DEBRIS FLOWS: BACK ANALYSIS OF TRAVEL DISTANCE AT BLUEBERRY CREEK USING UBCDFLOW

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ABSTRACT

Application of an empirical-statistical model, developed for prediction of debris flow travel distance, is reported for a site at Blueberry Creek in the Monashee Mountains of British Columbia. The event occurred in a forest clearcut, with an initial volume of 130m^3. Further entrainment and deposition of material led to a peak cumulative flow volume of nearly 1750m^3, and a travel distance of 1580m to the point of terminal deposition. Volume change along the event path, from point of origin, was simulated using the model UBCDFLOW. The model determines travel distance as the point along the path of movement where the cumulative flow volume diminishes to zero. A comparison of the modeled travel distance, with the actual distance from field observations, shows excellent agreement.

RÉSUMÉ

L'application d'un modèle empirique-statistique, développé pour prédire la distance d'écoulement de débris, est présentée pour un site à Blueberry Creek dans les Montagnes de Monashee en Colombie Britannique. L'événement d'écoulement de débris, qui avait un volume initial de 130 m^3, s`est produit dans une forêt coupée à blanc. Plus amples entrainments et la déposition de materiel ont mené à un volume maximal d'écoulement cumulatif de presque 1750m^3, et une distance totale de parcours de 1580m, pour atteindre le point de déposition ultime. A partir du point d'origine, le changement de volume le long du parcours du mouvement a été simulé en utilisant le modèle UBCDFLOW. Ce modèle détermine la distance totale de parcours à partir du point où le volume d'écoulement cumulatif diminue a zéro. Les resultats indiquent que la distance totale de parcours simulé et mesuré sont en accord.

1. INTRODUCTION

A study of landslides caused by forest roads and timber-harvesting in the Kootenay-Columbia region, south-eastern British Columbia, has been conducted by the B.C. Ministry of Forests over the last six years (Jordan, 2001). In 2002, UBC researchers expanded this project to document the physical characteristics and behaviour of debris movements, especially the runout distance and deposition of debris flows. This paper is a summary of field observations made on a representative debris flow event in this region. Interpretation of the field data addresses frequency of event type, transportation and deposition, travel distance, and channel debris yield rate.

A general classification system for slope movements has been established by Cruden and Varnes (1996). The system recognizes debris as a mixture of soil, rock, and organic material characterized by a significant percentage of coarse particles. Slide movements involve shear displacement along one or more surfaces and may be rotational or translational in character. Flow movements are characterized by large relative displacements within the mass and a fluid behaviour. Debris slides may progress to debris flows, particularly in gullies on steep mountain slopes.

Fannin and Rollerson (1993) have reported physical characteristics and debris flow behaviour from field surveys of post-logging landslides on the Queen Charlotte Islands (QCI). The QCI database comprises both single and multiple debris flow events. Single events follow a path that is not affected by adjacent landslide activity. Multiple events are a result of two or more events that share a common path as a result of flow convergence (Fannin and Rollerson 1993).

Downslope movement from the main scarp is usually accompanied by both entrainment and deposition of material along the event path. The path length downslope from the point of origin to the point at which the mass (or volume) becomes zero is defined as the travel distance, usage consistent with that of Van Gassen and Cruden (1989), Benda and Cundy (1990), and Fannin and Wise (2001).

The travel distance of a debris slide or flow is governed by properties of the material and the path of movement. Empirical and dynamic models are available to determine the travel distance (e.g. Benda and Cundy 1990; Cannon 1993; Fannin and Wise 2001; Hungr 1995; Perla et al. 1980). In dynamic models, simplifying assumptions are often made where input parameters cannot be measured easily. In many situations where our understanding of material properties is limited and the path of debris flow movement is controlled by subtle changes in terrain, empirical approaches offer a practical means of predicting behaviour. Empirical models are typically based on limiting criteria or statistical relations.

The empirical model for predicting travel distance and volume of debris flows proposed by Benda and Cundy

(1990) was developed for debris flows in confined mountain channels. In this model, channel gradient and tributary junction angle were used to predict the volume and travel distance. It deliberately avoided rheological properties and was therefore based on topographical inputs only. In this model, the junction angle between a contributing and a receiving channel has been used as a predictor of deposition of debris flows for channel gradients greater than 20°. A junction angle greater than 70° was found to be significant.

Fannin and Wise (2001) proposed an empirical-statistical model for predicting debris flow travel distance using field surveys of post-logging landslides on the Queen Charlotte Islands, British Columbia. In this approach, an event initiates with a known volume, along a defined path for which the slope morphology and reach geometry are also known. The model routes the initial volume into the second reach downslope, and calculates the change in volume based on morphological and geometrical variables, and the incoming flow volume. The process continues until the change in volume of the flow is negative (deposition) and the magnitude of the calculated deposition exceeds the incoming flow volume. The length of each reach through which flow has passed is summed to determine the travel distance.

This paper describes behaviour of debris flows in the Kootenay-Columbia region, with particular emphasis on a specific site (Blueberry Creek). Physical characteristics and debris flow behaviour from the data in this region are described and compared with other data in the Province. The empirical-statistical model of Fannin and Wise (2001) is then used for analysis of debris slides and flows to estimate the travel distance. Comparison is also made to the model of Benda and Cundy (1990). The field data are post-event measurements and observations of debris movement. The analysis is limited by the difficulty of accurately describing an event some years after it has taken place.

2. FIELD INVESTIGATION

Based on the results to date of a study of landslide frequency and terrain attributes in the Kootenay-Columbia region (Jordan 2001), additional fieldwork specific to issues of travel distance was undertaken.

The original project involved an inventory of natural and development-related landslides in several study areas totaling about 18,000 km^2, in southeastern British Columbia. Approximately 2200 landslides were inventoried by air-photo interpretation, and a subset of these (about 1/4) were field-checked.

One of the study areas, centred on the Castlegar-Slocan area of the southern Selkirk and Monashee Mountains, is of interest for this project. This area totals 3800 km^2, of which 2900 km^2 are forest, and includes 579 landslides in the forest land. Of these, 433 were larger than 0.05 ha, the size limit for data analysis. Average landslide densities were 0.32 landslides/km^2 in developed areas, and 0.05 landslides/km^2 in undeveloped areas (Jordan, 2002). The term "developed" is used with respect to forest development, through road construction and timber harvesting; developed land includes all areas covered by and downslope from roads and harvested areas. For developed land steeper than 25º, the average landslide density was 0.74 landslides/km^2 (Jordan 2001).

For the current project to date, field traverses have been examined for 25 selected events that were reasonably accessible, and which were sufficiently recent (about 10 years) to permit reliable field observations. The events were chosen to include a range of sizes and morphologies (both open-slope and confined in gullies). At each site of debris movement, a set of data was collected that describes slope morphology in the source area and physical characteristics of the event. The path of movement of each event was surveyed from the point of origin to terminal deposition. Measurements of length and width, estimates of depth of erosion or deposition, and a record of path slope and azimuth were made for each distinct segment or reach of an event. In this paper, some preliminary results on Blueberry Creek are discussed and compared with those on coastal British Columbia.

2.1 Site Description

Debris flow activity was examined at the Blueberry Creek site situated in southeastern British Columbia (see Fig. 1). Blueberry Creek is located in the southern Monashee Mountains, about 20 km southwest of Castlegar, B.C. The terrain in this area consists of plateaus and subdued mountains, with elevations ranging from about 500 m in the main valley bottoms, to mountain peaks at 2100 to 2376 m. This mountainous region was glaciated about 12,000 years ago (Holland 1964). Lower summits and crests are subdued and rounded and may have a thin covering of till. Drift is present on valley floors (along with fluvial materials) and on gentler mountain slopes at relatively low elevations. Steeper slopes consist of rock outcrops and rubbly colluvium.

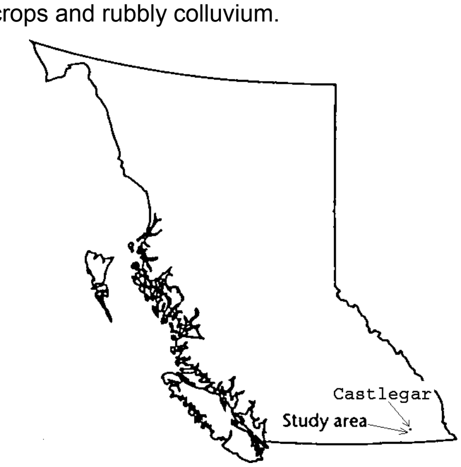

Figure 1. Site location

The Blueberry Creek watershed consists of coarse textured parent materials, including mainly granitic and gneissic rocks. Bedrock outcrops are found in alpine areas, gullies and steep hillslopes, where debris slides, flows and rock fall are common. The watershed lies in the Interior Cedar-Hemlock and Englemann Spruce-Subalpine Fir biogeoclimatic zones (Meidinger and Pojar, 1991), which are typified by warm, moist summers and mild winters with moderate snowfalls. Rossland, the most representative nearby climate station, is at an elevation of 1085 m and has mean daily temperatures that range from 17.0 in July to –5.8 in January. Annual precipitation at Rossland is 917 mm, with 417 mm falling as snow. Higher precipitation and proportions of snow would be expected in the upper Blueberry Creek watershed, which lies at a higher elevation. In this area, soils generally dry out only moderately or not at all during the late summer.

2.2 Landslide Field Data

In total, 25 (of approximately 29) debris flow events that have been surveyed to date are used in this paper for the analyses of travel distance. Most of the events originated in clear-cut areas that were logged between 6 and 15 years ago, or in unlogged forests below logging roads. One event was not development-related, but was located in an area burned by a forest fire.

At each site the event path was recorded as a series of reaches, including width of scour and/or deposition, depth of scour and/or deposition, slope angle and azimuth of each reach. Observations of slope morphology were recorded for each reach, to distinguish between a reach that is on open ground (unconfined flow) and one that is in a gully (confined flow).

2.2.1 Blueberry Creek Event

The event at Blueberry Creek occurred in May 1993, during a peak snowmelt event caused by hot sunny weather. The point of origin is located 44 m below a road culvert, and it was likely caused by drainage concentration by the road (since it occurred shortly after logging, loss of root strength is not believed significant). The event initiated as a small debris slide on an unconfined slope, with a gradient of 33º. The initial failure averaged 0.6 m in depth, and involved soil derived from weathered glacial till sliding on a surface of compact unweathered till, with bedrock occasionally exposed at the failure plane. It moved down the slope into a confined gully 130 m (slope distance) below, where it entrained additional material, and traveled an additional 1450 m down the channel to deposit on an alluvial fan in the valley bottom. Although the gully and fan had probably experienced numerous debris flows over the geologic past, there was no evidence that any events had occurred within the age of the present forest stand (about 100 to 200 y), and the gully was apparently heavily forested before the event. In addition to soil, many trees were carried by the debris flow to its depositional zone.

Characteristics of the event are reported in Table 1 and shown in schematically in Fig. 2. Field observations of slope length, and the width and depth of both scour and deposition, allow volumes of entrained and deposited material to be calculated for every reach of the surveyed event. The reported volume measurements are rather imprecise estimates: they are based on a width measurement and observations of erosion and deposition at a site about midpoint in the reach, which is visually judged as typical by the surveyor. As erosion and deposition features are often highly variable on a local scale, and the depths of scour and deposition can be difficult to judge, these estimates of volume are subject to considerable error. Slope gradient was measured in percent (%) during fieldwork, and converted to degrees for purposes of analysis (to +/- 0.1º). As will be shown later, the UBCDFLOW uses these angles to determine the travel distance and volume for each reach.

Slope gradients in the source area are in the range 24° to 33°, and are generally between 7° and 11° in the depositional zone (see Fig. 3). Typically slopes greater than 10° are necessary to maintain movement of debris in a confined channel (excluding depositional zone). The average gradient of the site in confined gullies, excluding the depositional zone, is 15°. While it is recognized that interpretation of slope gradient is dependent on confinement of the gully, and type and water content of the debris, this review of the site confirms that events initiating in the source area are likely to travel to the valley floor and deposit on the existing fan.

3. EVENT CLASSIFICATION - PHYSICAL CHRACTERISTICS

Typically erosion dominates in the upper reaches of a debris flow event, where there is little or no deposition.

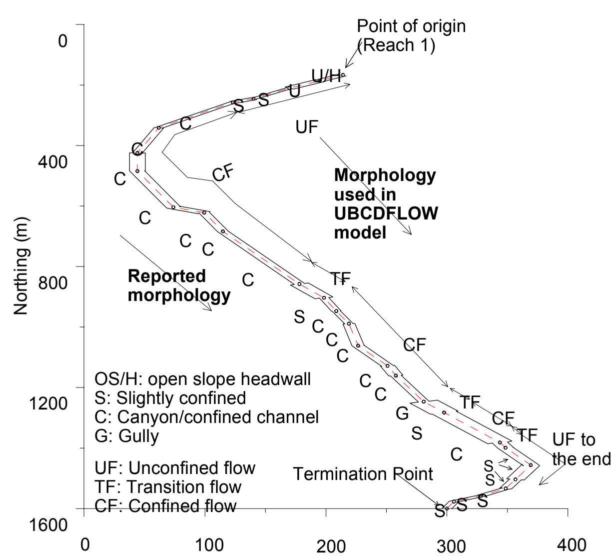

Figure 2. Schematic details of Blueberry Creek event (vertical scale 4 times horizontal scale)

Table 1. Recorded data for Blueberry Creek event

Reach Number	Length (m)	Width (m)	Slope angle (°)[1]	Scour width (m)	Scour depth (m)	Deposition width (m)	Deposition depth (m)	Slope morphology[2]	Material[3]
1	27	8	33.0	8	0.6	0	0	U-headwall	Mb
2	35	10	25.6	6	0.1	0	0	U	Mb
3	46	5	24.2	3	0.5	0	0	S	Mvb
4	21	8	26.6	4	0.3	0	0	S	Mv
5	104	6	26.6	3	0.5	0	0	C	Mv/Db
6	85	8	24.2	6	0.5	0	0	C	Db/Mv
7	60	13	19.3	5	0.5	4	0.3	C	Mv/Db
8	123	12	19.3	5	0.5	4	0.1	C	Mv/R
9	31	12	20.3	5	0.2	2	0.2	C	Mv
10	64	9	15.6	4	0.3	2	0.1	C	Mv
11	185	9	14.0	4	0.3	2	0.1	C	Mb
12	50	16	12.4	2	0.5	6	1.0	S	Mb
13	45	8	12.4	4	0.5	0	0	C	Mb
14	43	7	13.0	4	0.5	0	0	C	Mvb
15	73	10	12.4	5	0.5	2	0.1	C	Mv
16	71	10	12.4	4	0.75	0	0	C	Mv/Cv
17	33	12	15.1	3	0.5	2	0.5	C	Mv/Cv
18	89	9	15.6	4	0.5	0	0	G	Cv/R
19	40	25	10.2	0	0	15	2.0	S	Mv/Ff
20	109	22	10.2	0	0	10	0.75	C	Mv/Ff
21	18	13	10.2	0	0	10	0.5	S	Ff
22	61	13	6.8	0	0	10	0.5	S	Ff
23	49	15	9.1	0	0	10	0.2	S	Ff
24	31	10	11.3	0	0	3	0.2	S	Ff
25	32	7	8.5	0	0	3	0.2	S	Ff
26	29	6	6.3	0	0	4	0.3	S	Ff
27	24	8	7.4	0	0	3	0.2	S	Ff

[1] from field measurement in %
[2] U: Unconfined – open slope, S: Slightly confined, C: Confined, G: Gully (V shaped)
[3] M: Morainal, b: blanket (surface expression), v: veneer, D: Weathered bedrock, R: Bedrock, C: Colluvium, F: Fluvial, f: fan

Some deposition occurs in the transportation and erosion zone, usually in the form of distinct levees, but it is not significant. Such deposition may be triggered by a change in slope gradient or alignment of the flow path. Significant deposition of material occurs only in a relatively short section, termed the deposition area.

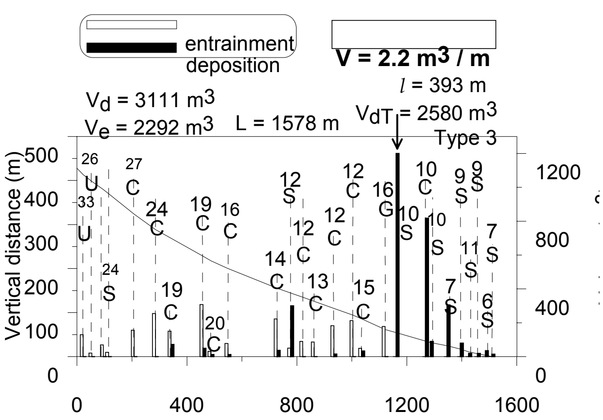

Figure 3. Profile and volume changes of Blueberry Creek event

A classification based on slope morphology, developed by Fannin and Rollerston (1993) on a database from the Queen Charlotte Islands (QCI), British Columbia, was used to describe movement observed in the field. Three classes of event recognized in the classification are described below. A summary of the system is given in Table 2 with reference to the event, path, and channel gradient (β).

A type 1 event is defined as a single event, which initiates on, and travels down, a relatively uniform or open, planar slope (OS). Slide movements appear rare except in the source area. Evidence of flow movements is common, particularly around obstructions and in the form of levees, suggesting a complex progression from sliding to flow. On occasion these events will include a short reach in the path that is a gully. Deposition typically occurs on a relatively uniform, planar slope (15 ± 8°). There are 6 events of this type in the Kootenay-Columbia field data. A characteristic event may start on a midslope and stop on a lower slope. Most deposition occurs on the last few reaches of the path.

Table 2. Event classification system

Event type	Path	Characteristic reach slope angle, β (°)
1	OS	N/A
2	OS → G; G	$\beta > 15°$
3	OS → G; G	$15° > \beta > 5°$

A type 2 event is defined as a single event which initiates on an open slope (OS) and enters a gully (G) or initiates in a gully. The events travel down relatively steep, confined channels. Although channel gradients are typically steeper than 15°, occasional short, gentler reaches less than 50 m long may be included in the path. Deposition typically occurs on relatively steep (12 ± 6°), unconfined fans at the base of the gully. There are 4 events of this type in the Kootenay-Columbia data. A characteristic event may initiate in a slightly confined area and traveled down a confined channel. Deposition along the path of the debris flow may be reported for reaches of gradient in the range 21° - 16°.

A type 3 event is defined as a single event which initiates on an slope and enters a gully or initiates in a gully. The events travel down relatively steep, confined channels similar to those of type 2 and then continue, often for long distances, along more gentle, confined channels. Channel gradients in the lower reaches of the gully are typically between 5° and 15°: any event with a reach of gradient less than 15° and longer than 50 m was classified as a type 3. Deposition typically occurs on gentle (7° ± 4°), unconfined fans at the base of the gully. On occasion deposition occurs entirely within the confined channel. There are 15 events of this type in the Kootenay-Columbia data. A characteristic event of this type has a slightly confined headscarp in the source area. Most deposition occurs in the last few reaches of the path.

3.2 Event Classification at Blueberry Creek Site

The variation of entrainment and deposition along the length of the Blueberry Creek event is shown in Fig. 3. This figure shows entrainment of material to dominate following initiation of the event and travel within the confined reaches of the channel. The initial failure volume on the unconfined slope was 130 m^3. Entrainment through the successive reaches contributed more volume of material in the channel system until the event moved out onto a slightly confined slope below it. Both entrainment and deposition were noted in the 7th to 12th reaches, leading to a net depositional volume of approximately 1000 m^3. Deposition dominates thereafter on the lower slopes of the event path, with the last nine reaches showing deposition only. The event initiated on a slope angle of 33° (65%) and terminated on a slope angle of 7° (13%).

Examination of the data for the Blueberry Creek landslide reported in Fig. 3 reveals the total volume of entrained material (ΣV_e = 2292 m^3) is less than the total volume of deposited material (ΣV_d = 3111 m^3). Some of the difference is attributed to the precision of the survey work, and some to the nature of the forensic observations that were made nine years after the event occurred.

Characteristics of the Blueberry Creek site place it in the steep/gentle channel and gentle fan category (see Table 2). The gentle, confined channel in the lower reaches exhibits gradients in the range 7° to 16°. Thus the event is classified as Type 3.

3.3 Channel Debris Yield Rate

The magnitude of an event may be described by the total volume of debris material transported onto the fan, expressed by a channel debris yield rate (m^3/m). Hungr et al. (1984) define "channel debris yield rate" as the magnitude normalized by the length of channel (including any major tributaries) upstream of the depositional area, to the point (points) of origin. Hungr et al. (1984) and Fannin and Rollerson (1993) report derived channel debris yield rates for documented events of known magnitude in the British Columbia coast range. The values lie between 5 and 18 m^3/m. An estimation of channel debris yield rate can be made for the site at Blueberry Creek, based on the length of the transportation and erosion zone, and with reference to the measurements of transported fill material resident in this part of the channel (Fig. 3). As such, it does not account for any contributing material from the source area and any erosion of the flow channel by the event itself. Rather the estimation simply implies that all debris resident in the channel is deposited on the fan, and is replaced by material from the source area and additional erosion of the channel.

A descriptive summary of the Blueberry Creek event is reported in Fig. 3 (inset) as values of measured and calculated variables. Total length L is defined as slope distance from the main scarp to the end of deposition. Length l of the terminal depositional area was established from examination of the event profile, and is noted by the symbol (↓). An estimate of the channel debris yield rate is made from these field records. The yield rate (V) in cubic meters per meter of channel is calculated as:

$$V = \frac{V_{dT}}{(L - l)} \quad [1]$$

where V_{dT} is the volume of debris material recorded in the terminal depositional zone.

A maximum debris yield rate of 2.2 m^3/m is calculated for the Blueberry Creek event. Fannin and Rollerson (1993) have reported a geometric mean of 6.7 m^3/m for similar

Type 3 events in QCI. Preliminary analysis of seven similar channels (Type 3) in the Kootenay-Columbia region (Eliadorani and Fannin 2003) indicates an average value of 2.1 m^3/m for the debris yield rate. It appears that, in general, events in the Interior of British Columbia may exhibit a smaller value of debris yield rate in comparison with those reported in coastal regions of British Columbia. This difference may be due to lower rates of weathering, and shallower soils, which are typical in the drier and colder interior climate.

Channel debris yield rates of 5.5, 6.2 and 7.8 m^3/m are reported for three events in Howe Sound, a yield rate of 12.9 m^3/m is reported for an event near Port Alice on Vancouver Island, and a yield rate of 18.4 m^3/m is reported for an event at Wahleach A in the Fraser Valley (Hungr et al. 1984). In all cases these values are for channelized locations. The three events in Howe Sound and the event at Port Alice were single-channel events. The event at Wahleach A involved two major branches and was therefore a multiple-channel event. Fannin and Rollerson (1993) reported yield rates of 11.3, 6.5, and 6.7 m^3/m for types 1, 2, and 3, respectively for the events on Skidegate Plateau, QCI. A comparison of channelized events in the study area with open slope and channelized events in British Columbia indicates that the Kootenay-Columbia Type 3 events have yield rates that are approximately 30% of those observed in the QCI data.

4. TRAVEL DISTANCE

Fannin and Wise (2001) established five regression equations that are incorporated into a simulation routine called UBCDFLOW (Table 3). For these equations, three predictor variables that are measured, namely reach length, width (entrainment or deposition), and slope angle, and two predictor variables that are derived, namely incoming flow volume and a bend-angle function are used. Reach morphology (unconfined, UF, confined, CF, and transition, TF, reaches) and slope angle determine the governing equation in a generalized model framework. A transition reach is defined as an unconfined reach immediately downslope of a confined reach. The model imposes no deposition for flow in a confined reach and no entrainment for flow in a transition reach. Knowing the initial failure volume and changes in event magnitude arising from entrainment and deposition along the path of movement, the point at which the cumulative flow volume diminishes to zero and therefore the total travel distance is determined.

The travel distance of the event is determined by summing the path length of all reaches upslope from the end of that reach in which the event terminates. It should be noted that the approach allows the flow volume to be deduced at key points along the event path, given the reach-by-reach basis for calculation.

Application of the UBCDFLOW model to the Blueberry Creek event is shown in Fig. 4(a). Observed and modeled volumes of entrainment and deposition are reported along the path, together with the respective cumulative flow volumes. The event initiated on an open slope as a relatively small failure (approximately 130 m^3) and traveled 130 m, before entering a gully through which it moved before depositing on a moderate-sized fan at the base of the gully. The event entrained sufficient material to generate a peak flow volume greater than 2000 m^3. Since flow volume is calculated for each reach, the severity or volume of material at a point of interest can be determined to estimate potential environmental damage.

Agreement between the observed and predicted travel distance of this debris flows is very good. Curves for the respective cumulative debris flow volume rise in response to entrainment that dominates in the upslope portion of the event (Figs. 3 and 4a), and fall as the event leaves the gully to flow over the flatter open slope below. Inspection of the reach i=20 in the event reveals a modeled flow behaviour that differs from the observed behaviour. The model yields no change in volume because only deposition was observed in that reach (hence $W_e = 0$). In all other reaches, modeled volume changes agree with the observed values.

Histogram bars (Fig. 4a) show the calculated net change in volume that occurs in each reach, based on the regression equations, following on from the initial volume (130 m^3) in the first reach. Again, good agreement is observed, with the possible exception of the 20th reach, where the model calculates no volume change, while the observed flow volume deposits 820 m^3.

Table 3. Regression equations (UBCDFLOW)

Flow behavior	Mode Of flow	Regression equation	Slope range
UF	Deposition	$\ln(-dV_i) = -0.514 - 0.988\ln(W_{di}) - 0.101(BAF_i) - 0.731\ln(L_i) + 0.0155(TH_i)$	$0 \le TH_i \le 18°$
UF	Entrainment	$\ln(+dV_i) = 1.13\ln(W_{ei}) + 0.787\ln(L_i) - 0.0636\ln(\sum V_{i-1})$	$19 \le TH_i \le 29°$
UF	Entrainment	$\ln(+dV_i) = 0.728 + 1.31\ln(W_{ei}) + 0.742\ln(L_i) - 0.0464(TH_i)$	$30 \le TH_i \le 55°$
CF	Entrainment	$\ln(+dV_i) = 0.344 + 0.851\ln(W_{ei}) + 0.898\ln(L_i) - 0.0162(TH_i)$	$10 \le TH_i \le 55°$
TF	Deposition	$\ln(-dV_i) = -1.54\ln(W_{di}) - 0.90\ln(L_i) + 0.123(BAF_i)$	$0 \le TH_i \le 20°$

The results presented in Fig. 4(a) show that, for open-slope reaches below the point of origin, an excellent agreement exists between the modeled and observed cumulative flow volume. However, for confined reaches, the comparison is not so good, as only entrainment can be predicted. In the UBCDFLOW volumetric model, the event is assumed to terminate when the cumulative debris flow volume is zero. Inspection of the curves shows the modeled flow volume (Fig. 4a), diminishes to zero in the last reach for which field data are reported. Hence the modeled travel distance equals the observed travel distance: the travel distance is correctly determined as 1580 m.

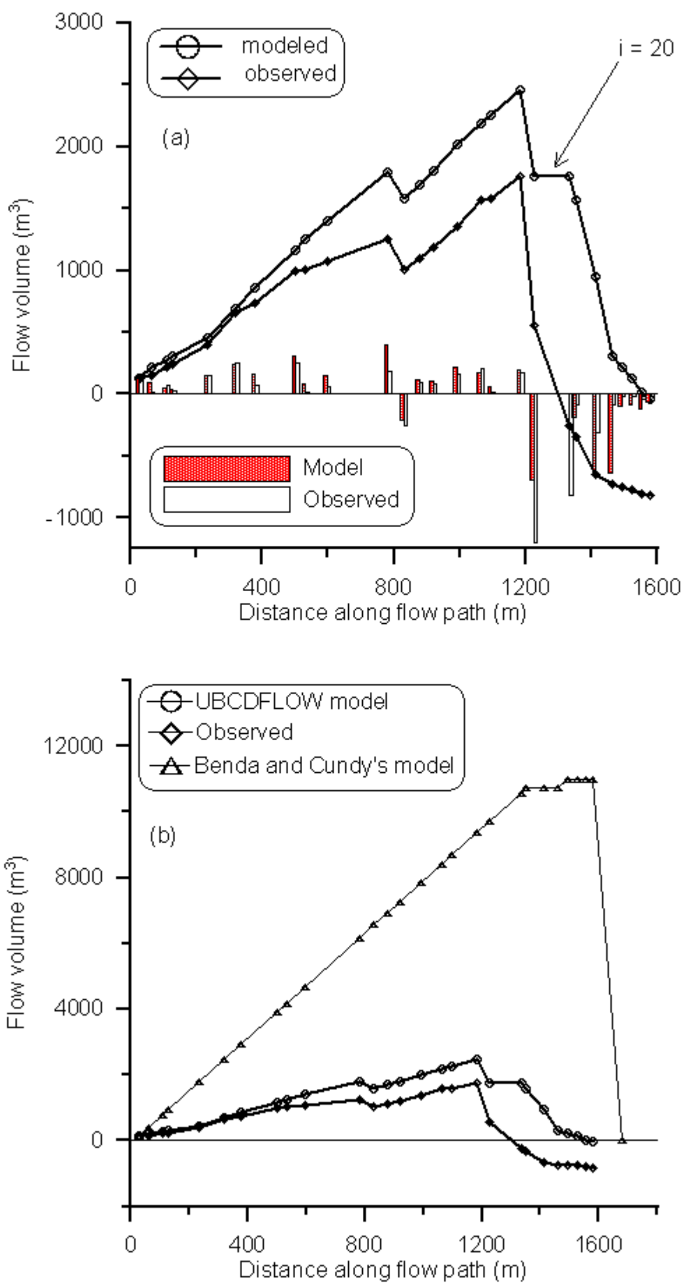

Figure 4. (a) Observed and modeled volume of Blueberry Creek event (b) Comparison of UBCDFLOW model and Benda and Cundy's model

Although the predicted net volume change (histogram bars in Fig. 4a) is identical in most of the reaches, the predicted cumulative volume along the path, especially at the peak differs from the observed field data. For this case, the modeled peak volume is 40% greater than the observed value. This may show that the prediction of entrainment (due to the cumulative volume before the peak) is less reliable than that of deposition. However, it appears that UBCDFLOW, which was originally developed from the data in coastal B.C., can correctly predict the flow mode (entrainment or deposition) at this new site.

Fig. 4(b) shows a comparison between the UBCDFLOW model and the empirical model of Benda and Cundy (1990). In this model, analysis begins by identifying the location of a potential landslide site. Next, the gradient of the receiving channel is evaluated. The minimum slope necessary for failure of landslide debris in a channel is 20°. Following the evaluation of steep channels ($\beta > 20°$), subsequent reaches are evaluated until either a channel gradient of less than 3.5° or a junction angle of greater than 70° is encountered. When either of these criteria is satisfied, deposition is predicted. When deposition is predicted based on channel-junction angle, the point of deposition is at the junction. The approximate volume of the debris flow is determined by measuring the length of channel traveled with a gradient greater than 10°. This length, multiplied by an assigned average channel yield rate of 8 m^3/m, plus the volume of the original failure, gives the estimated volume at termination. Inspection of the curves shows the UBCDFLOW model provides a better fit to the data at Blueberry Creek.

5 SUMMARY AND CONCLUSIONS

Debris flows in the Kootenay-Columbia region of British Columbia, which initiated on logged terrain, were surveyed as part of a study of landslide activity related to forest development. Field observations describe the path of movement, as a series of reaches, from the point of origin to terminal deposition. A distinction is made between unconfined terrain on open slopes and confined terrain in a gully. It enables three categories of reach morphology to then be assigned, for purposes of modeling volumetric behaviour of the event.

The model, UBCDFLOW, determines the volume of entrainment and/or deposition for every reach of the event. Given an initial failure volume, changes in event magnitude arising from predicted entrainment and deposition along the path of movement are used to establish the point at which the cumulative flow volume diminishes to zero, and therefore the total travel distance.

The following conclusions are made from preliminary analysis of the event at Blueberry Creek:

(1) Physical characteristics and flow behaviour lead it to be classified as a Type 3 event, based on observations from a database of similar debris flows on logged terrain on the Queen Charlotte Islands (QCI). Type 3 events travel down relatively steep, confined channels and then continue, often for long distances, along more gentle, confined channels.

(2) Field observations determine a channel debris yield rate of 2.2 m^3/m at Blueberry Creek, and an average yield rate of 2.1 m^3/m for seven Type 3 events that were surveyed in the Kootenay-Columbia study area.

(3) By comparison, Type 3 events on the QCI database exhibited a mean yield rate of 6.7 m^3/m. It appears that, in general, recent debris flow events in the study area exhibit a significantly lower channel debris yield rate than similar events at the coastal QCI location that were surveyed in 1985-86. This comparison, based on a preliminary analysis of the new data, suggests a yield rate in the study nearly 30% of that for the QCI data.

(4) UBCDFLOW uses morphology and slope angle to determine the occurrence of entrainment and/or deposition along the path of movement. Back analysis of the event at Blueberry Creek yields a modeled peak value of cumulative flow volume that exceeds field observations at the site. However, the calculation of debris flow travel distance, from a consideration of the point on the hillslope where the modelled cumulative flow volume diminishes to zero, provided an excellent agreement with the actual event.

(5) The application of UBCDFLOW, at this site, has produced a better fit to the field data than another model with similar empirical origins.

(6) The UBCDFLOW model was developed from field survey data from glaciated hillslopes in coastal British Columbia that were clear-cut logged. Consequently, the empirical basis limits its application to similar soils and terrain. Back-analysis of the Blueberry Creek event confirms a potential for successful applications in other regions of British Columbia.

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