A Sensitivity Analysis of Debris Flow Travel Distance at Blueberry Creek, B.C.

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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, British Columbia. The event occurred in a forest clearcut, with an initial volume of 130 m³, and travelled 1580 m to the point of terminal deposition. Back-analysis of the event using the model shows the debris flow travel distance to be insensitive to the initial failure volume. It also reveals the cumulative flow volume to be insensitive to that initial volume. Travel distance was found somewhat sensitive to the width of the event path, but not overly so. However the cumulative flow volumes, and hence overall magnitude of the event, proved very sensitive to the width of the event path. The findings imply the UBCDFLOW model provides a useful means of establishing travel distance, for similar types of debris flow.

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, British Columbia. L’événement s’est produit dans une forêt coupée à blanc avec un volume initial de 130 m³, et une distance totale de parcours de 1580 m, pour atteindre le point de déposition ultime. La back-analyse de l’événement en utilisant le modèle montre que la distance de parcours de débris est insensible au volume initial d’échec. Il révèle aussi que le volume d’écoulement cumulatif est insensible au volume initial. La distance d’écoulement est un peu sensible à la largeur du parcours du mouvement, mais pas excessivement. Cependant les volumes d’écoulement cumulatifs, et donc la magnitude générale de l’événement, sont très sensibles à la largeur du parcours du mouvement. Les résultats impliquent que le modèle UBCDFLOW fournit un moyen utile d’établir la distance de parcours pour des types similaires d’écoulement de débris.

1. INTRODUCTION
The Monashee Mountains, part of the Columbia Mountains system in the southern interior of British Columbia, form a northerly trending range about 400 km long, and 40 to 50 km wide. The terrain in the Monashee Mountains consists of plateaus and mountains, with elevations ranging from 500 m in the valleys to over 3000 m. The entire range was glaciated; glaciers retreated from all but the highest elevations 12 000 years ago. Lower summits and crests are subdued and rounded, and often have a thin covering of till. Drift is present on valley floors, along with fluvial materials, and on the gentler mountains slopes at lower elevations. The steeper slopes consist of rock outcrops and rubbly colluvium (Holland 1964).

The Blueberry Creek watershed is located in the southern Monashee Mountains and covers an area of 152 km². It is approximately 25 km long, with an average of 6 km wide. The surface geology consists of coarse textured parent materials including sandy soils and granitic and gneissic rocks. Bedrock outcrops are found in alpine areas, gullies and steep hillslopes where debris flow and rock slides are common. The watershed lies in the Interior Cedar-Hemlock and Engelmann Spruce-Subalpine Fir biogeoclimatic zones (Meidinger and Pojar, 1991).

The Blueberry Creek event is so named because of its location within the watershed (Figure 1). The site is located 17 km west-southwest of Castlegar, BC, in a forest clearcut at roughly 49°16’N and 117°52’W. The event initiated at an elevation of 1600m. The cutblock (#14-11) is 38 ha in size, and is located on an east facing slope of gradient 55-60%. It was logged at two different times: 18 ha were removed in 1986, and 20 ha in 1991. The portion of the cutblock affected by the event was logged in 1991 using cable logging methods. The Blueberry Creek landslide event occurred in May 1993. It initiated as a small debris slide on an unconfined slope, and travelled downslope to enter a confined gully.

Fannin and Wise (2001) proposed an empirical-statistical model for predicting debris flow travel distance, using field survey data of post-logging landslides on the Queen Charlotte Islands, B.C. (Figure 1). Eliadorani et al. (2003) used the model to back-analyse the travel distance of the Blueberry Creek event, and found it to provide very good agreement with the actual event. In this paper, we,
2. NATURE AND ORIGIN OF THE EVENT

A number of weather stations are located in the vicinity of the study site. The closest geographically is the Castlegar BCHPA Dam weather station, which is located 10 km northeast of the study site at an elevation of 435m. This weather station receives an average total annual precipitation of 635 mm, of which approximately 80% falls as rain and 20% falls as snow. The Rossland City Yard weather station is further away at 23.5 km south-southeast, but is considered more representative of the study site in terms of elevation at 1039 m. This weather station receives a total of approximately 920 mm of precipitation annually, of which about 55% falls as rain and 45% as snow.

The Blueberry Creek debris flow occurred on or about May 11, 1993 (Jordan 1993). As high volumes of precipitation are often associated with landslide occurrence, precipitation rates for the surrounding area were examined. Precipitation data for the two most inherently representative weather stations, the Castlegar BCHPA Dam (the one geographically closest) and the Rossland City Yard (the one most similar in elevation) were initially compared for the month of May 1993. However, as no consistent correlation was observed between the two data sets, data from several other area
weather stations were included in the comparison (the Deer Park weather station, located 20 km northwest of the study site at an elevation of 485 m, the Warfield weather station located 22 km south southeast of the study site at an elevation of 605 m, and the Castlegar A weather station located 19 km east of the study site at an elevation of 495 m). The records show no precipitation was recorded at any of the area weather stations on or around May 11, 1993 during the time that the Blueberry Creek event likely occurred. Accordingly, the initiation is not attributed to rainfall.

Snow pack levels for the area were therefore investigated. In order to determine the approximate snow depth at the study site, data were taken from snow survey stations in the vicinity at similar elevations and latitudes for May 1993. As direct relations were observed between elevation and snow depth, approximate snow depths were interpolated from the data for the Blueberry Creek site. The snow depth at the site for the beginning of May 1993 was likely between 110 and 120 cm and approximately 0 cm by the end of the month. This rate of snowmelt over a one-month period is typical for the region, so average snowmelt rates for the month were not unusually high. However, the temperature data in Figure 2b suggest that much of the snowmelt for the month may have occurred in about a 10 day period.

Blueberry Creek is not gauged, hence snowmelt rates can only be inferred from temperature data. A plot of the daily temperatures for the same weather stations used in the precipitation analysis reveals a significant increase in mean temperature from an average of 10°C to 20°C at the different locations between May 9 and 11. This sharp increase in temperature is believed to have led to an unusually high snowmelt rate, and likely caused the Blueberry Creek event to occur.

Several other landslide and erosion events occurred in the southern Columbia Mountains during the same one-week period of warm weather, which were investigated by the third author. These events were all attributed to high snowmelt rates, which in some cases were exacerbated by enhanced snowmelt in clearcuts, or by drainage concentration by roads.

The point of initiation (Figure 3) is located 44 m below a road culvert where the slope steepens from 55% to 66% (Jordan 1993). Poor placement of the culvert may have contributed to the slope failure. It was placed approximately 10 m to one side of a natural drainage hollow in order to coincide with a low spot in the road. Unfortunately, drainage was diverted from the hollow to the culvert, and saturation below the culvert led to the landslide (Jordan and Nicol 2002). A reduction in root cohesion is not believed to have played a factor since the event occurred less than 2 years after logging. The initial failure averaged 0.6 m in depth and involved 130 m$^3$ of soil derived from weathered glacial till on a surface of compact unweathered till, under which bedrock was occasionally exposed at the failure plane (Eliadorani et al 2003).

The event travelled 130 m down the open slope and into a steep, narrow gully where it became a channelized debris flow (Figure 4). After entering the gully, the debris flow entrained additional material and travelled 1450 m further down the channel to near the bottom of the Blueberry Creek Valley where it terminated on an alluvial fan (Jordan 1993). Many trees were carried with the debris to the zone of deposition. There was no evidence of previous landslide activity in the present forest stand (100-200 yrs) although it is likely that the gully and fan have experienced numerous debris flows in the geologic past (Eliadorani et al 2003).

3. UBCDFLOW MODEL OF TRAVEL DISTANCE

UBCDFLOW is an empirical-statistical model for the estimation of debris flow travel distance. The model was developed based on field observations of 449 landslide events that occurred in the Queen Charlotte Islands of British Columbia. Volume-change, in which the contributions of entrainment and deposition are treated separately, defines travel distance. The debris flow path is described as a series of reaches which are classified...
Table 1. Flow behaviour, mode of flow, and regression equations for UBCDFLOW (after Fannin and Wise 2001).

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>Mode of Flow</th>
<th>Regression Equation</th>
<th>Slope Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF</td>
<td>Deposition</td>
<td>( \ln(-dV_i) = -0.514 - 0.988\ln(W_{W_i}) - 0.101(BAF_i) - 0.731\ln(L_i) + 0.0159(TH_i) )</td>
<td>( 0 \leq TH_i \leq 18^\circ )</td>
</tr>
<tr>
<td>UF</td>
<td>Entrainment</td>
<td>( \ln(+dV_i) = 1.13\ln(W_{W_i}) + 0.787\ln(L_i) - 0.0636\ln(\sum_i V_{i-1}) )</td>
<td>( 19 \leq TH_i \leq 29^\circ )</td>
</tr>
<tr>
<td>CF</td>
<td>Entrainment</td>
<td>( \ln(+dV_i) = 0.728 + 1.31\ln(W_{W_i}) + 0.742\ln(L_i) - 0.0464(TH_i) )</td>
<td>( 30 \leq TH_i \leq 55^\circ )</td>
</tr>
<tr>
<td>TF</td>
<td>Deposition</td>
<td>( \ln(-dV_i) = -1.54\ln(W_{W_i}) - 0.90\ln(L_i) + 0.123(BAF_i) )</td>
<td>( 10 \leq TH_i \leq 55^\circ )</td>
</tr>
</tbody>
</table>

Note: \( \sum_i V_{i-1}, TH_i, W_{W_i}, BAF_i \)

Blueberry Creek debris flow. A schematic representation of the travel distance and flow behaviour in each reach is provided in Figure 5. The debris flow behaviour over the first approximately 130 m was classified as unconfined since it occurred on an open slope. For the next 1220 m, the flow occurred in a gully, and was therefore classified primarily as confined flow, or in some cases (reaches 12, 19, and 21), as transition flow. For the final 225 m of travel, the debris flow behaved once again in an unconfined manner as it approached and spread out on the valley floor.

Results of the UBCDFLOW back analysis are reported as a cumulative volume curve in Figure 6. Also included is a curve for the material balance that is based on volumes of entrainment and deposition reported from field observations of slope length, together with forensic estimates of the width and depth of scour, and the width and depth of deposition in every reach of the event path. It is not possible to ascertain the actual flow volumes that occur in such events, based on forensic observations. Hence the material balance curve is an approach used to describe the “observed” behaviour, and thereby enable a comparison with result of the model. It should be noted these “observed” material balance volumes are rather imprecise and that the point at which the material balance cumulative volume diminishes to zero is not coincident with the point where the debris flow was found to terminate in the field. The material balance volumes are estimates based on width measurements taken where the surveyor observed either erosion or deposition within a
reach. Erosion and deposition features are highly variable on a local scale, and the depths of scour and deposition are difficult to judge. Bulking of the debris flow material upon failure might also lead to a positive bias in estimating deposited volumes. In addition, the field survey at this site was completed nine years after the event initiated, during which time changes to the event path may have occurred. UBCDFLOW determined that a process of entrainment would dominate the first 1200 m of the travel distance, over which 2330 m$^3$ of material would be added to the initial volume of 130 m$^3$ to yield a maximum flow volume of 2460 m$^3$. Although the maximum cumulative volume, established form forensic observations, was 28% less than that calculated by the model, the modelled response closely follows that determined by the corresponding material balance calculations up until this point. Over the last 400 m of the event path, flow behaviour was observed to yield a net deposition in every reach. Inspection shows the UBCDFLOW results to generally follow the same trend of deposition in the last 400 m, except in Reach 20 where no change in volume occurred.

UBCDFLOW determined that the final volume of material at the end of Reach 27 (the location the debris flow was observed to terminate in the field) was approximately 140 m$^3$. While the model did not establish that the cumulative volume would diminish to zero prior to the conclusion of the survey data, it did compute that the peak flow volume would be reduced by 95%. An extrapolation of the model results suggests it is likely the cumulative volume would diminish to zero over an additional 40 m (a total travel distance of 1620 m). This estimated travel distance is approximately 2.6% greater than the actual travel distance (1580 m) recorded for the Blueberry Creek event. This error is very small, when the importance of unpredictable factors such as log jams and irregular topography on the deposition process is also considered.

4. SENSITIVITY ANALYSIS OF TRAVEL DISTANCE

A sensitivity analysis was conducted on the UBCDFLOW back analysis of the Blueberry Creek debris flow travel distance. The reach length, slope angle, and slope azimuth data were collected with a reasonable degree of certainty. Conversely, the initial flow volume was an approximation based on the width, length and scour-depth of the first reach and therefore involves an element of speculation. Additional uncertainty is associated with the widths of entrainment and deposition, because these measured widths are highly variable on a local scale and the traverse itself was conducted nine years after the event occurred. Thus, analyses were conducted to determine the sensitivity of UBCDFLOW to the initial flow volume and to the widths of entrainment and/or deposition for the Blueberry Creek Event.

4.1 Initial failure volume

In order to perform the sensitivity analysis, the model was run with different initial volumes while keeping each of the other input variables unchanged. Three scenarios are reported in Figure 7, in terms of cumulative flow volume along the path of the event. The scenarios examine an initial failure volume that is ±50% of the “observed” value at the point of origin on the hillslope.

Although the initial volumes examined in this sensitivity analysis varied from 65 m$^3$ (-50%) to 195 m$^3$ (+50%), the magnitude of the cumulative flow volume at each reach did not change significantly from the base curve (the original back analysis curve of the Blueberry Creek travel distance, for an initial failure volume of 130 m$^3$). Inspection shows the difference between the curves is nearly constant in each reach.

Although survey data were not recorded for reaches beyond the termination of the event in the field, an estimate can be made of travel distance using these curves by presuming debris continued to be deposited at the same rate as that calculated over the penultimate five reaches of the event. The approach yields a minimum travel distance of 1605 m (1% less than the base value) for the -50% initial flow volume curve and 1635 m (1% more than the base value) for the +50% initial flow volume curve.

These findings indicate the travel distance and cumulative flow volume are subject to little change when the initial failure volume is varied over a significant range. Accordingly, both travel distance and magnitude of the event are considered quite insensitive to initial failure volume of the Blueberry Creek event.

4.2 Width of the event

A companion sensitivity analysis to the width of entrainment and deposition along the event path was conducted using a similar approach. In this case, the respective values of measured width in all reaches were varied by a constant percentage from the base value, while maintaining all other input parameters constant. Results are again reported for three scenarios, in which the base case is compared with that of the measured widths varying by ±50% (Figure 8).