent, snow avalanche, and debris torrent–snow avalanche basins), fan area

Table 4. Mean value rankings for morphometric variables.

Variable	Ranking
Top elevation	Debris torrent < streamflow < debris torrent–snow avalanche < snow avalanche
Bottom elevation	Debris torrent < streamflow < debris torrent–snow avalanche < snow avalanche
Relief	Snow avalanche < streamflow < debris torrent–snow avalanche < debris torrent
Channel/path length	Snow avalanche < debris torrent–snow avalanche < debris torrent < streamflow
Channel/path gradient	Streamflow < debris torrent–snow avalanche < debris torrent < snow avalanche
Fan/runout gradient	Debris torrent < streamflow < debris torrent–snow avalanche < snow avalanche
Basin area	Snow avalanche < debris torrent–snow avalanche < debris torrent < streamflow
Fan area	Debris torrent–snow avalanche ≤ snow avalanche < streamflow < debris torrent
Melton's *R*	Streamflow < debris torrent–snow avalanche < debris torrent < snow avalanche

Table 5. Tukey-Kramer pairwise comparisons, showing the difference in means of morphometric parameters for significantly different pairs of basin types (significance level = 0.05).

	Basin pair					
Parameter	Snow avalanche: debris torrent	Snow avalanche: debris torrent–snow avalanche	Snow avalanche: streamflow	Debris torrent: debris torrent–snow avalanche	Debris torrent: streamflow	Debris torrent–snow avalanche: streamflow
Top elevation (m)	481	175	428	–306	NSD	253
Bottom elevation (m)	713	335	438	–378	–275	NSD
Relief (m)	–232	–160	NSD	NSD	221	NSD
Channel or path length (m)	–837	–561	–855	NSD	NSD	NSD
Channel or path gradient* (degree)	3.7	5.8	12.9	NSD	9.2	7.2
Fan or runout gradient (degree)	4.3	2.9	NSD	NSD	NSD	NSD
Basin area† (km^2)	–1.05	–0.99	–2.12	NSD	–1.07	–1.13
Fan area† (km^2)	NSD	NSD	NSD	0.045	NSD	–0.033
Melton's *R*	0.28	0.32	0.80	NSD	0.52	0.48

* Above the fan or runout.
† Except for the area of streamflow basins the natural logarithm of these variables is used for the Tukey-Kramer HSD pairwise comparisons.
NSD = no significant difference.

(snow avalanche and debris torrent–snow avalanche basins) and bottom elevation (debris torrent basins) the morphometric data possess only slightly skewed distributions. Few of the morphometric variables possess a mesokurtic distribution, with leptokurtic (peaked) distributions being most common. Only streamflow basins possess consistently platykurtic (non-peaked) distributions.

The results of the Tukey-Kramer HSD pairwise comparisons at a significance level of 0.05 are presented in Table 5. They show significant differences in all morphometric variables except fan area between snow avalanche basins on the one hand and debris torrent and debris torrent–snow avalanche basins on the other. Only top and bottom elevations and fan area are significantly different between debris torrent and debris torrent–snow avalanche basins. Five or six variables are significantly different between streamflow basins on the one hand and the three other basin types on the other; of these channel/path gradient, basin area and Melton's *R* differ between all three basin pairs. Fan/runout gradient is not significantly different between any of the three pairs.

Given the similarity between debris torrent and debris torrent–snow avalanche basins as indicated by the Tukey-Kramer pairwise comparisons (Table 5), these two basin types are then combined into one group and its morphometric variables tested against the snow avalanche basin type using ANO-

Table 6. Discriminant analyses for combinations of basin types.

		Number of basins predicted (percent)			
Basin type	Test number*	Debris torrent	Snow avalanche	Debris torrent–snow avalanche	Debris torrent and debris torrent–snow avalanche
Debris torrent	1	29 (81)	0 (0)	7 (19)	
(*n*=36)	2	36 (100)	0 (0)		
Snow	1	4 (5)	64 (82)	10 (13)	
avalanche	2	6 (8)	72 (92)		
(*n*=78)	3		69(88)		9 (12)
Debris torrent–snow avalanche (*n*=45)	1	12 (27)	9 (20)	24 (53)	
Debris torrent and debris torrent–snow avalanche (*n*=81)	3		14 (17)		67 (83)

* 1, Debris torrent, snow avalanche, debris torrent–snow avalanche basins. Discriminant functions = bottom elevation, channel/path gradient. 2, Debris torrent, snow avalanche basins. Discriminant functions = bottom elevation, channel/path gradient, Melton's *R*. 3, Debris torrent and debris torrent–snow avalanche basins combined, snow avalanche basins. Discriminant functions = bottom elevation, channel/path gradient.

VA (SYSTAT 1992). The results show that all of the variables except fan area are significantly different at the 0.001 level. Snow avalanche basins are smaller and at higher elevation, and possess lower relief, shorter and steeper channels and a higher Melton's *R*.

The results of the initial discriminant analysis are shown in Table 6 (test 1), employing bottom elevation and channel/path gradient as the discriminant functions on the basis of the *F* values obtained. The overall number of debris torrent, snow avalanche, and debris torrent–snow avalanche basins correctly classified is 117 out of a total of 159 (73.6%). The best results are obtained for debris torrent and snow avalanche basins where 81% and 82% respectively are correctly classified. Only 53% of debris torrent–snow avalanche basins are correctly classified. Given this modest performance and the morphometric similarity of debris torrent and debris torrent–snow avalanche basins described above, the discriminant analyses are performed again using different groups of basin types. Table 6 (test 2) shows the results employing only debris torrent and snow avalanche basins with bottom elevation, channel/path gradient and Melton's *R* as the discriminant functions. The overall number of basins correctly classified is 108 out of a total of 114 (94.7%), with 100% of debris torrent basins and 92% of snow avalanche basins being correctly classified. Table 6 (test 3) shows the results employing debris torrent and debris torrent–snow avalanche basins as one group and snow avalanche basins as another, with bottom elevation and channel/path gradient as the discriminant functions. The overall number of basins correctly classified is now 136 out of a total of 159 (85.5%), with 83% of the combined debris torrent and debris torrent–snow avalanche basins and 88% of the snow avalanche basins being correctly classified.

The Pearson product-moment correlations in Table 7 show that strong positive correlations exist between basin area and relief in debris torrent and debris torrent–snow avalanche basins but not in snow avalanche and streamflow basins. Strong positive correlations also exist between basin area and channel length, and strong negative correlations between basin area and channel gradient, in all basins except snow avalanche basins. Basin area shows weak or modest negative correlations with fan/runout gradient. Melton's *R* also shows weak or modest positive correlations with fan/runout gradient. Basin area exhibits a modest positive correlation with fan area in debris torrent and debris torrent–snow avalanche basins, and actually a modest negative correlation in streamflow basins. The significant positive correlation between path and fan areas in snow avalanche basins is misleading because 11 of the 12 sites cluster very tightly on a scatterplot of these two variables.

Table 7. Pearson product-moment correlations (r) between basin area and other morphometric parameters. Correlations with Melton's R are shown in paranthesis.

Parameter	Basin type: Debris torrent[1]	Snow avalanche[2]	Debris torrent-snow avalanche[3]	Streamflow[4]
Relief	+0.76*	+0.37*	+0.72*	–0.53**
Channel/path length	+0.92*	+0.34*	+0.89*	+0.77*
Channel/path gradient	–0.71*	+0.03***	–0.77*	–0.85*
Fan/runout gradient	–0.19*** (+0.35**)	–0.32* (+0.15***)	–0.47* (+0.54*)	–0.62* (+0.58**)
Fan area	+0.58*	+0.69*	+0.41*	–0.53**

[1] $n=36$ except for fan area where $n=35$. [2] $n=78$ except for fan area where $n=12$. [3] $n=45$ except for fan area where $n=42$.
[4] $n=14$. * Significance level ≤ 0.01; ** Significance level = 0.05; *** Significance level > 0.1

Discussion

The results show that differentiation of the four types of basins can be achieved in the study area by employing morphometric variables. The similarities in some of the morphometric variables between basin types are also of interest because they shed light on the underlying processes. The results also point to strong structural controls on some of the weaker morphometric relations at individual basin types. A more detailed discussion follows.

Morphometric differences between basin types

Tables 5 and 6 indicate that the morphometric character of snow avalanche basins in the study area is fundamentally different from debris torrent and debris torrent–snow avalanche basins. This reflects the very different nature of snow avalanching and debris torrents and the environmental controls on these processes, which can be summarised as follows. Snow avalanche basins are situated at higher elevations, and possess lower relief because of lower available relief in the higher elevation valleys, especially along Hwy 5 in the Boston Bar Creek valley. Basin areas are much smaller since the basins do not need to store sediment and concentrate runoff in the way that debris torrent basins do. The large relief relative to the small area of snow avalanche basins produces Melton's R values that are significantly higher than for debris torrent and debris torrent–snow avalanche basins. Avalanche path gradients are significantly steeper than gradients of debris torrent and debris torrent–snow avalanche channels in order for avalanches to be able to maintain momentum. Avalanche runouts are also much steeper than debris torrent and debris torrent–snow avalanche fans. They are also steeper than what is typical of avalanche runouts (McClung and Schaerer 1993), probably because the narrowness of the valleys of Coquihalla River and Boston Bar Creek cause avalanches to terminate in the water courses instead of extending onto low angled valley floors. The fan area of snow avalanche basins is not significantly different from debris torrent and debris torrent–snow avalanche basins, probably because the fans are primarily the product of fluvial processes rather than avalanching.

There are few significant morphometric differences between debris torrent and debris torrent–snow avalanche basins (Table 5), which accounts for the poor classification of the latter type in the discriminant analysis (Table 6, test 1). The lack of difference suggests that the debris torrent–snow avalanche basins are essentially debris torrent basins where avalanching might never have occurred but for the presence of debris torrent activity. In other words, debris torrents initially erode a channel which then becomes suitable for snow avalanching. This interpretation rests on the assumption that, unlike other mountain environments where snow avalanches can perform a direct geomorphic role or contribute to other mass movement activity through hydrologic effects (Sosedov and Seversky 1966; Gardner 1970; Luckman 1977; Bell *et al.* 1990; de Scally 1996), snow avalanches in this environment are unlikely to be geomorphically significant. The very low sediment content of most observed avalanche deposits and the dense brush in the starting zones of many of the avalanche paths lend support to this assumption, as do the generally lower gradients of the debris torrent–snow avalanche fans compared to similar fans in the Canadian Rockies where avalanche transport of sediment helps to construct steeper fans (Kostaschuk *et al.* 1986; Jackson 1987).

Despite the overall similarity between debris torrent and debris torrent–snow avalanche basins, their top and bottom elevations differ significantly, reflecting the elevational zonation of these processes in the study area. Most debris torrents in southwestern British Columbia occur in the late fall and winter when the possibility of saturated ground conditions, heavy rainfall, and rising freezing levels with associated snowmelt is greatest (Van Dine 1985; Church and Miles 1987; Slaymaker 1990). However, at these times of year they can only occur at lower elevations where a deep and continuous snow cover is absent. In fact, the bottom elevations of the numerous debris torrent basins along Hwy 1 are near sea level which accounts for the positive skewness in the data (Table 3). Above the winter snowline the snowpack and lack of melt prevent the formation of debris torrents but promote snow avalanching. This climatically related zonation by elevation of debris torrent and snow avalanche activity may in the Canadian Cordillera be confined to coastal regions of British Columbia. Further inland, debris torrent triggering occurs primarily as a result of rapid spring snowmelt or heavy summer rain (Owens 1973; Van Dine 1985; Toews 1991) and therefore would not be expected to exhibit such zonation. The zonation may also be related partly to the history of Pleistocene glaciation in the study area. Glacial and glaciofluvial sediments at lower elevations in the valleys of the Fraser, Coquihalla and Nicolum Rivers (Slaymaker *et al.* 1987) supply abundant material for debris torrents in "drift-dominated" (Bovis and Dagg 1987) or "transport-limited" (Jakob 1996) basin types. On the other hand at higher elevations only thin veneers of Holocene colluvial sediments may inhibit debris torrent activity in the manner of "rockslope-dominated" (Bovis and Dagg 1987) or "weathering-limited" (Jakob 1996) basins. The importance of sediment availability to debris torrent generation is demonstrated by Jakob (1996) and Jakob and Bovis (1996) who employ two area-normalised measures of debris supply processes in addition to morphometric criteria to predict debris torrent frequency and magnitude. They also demonstrate that stratifying basins into "weathering-limited" and "transport-limited" types, largely on the basis of lithology, improves the predictive power of their model.

Debris torrent–snow avalanche basins occur at elevations intermediate between debris torrent basins and snow avalanche basins for the following reason: they have to be low enough for adequate sediment to be available and the winter snowline to be able to fluctuate above a portion of the basin for debris torrent occurrence, but high enough that the higher parts of the basin possess snow conditions suitable for avalanching. This snow cover at the higher elevations may account for the much smaller debris torrent–snow avalanche fans compared to debris torrent fans (Tables 3 and 5): the portion of the basin usually covered with snow may be a relatively unimportant source of sediment for fan formation.

The results of the discriminant analyses (Table 6) indicate that the bottom elevation and channel/path gradient of basins are the most useful variables for identifying debris torrent-prone basins. Jakob (1996) and Jakob and Bovis (1996) show basin relief and ruggedness to be the most useful morphometric variables in a multivariate predictive model of debris torrent frequency and magnitude. Their variables probably reflect the same requirement that channel/path gradient does in this study, which is a sufficiently steep slope for debris torrents to be able to maintain momentum. The bottom elevation of basins may be a useful diagnostic variable in areas where debris torrents exhibit the type of elevational zonation found in this study. However, a group of debris torrent basins from a larger area with greater climatic variation, such as employed by Jakob (1996) and Jakob and Bovis (1996), would not be expected to conform to such elevational controls.

Table 5 shows that streamflow basins can be differentiated from snow avalanche basins on the basis of six of the nine morphometric variables, and from debris torrent and debris torrent–snow avalanche basins on the basis of five variables. The latter differentiation is particularly significant given that none of the streamflow basins are large basins from which debris torrent activity would in any obvious way be absent. Table 3 shows that all of them fall well below the 10 km^2 size threshold at which a transition from debris torrent activity to fluvial activity at the basin mouth generally occurs in the Canadian Cordillera (Van Dine 1985; Jackson 1987; Jackson *et al.* 1987; Kellerhals and Church 1990; Jakob and Bovis 1996; de Scally 1999).

Relationships between morphometric variables

Table 7 shows that a significant positive correlation exists between the area and relief of debris torrent and debris torrent–snow avalanche basins, indicating that larger basins are more likely to contain higher peaks than smaller basins. This corresponds well with earlier research on debris torrent basins in the Canadian Cordillera (Ryder 1971a; Jackson 1987). The area–relief relationship is, however, not as evident in streamflow basins (Table 7). Table 7 also shows that in debris torrent, debris torrent–snow avalanche and streamflow basins the channel length increases and channel gradient decreases with increasing basin area. Such relations, common in large fluvial basins (Knighton 1998), therefore also appear to hold true in steep first- and second-order basins. These relationships are weak in snow avalanche basins presumably because avalanches in the study area are unable to carry out erosional work and transport sediment in the way that debris torrents and streamflow can.

Assuming that alluvial fans can develop independently of any constraints to their size or gradient, their morphometry may be expected to be related to morphometric characteristics of the contributing basin since these control the nature of sediment delivery to the fan (Bull 1964, 1977; Ryder 1971a; Church and Mark 1980; Van Dine 1985; Kostaschuk *et al.* 1986; Jackson *et al.* 1987; Kellerhals and Church 1990). Table 7 shows that weak or modest correlations exist between the Melton's R or area of the basin and fan gradient, and basin area and fan area. This suggests that the fan characteristics reflect the characteristics of the deposition area or trunk valley as much as they do the characteristics of the contributing basin. This can occur for two reasons in the study area. First, since much of the sediment in trunk valleys is paraglacial in origin (Ryder 1981), it is likely that the fans are also paraglacial. In that case the short duration of fan construction would allow insufficient time for the effects of basin characteristics to be transmitted to the fan (Ryder 1971a, b; Kostaschuk *et al.* 1986). Second, the confined valley bottoms may constrain fan development through erosion of fan toes by the trunk streams. The weak correlations between Melton's R and fan gradient may also be caused partially by the nature of the distribution of high peaks in British Columbia, which affects the values of H_b in the equation for R (Table 2). Larger basins are more likely to contain higher peaks and therefore the expected increase in fan gradient with increasing relief is masked by the effect of increasing basin area on the value of Melton's R (Ryder 1971a).

Hazard identification

The gradient of a fan has no controlling influence on the ability of the contributing basin to initiate debris torrents and maintain their momentum. However, this gradient is potentially useful for identifying debris torrent hazards on the fan itself, since a minimum slope is required to permit debris torrent motion over the fan. The gradient in this case is generally taken as the average gradient from the toe to the apex of the fan as measured along the fan axis. The minimum gradient of debris torrent fans in this study (4°; Table 3) occurs on two fans with a low probability of debris torrent occurrence. The next lowest gradient of 5° occurs on two fans with moderate and moderate to high probabilities of occurrence. One debris torrent–snow avalanche fan possesses a gradient of 3° (Table 3) but the high probability of debris torrent occurrence in this basin is created by an artificial sediment source (Thurber Consultants Ltd 1985). The next lowest gradients on debris torrent–snow avalanche fans are 6° (low to moderate probability) and 7° (three fans; low to very high probabilities). These results suggest that fans prone to debris torrents in the Cascade Mountains possess a lower threshold of gradient (4°) similar to fans in the Front Ranges of the Canadian Rockies (Jackson *et al.* 1987). However, the usefulness of this technique for identification of debris torrent hazard depends on a non-overlapping upper threshold of gradient for streamflow fans with no debris torrent potential. For example, Jackson *et al.* (1987) found no such overlap. Table 3 shows the mean gradient of streamflow fans (12.7°) to be significantly higher than the 4° lower threshold of debris torrent-prone fans, with a maximum value of 30°. In fact only two of the streamflow fans possess a gradient of 4° or less. Assuming that Thurber Consultants Ltd (1985) are correct in assessing these basins to be free of debris torrent potential, the gradients of streamflow fans supplied by small, steep basins in the Cascade Mountains do not appear to possess an upper threshold that would allow easy differentiation from debris torrent fans. Other factors, such as sediment availability in the basin, probably play a more important role in the differentiation of debris torrent and streamflow basins.

An index of ruggedness such as Melton's R may be useful for identifying basins with the potential for generating debris torrents capable of reaching the fan, because a lower threshold of R theoretically reflects the minimum gradient necessary for maintaining debris torrent motion when other factors, such as moisture and clay content of sediment, are optimal (Owens 1973; Rodine and Johnson 1976; Hungr *et al.* 1984; Van Dine 1985). For debris torrent basins in this study the two lowest *R* values (0.38, 0.39; Table 3) are associated with low probabilities of debris torrent occurrence. The next lowest *R* value of 0.55 is for a basin with a high probability of occurrence. For debris torrent–snow avalanche basins the minimum *R* value is 0.23 but this is unrepresentative because the debris torrent potential (which is low) occurs only in a steep first-order channel immediately above the fan whereas *R* is calculated for the entire large basin. The next lowest *R* value is 0.53 for a basin with a moderate probability of occurrence. The lower threshold of 0.38 compares to a value of 0.25 to 0.30 in continuously graded and unglacierised basins in the Rockies' Front Ranges (Jackson *et al.* 1987). However, as with fan gradient, the usefulness of this technique for identification of debris torrent hazard depends on a non-overlapping upper threshold of *R* for streamflow basins as found by Jackson *et al.* (1987). Table 3 shows the mean Melton's *R* of streamflow basins (0.59) to be significantly higher than the 0.38 lower threshold of debris torrent-prone basins, with a maximum value of 1.34. Only seven of the streamflow basins possess a Melton's *R* of 0.38 or less, with even some larger (>1 km^2) basins falling above this threshold. Therefore, as with fan gradient, values of Melton's *R* for streamflow basins in the Cascade Mountains do not possess an upper threshold that would allow easy differentiation from debris torrent basins. Insufficient sediment for debris torrent initiation or the presence of sediment traps in the channel long profile probably explain why such high Melton's *R* values are associated with streamflow basins.

The maximum values of basin area for debris torrent and debris torrent–snow avalanche basins (Table 3) are misleading because in both cases the debris torrent activity occurs in only a small first-order tributary and not the whole basin. They are largely responsible for the high degree of positive skewness in the basin area data. If they are omitted the maximum sizes of debris torrent and debris torrent–snow avalanche basins (6.8 and 7.4 km^2 respectively) fall well below the 10 km^2 threshold at which a transition to fluvial activity on fans in the Canadian Cordillera generally occurs (see above). The relatively small size is significant, especially given the large debris torrents these basins are capable of generating (Thurber Consultants Ltd 1985). The areas of the streamflow basins are even smaller (Table 3), compromising the potential usefulness of this variable for unambiguous identification of debris torrent basins.

Conclusions

All of the morphometric variables analysed in this study differ significantly in snow avalanche basins compared to debris torrent and debris torrent–snow avalanche basins, reflecting the very different nature of these processes and the environmental controls on them. In general, snow avalanche basins are characterised by the highest top and bottom elevations, lowest relief, shortest channel or path length, steepest gradient, smallest area and highest Melton's *R*. Only top and bottom elevations and fan area are significantly different between debris torrent and debris torrent–snow avalanche basins, implying that the latter are really debris torrent basins in origin. Particularly noteworthy is the distinct elevational zonation of debris torrent and snow avalanche activity which is related to the seasonal pattern of debris torrent activity in southwestern British Columbia. The occurrence of most debris torrents in late fall or winter may also explain why debris torrent fans are much larger than fans of basins affected by both debris torrents and snow avalanches: the size of debris torrents may be limited by the presence of snow cover at the higher elevations in the latter basin type. Streamflow basins can be differentiated from the other three basin types by as many as five or six morphometric variables, which is especially significant given that these are not large basins from which debris torrent activity is obviously absent.

Discriminant analyses indicate that the bottom elevation and channel/path gradient of basins are the best variables for classifying basins by the type of process. Snow avalanche basins are easily differentiated from debris torrent and debris torrent–snow avalanche basins using this technique. However, debris torrent–snow avalanche basins are less easily differentiated from debris torrent basins, supporting the conclusion above that these basin types are fundamentally the same.

Weak correlations exist between morphometric variables in snow avalanche basins, suggesting that avalanches in the study area are unable to carry out geomorphic work in the manner of debris torrents and streamflow. Significant correlations generally exist in debris torrent, debris torrent–snow avalanche and streamflow basins between basin area on the one hand and relief, channel length and channel gradient on the other. The strong relation between the area and relief of debris torrent and debris torrent–snow avalanche basins is especially significant since it indicates that larger drainage basins are more likely to contain higher peaks than smaller basins. Weak or modest correlations are present between the area or Melton's *R* of a basin on the one hand and fan gradient and area on the other. Possible reasons for this include the paraglacial history of fan formation, the confined nature of many valley bottoms in the study area, and the distribution of high peaks which affects the calculation of Melton's *R*.

Analyses of fan gradient and Melton's *R* indicate that these variables possess definable lower thresholds in basins affected by debris torrents in the Cascade Mountains. A similar analysis of the area of debris torrent basins indicates an upper threshold that is significantly smaller than the 10 km^2 frequently cited for the Canadian Cordillera. The use of these thresholds for identification of debris torrent hazard appears to be complicated by significant overlaps with the corresponding upper thresholds for fans affected by only streamflow processes. Given the limited sample of small, steep streamflow basins available for this study, a larger sample of such basins should be investigated to evaluate fully the usefulness of this morphologic approach to identifying debris torrent hazard.

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