SENSITIVITY ANALYSIS OF UBCDFLOW AND DEBRIS FLOW TRAVEL DISTANCE IN MOUNTAINOUS FORESTED TERRAIN AROUND THE KOOTENAY, BRITISH COLUMBIA REGION

by

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ABSTRACT

Two current approaches for the analysis of debris flows exist; semiempirical and empirical approaches. Fannin and Wise (2001) have proposed and developed an empirical–statistical model for predicting debris flow travel distance. This empirical-statistical model is known as UBCDFLOW. Application of the UBCDFLOW model was completed for five sites within British Columbia. Forensically informed UBCDFLOW simulations, where the governing mode of flow in a reach was known beforehand, were compared against path informed simulations, where the benefits of knowing the mode of flow were not realized. It was observed that, due to the variances in entrainment and deposition widths, minor fluctuations in cumulative volume resulted. However, no significant variance in travel distance was observed. It was found that UBCDFLOW cumulative flow and travel distance was insensitive to variations in initial volume. Further, it was confirmed that the flow volumes generated by UBCDFLOW are moderately sensitive to a change in the event width while the predicted travel distance appears insensitive.
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1.0 INTRODUCTION/ PURPOSE

This report presents a literary review of methods which can be utilized to predict debris flow travel distance, while presenting back-analysis of five events from the Kootenay-Columbia Mountain region in British Columbia. The five events back-analyzed are: Shannon Creek #5004, Bigmouth #11, Airy Creek #1620, Airy Creek #1621 and Airy Creek #3017. The landslide event data are utilized in this report was selected from a portion of the data collected during field surveys of the respective sites, done over six years by the Ministry of Forests (Jordan, 2001).

As defined by Fannin and Wise (2001), and as used throughout this paper, travel distance is defined as the path length downslope from the point of origin to the point at which the mass (or volume) of a debris flow becomes zero. It should be noted that the term travel distance is distinct from the term runout distance, defined as the distance travelled downslope from the onset of large-scale deposition. Fannin and Wise (2001) have reported that this definition of travel distance is consistent with that of Van Gasses and Cruden (1989) and Benda and Cundy (1990).

The purpose of this report is to critique the UBCDFLOW model while further fine-tuning and developing the UBCDFLOW website. Limitations of the UBCDFLOW model are assessed in detail and recommendations for areas of further investigation and model development are proposed.
2.0 MAIN STUDY AREA AND BACKGROUND INFORMATION

2.1 Topography, Geology, and Overall Setting

The data set utilized in the development of this report was from a study of landslides caused by forest roads and timber harvesting in the Kootenay-Columbia region in south eastern British Columbia (Jordan, 2001; Fannin et al., 2003). Figure 1 below shows the study area.

Figure 1: Location of Kootenay-Columbia debris flow study area (note QCI = Queen Charlotte Islands). (Outline map ref: http://geography.about.com/library/blank)

The landslide data utilized in this report is a subset of the larger Ministry of Forests dataset (Jordan, 2001). All events in the aforementioned data set have occurred in the Columbia Mountain system in the southern interior of British Columbia. The Columbia
Mountain system forms a northerly trending range about 400 km long, and 40 to 50 km wide (Fannin et al., 2006). Figure 2 outlines the regional terrain of the Columbia Mountain system.

This entire range has experience glaciation, with glaciers from all but the highest elevations retreating 12 000 years ago (Holland, 1964). The terrain in this area consists of plateaus and subdues mountains with elevations ranging from 500m in the valley to over 3000m (Fannin et al., 2006). Figure 3 shows a local terrain map of the Kootenay-Columbia study region.
The lower summits and crests are typically covered by a thin layer of till with drift and fluvial materials are present along the valley floors. On the lower elevation gentler
mountainous slopes, drift and fluvial material is common while on the steeper slopes rock outcrops and rubbly colluviums is typical (Holland 1964). The surface geology of this region typically exhibits coarse textured parent materials including sandy soils and granitic and gneissic rocks (Fannin et al., 2006).

2.2 Typical Debris Flow Description

Many mechanisms can lead to strength loss in the form of landslides. As outlined by Hungr (2007), this loss of strength can occur instantaneously as part of a brittle failure of soil or rock material or as a result of changes in pore water pressures along the rupture surface during displacements. More generally the strength loss can be characterized into two groups, instantaneous strength loss mechanisms and strength loss requiring large displacements (Hungr, 2007). Table 1 summarizes the primary mechanisms associated with the primary strength loss categories.

By utilizing the Varnes (1978) general classification system for slope movements, subsequently updated by Cruden and Varnes (1996), debris can be described as a mixture of soil, rock, and organic material characterized by a significant percentage of coarse particles. Debris flows are a type of landslide activity that commonly occurs on steep mountainous terrain (http://www.civil.ubc.ca/ubcdflow). Debris flows are extremely rapid, surging flows of unsorted, saturated debris typically in predefined channels (Hungr et al. 2001). According to the Cruden and Varnes (1996) landslide velocity scale, very rapid and extremely rapid debris flows/landslide failures are described as having typical velocities on the order of $5 \times 10^1$ mm s$^{-1}$ and $5 \times 10^3$ mm s$^{-1}$ respectively (or approximately 3 m min$^{-1}$ and 5 m s$^{-1}$ respectively). Many debris flows form from debris avalanches
starting on steep slopes and entering a channel (Hungr, 2007). In addition many debris slides may progress to debris flows, particularly in gullies on steep mountain slopes (Fannin and Rollerson, 1993). Hutter et al., (1995) further describes debris flows as a mixture of sediment particles of various sizes which flows together with water down a confined or unconfined channel. Photographic examples of debris flows are show in Figure 4 and 5. Figure 6 shows a view down an eroded debris flow channel in the Columbia Mountain region.

*Figure 4:* Example of channelized or confined debris flow (Horel, 2007), on left and *Figure 5:* Example of non channelized or unconfined debris slide/flow, on right (Horel, 2007).
**Table 1: Landslide strength loss mechanism (Table created from Hungr, 2007 text).**

<table>
<thead>
<tr>
<th>Instantaneous Strength Loss Mechanisms</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loss of Cohesion in Rocks and Cemented or Unsaturated Soils</strong></td>
<td>Cohesion of cemented granular soils disappear instantaneously as connected grains separate under excessive shear or tensile strength.</td>
</tr>
<tr>
<td><strong>Liquefaction of Granular Soils</strong></td>
<td>Collapse of loose soil skeleton due to excessive strain, followed by and increase in pore water pressure and a loss of strength under undrained conditions.</td>
</tr>
<tr>
<td><strong>Remolding of Sensitive Clays</strong></td>
<td>Extreme loss of strength on remoulding following shear failure, e.g. “quick clays”.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strength Loss Requiring Large Displacements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Roughness Reduction in Rock Discontinuities</strong></td>
<td>Large shearing displacements applied to rock discontinuities reduce the dilatancy component of frictional strength, producing residual friction. (Hoek and Bray, 1997 is a further reference)</td>
</tr>
<tr>
<td><strong>Shearing in Clays</strong></td>
<td>Long shear displacement leading to the decrease in frictional strength of clay, as a result of reorientation of the platy clay particles and the development of shear structure. (Skempton 1985 is a further reference)</td>
</tr>
<tr>
<td><strong>Sliding Surface Liquefaction</strong></td>
<td>Once failure occurs and is followed by large displacement, the intense shearing within a thin shear band leads to a textural change within the material (grain crushing). The now finer material leads to denser packing, then increased pore pressures under undrained conditions and results in a loss of strength. (Sassa, 2000 is a further reference)</td>
</tr>
<tr>
<td><strong>Frictional Heating</strong></td>
<td>Frictional sliding produces heat then, as thermal expansion of water is greater than that of mineral particles, undrained heating of saturated soils results in increased pore water pressures, further resulting in a loss of strength.</td>
</tr>
<tr>
<td><strong>Loss of Internal Coherence of the Sliding Body</strong></td>
<td>Strength of the rupture surface as well as the mobilized internal strength can affect the resisting forces. In some cases a brittle loss of cohesion. The internal brittleness of a rigid slide may in some cases add brittleness to the sliding body.</td>
</tr>
<tr>
<td><strong>Material Entrainment and Rapid Undrained Loading</strong></td>
<td>This appears to be the principal mechanism of mobilizing earth flow movements on gentle slopes. Generally, porewater pressures increase to bear the basal surface of an earth flow subjected to rapid deposition from upslope material.</td>
</tr>
<tr>
<td><strong>Entrainment of Water, Dilution</strong></td>
<td>Rapid moving landslides incorporate surface water flowing in the path. Especially true for confined debris flows which can result in an increased runout distance.</td>
</tr>
</tbody>
</table>
Debris flow movements are characterized by large relative displacements within a mass exhibiting fluid like behavior (Fannin and Rollerson, 1993). The downslope movement of debris flows from the main scarp is usually accompanied by both entrainment and deposition of materials along the event path (Fannin and Wise, 2001). The process of surge formation, typically conditioned by the presence of a channel, give debris flows their extraordinary mobility and destructive character (Hungr, 2007). In coarse debris flows the surge results from longitudinal sorting of heterogeneous material (Hungr, 2000). A schematic profile of a debris flow surge is shown in Figure 7, after Pierson (1986).
The travel distance of debris flows is a complex phenomenon governed by the properties of the materials and the topographical characteristics of the path of movement (Denlinger and Iverson, 2001; Zhu and Yu, 2005; Lan et al., 2008). In addition to the strength loss mechanisms outlined in Table 1, material entrainment and dilution by surface water are very important process in controlling the dynamics of debris flows and should be taken into consideration (Hungr, 2007).

3.0 UBCDFLOW MODEL

3.1 Underlying Theory

Fannin and Rollerson (1993) describe/summarize field observation of 449 debris flows in the Queen Charlotte Islands (QCI). These 449 events on the QCI were used to develop the UBCDFLOW model for prediction of travel distance and are referred to as the QCI database (Fannin and Wise, 2001). The study area for the QCI database was restricted to
clear-cut areas that were between 6 and 15 years old and found on the Skidegate Plateau in the QCI (Fannin and Rollerson, 1993). The lower age limit was chosen to allow for root strength to deteriorate and terrain be acted upon by large storms, while the upper age limit was set as conifer regeneration beyond this age was found to mask the landscape (Fannin and Rollerson, 1993). Fannin and Rollerson (1993) developed a classification based on slope morphology to describe debris movement based on seven recognized classification classes of events as observed in the field. Table 2 summarizes the classification system developed and utilized by Fannin and Rollerson (1993) with reference to the event path, and channel gradient $i$.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Event$^a$</th>
<th>Path$^b$</th>
<th>Characteristic reach slope angle, $i$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S</td>
<td>OS</td>
<td>na</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>OS→G; G</td>
<td>$i &gt; 15$</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>OS→G; G</td>
<td>$15 &gt; i &gt; 5$</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>G</td>
<td>na</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>OS→G; G</td>
<td>$i &gt; 15$</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>OS→G; G</td>
<td>$15 &gt; i &gt; 5$</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>OS→G; G</td>
<td>na</td>
</tr>
</tbody>
</table>

**Table 2**: Event classification system developed for/from the Queen Charlotte Islands database (Fannin and Rollerson, 1993).

For each of the 449 landslide events, data from the event path is reported according to channel reach (defined as a portion of an event path having a distinctive morphology), width and orientation (Fannin and Wise, 2001). Figure 8 presents a schematic plan view which illustrates how the data from the event path is reported.
As shown in Figure 8 the length path ($L_i$), path azimuth ($AZ_i$) and slope angle ($TH_i$) of every reach were measured. The width ($W_i$) of entrained or deposited material along with respective depths were estimated in field (Fannin and Wise 2001). The QCI data was obtained from ground surveys of each event however they are considered forensic as they occurred months, and at most sites years, after the events had occurred (Fannin and Wise 2001).

**Figure 8:** Schematic plan view of debris flow path (Ref: www.civil.ubc.ca/ubcdflow). Note that in this figure initiation is on an open slope or in a gully headwall, followed by flow within a gully leading to termination on an open slope. (Fannin and Wise 2001)

Based on the field data, the observed magnitude of entrained volume ($+dV_{i,o}$) and/or deposited volume ($-dV_{i,o}$) can be determined. From the point of initiation the observed net change in volume that occurs allows for the calculation of cumulative flow volumes along the event path. It became apparent from inspection of field data and cumulative flow volume plots, that the total entrained volume along the event path often did not
equal the total volume deposited. Thus in order to account for this volumetric error ($V_{err}$) a conservation of volume was imposed on the events used in developing the regression analysis and resulting UBCDFLOW model. By assuming that entrainment and deposition contributed equally to $V_{err}$ the following proportion adjustment was made to all observed volumes (Fannin and Wise 2001):

$$
\begin{align*}
0.5 \left( \sum_{i=1}^{n} \left| + dV_{i,o} \right| + V_{err} \right) + dV_{i} &= + dV_{i,o} - 0.5 \left( \sum_{i=1}^{n} \left| dV_{i,o} \right| \right) \\
0.5 \left( \sum_{i=1}^{n} \left| - dV_{i,o} \right| - V_{err} \right) - dV_{i} &= - dV_{i,o} + 0.5 \left( \sum_{i=1}^{n} \left| - dV_{i,o} \right| \right)
\end{align*}
$$

where $n$ is defined as the number of reaches, $i=1$ is the initiation and $V_{err}$ is defined as

$$
V_{err} = \sum_{i=1}^{n} \left| + dV_{i,o} \right| - \sum_{i=1}^{n} \left| - dV_{i,o} \right|
$$

This leads to the UBCDFLOW definition that, with a summation to zero, the travel distance can be defined as the distance along the event path ($\sum L_i$) from the point of origin to the end of terminal deposition (Fannin and Wise 2001).

As reported by Wise (1997), field observations and inspection of the QCI survey data show that reach morphology exerts a strong influence on flow behaviour. The observed flow behaviour can be identified and grouped into the following modes:

- **Unconfined flow (UF)**, on an open-slope reach (including the headwall, sidewall, or fan of a gully or road);

- **Confined flow (CF)** in a gully channel; and

- **Transitional flow (TF)**, defined to occur on the first open-slope reach after a gully channel.
A volume-based approach was used to model the travel distance and develop the proposed UBCDFLOW model. In the UBCDFLOW model, initiation occurs for a user-defined initial failure volume in the first reach of the event. The morphology of each subsequent reach determines the flow behavior (UF, CF or TF), and slope angle of the reach determines the mode of flow (entrainment $+dV$, or deposition $-dV$).

(www.civil.ubc.ca/ubcdflow/regression.php)

Fannin and Rollerson (1993) reported that for the QCI database, typically erosion dominated in the upper reaches of an event, where little to no deposition results. Following this, some deposition occurs in the transportaion and erosion zone with significant deposition typically occurring in a relatively short section (termed the depositional area). Wise (1997) goes on to report that transitional flow typically occurs on fan apexes or where confined events cross roads. These transitional reaches experience large volumes of deposition with only occasional and minimal entrainment. Further, unconfined-flow reaches typically exhibited a wide range of entrainment and deposition.

Recognizing that some reaches experience both entrainment and deposition the UBCDFLOW model was adjusted to model the dominant behaviour by applying a filter or logical rule flow net to the data set (Fannin and Wise, 2001). Figure 9 shows the generalized model framework for the current UBCDFLOW model. Note that the limits are somewhat subjective however, as they are based on field experience and judgement gained from inspection of the data set (Fannin and Wise, 2001). The limits of the model
framework have been slightly updated since Fannin and Wise published their 2001 paper on the ‘empirical-statistical model for debris flow travel distance’. The online UBCDFLOW website has been developed based on the model slope limits as illustrated in Figure 9.

![Figure 9: Generalized UBCDFLOW model framework](http://www.civil.ubc.ca/ubcdflow/regression.php)

The volume of entrainment and (or) deposition is calculated using regression equations (www.civil.ubc.ca/ubcdflow; Fannin and Wise, 2001), and is based on independent predictor variables as described in the next section.

### 3.2 Input Data

The total travel distance (L) is given by the sum of all reach lengths through which the event has passed (Fannin and Wise, 2001). The independent predictor variables can either
be measured or derived from field observations. These predictor variables describe the geometry of each reach. The measured predictor variables are:

- Length ($L_i$),
- Width of entrainment ($W_e$) or deposition ($W_d$), and
- Azimuth ($AZ_i$)
- Slope ($TH_i$).

As defined by Fannin and Wise (2001) the derived predictor variables are then the incoming flow volume ($V_{i-1}$) and a bend angle function ($BAF_i$), where the latter physical based variable is defined as:

$$BAF_i = \cos(dTH_i) \cos(dAZ_i) \ln \sum (V_{i-1})$$

The changes in slope angle and path azimuth respectively are

$$dTH_i = |TH_i - TH_{i-1}|$$
$$dAZ_i = |AZ_i - AZ_{i-1}|$$

After narrowing down the QCI data base to a subset of events, all involved a single travel path of three or more reaches with a volumetric error

$$V_{crit} \leq 0.4 \left[ \sum_{t=1}^{n} |dV_{i-o}| + \sum_{t=1}^{n} |dV_{i-o}| \right]$$

the following recursion equations were developed (Table 3).

<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(-\Delta V_i) = 0.514 - 0.988 \ln(W_{q_i}) - 0.10 \ln(BAR_i) - 0.731 \ln(L_i) + 0.0155(TH_i) )</td>
<td>( 0 \leq TH_i \leq 18.5^\circ )</td>
</tr>
<tr>
<td>UF</td>
<td>Entrainment</td>
<td>( \ln(+\Delta V_i) = 1.13 \ln(W_{q_i}) + 0.727 \ln(L_i) - 0.0538 \ln(\sum V_{n,2}) )</td>
<td>( 18.5 \leq TH_i \leq 29.5^\circ )</td>
</tr>
<tr>
<td>CF</td>
<td>Entrainment</td>
<td>( \ln(+\Delta V_i) = 0.728 + 1.31 \ln(W_{q_i}) + 0.742 \ln(L_i) + 0.048 \ln(TH_i) )</td>
<td>( 29.5 \leq TH_i \leq 55^\circ )</td>
</tr>
<tr>
<td>TF</td>
<td>Deposition</td>
<td>( \ln(-\Delta V_i) = 0.344 + 0.051 \ln(W_{q_i}) + 0.898 \ln(L_i) - 0.0162(TH_i) )</td>
<td>( 10.5 \leq TH_i \leq 55^\circ )</td>
</tr>
</tbody>
</table>

Note: \( \text{BAR}_i = \cos(\Delta T_h) \cos(\Delta Z) \ln(\sum V_{n,2}) \)

The change in flow volume is determined by one of five equations (as shown in Table 3) depending on the slope angle and flow type. Each equation determines the change in volume for a reach \( (i) \). This change is negative in the case of deposition (flow volume decreases) and positive in the case of entrainment (flow volume increases).

(www.civil.ubc.ca/ubcdflow/regression.php). Further details on the development of the regression equations and natural-logarithm transformations utilized to help approximate by a linear model can be found in Fannin and Wise’s 2001 paper.

To run the online UBCDFLOW model a spreadsheet with the following input variables can be created in rows in the following order: reach number, length (in meters), reach width (in meters), slope angle (in degrees), azimuth (in degrees) and predicted flow type (http://www.civil.ubc.ca/ubcdflow/launchdflow.php). Note that the generalized UBCDFLOW model framework/logical flow diagram (Figure 9, and also found online at www.civil.ubc.ca/ubcdflow/regression.php) can be used to assist in simulating the expected flow type/behavior. Once the user has inputted data into a spreadsheet they can save the file as a .csv (comma-separated value) file however, they must ensure as not to include column heading in the file.
The recursion algorithms outlined in this section have been adopted and are referred to in this report as the UBCDFLOW model.

### 3.3 UBCDFLOW Website

The UBCDFLOW model was originally developed with financial support from the B.C. Science Council, with supplemental funding from Golder Associates and the B.C. Ministry of Forests, Vancouver Forest Region. Further, the UBCDFLOW website was developed with additional support from the B.C. Ministry of Forests and Range, Northern Interior Forest Region. (http://www.civil.ubc.ca/ubcdflow/acknowledgements.php)

The online UBCDFLOW website was designed by the UBC civil engineering department (see reference list for further details) and implemented in 2007. UBCDFLOW is an online PHP/Javascript application which allows users to upload the initial slope input data, run calculations and view and save results (http://orangellous.com/science_software.php#ubcdflow). The UBCDFLOW application can be run with either input data in .csv (comma-separated value) file format or by typing in default values into the online application. The UBCDFLOW application can be found online at [www.civil.ubc.ca/ubcdflow](http://www.civil.ubc.ca/ubcdflow). The current layout of the UBCDFLOW website as of February, 2010 along with the UBCDFLOW user guide is included as Appendix A.
3.3.1 Logical Flow Statements

The online UBCDFLOW application has been developed in accordance with the regression equations as presented in section 3.2. This being stated the originally developed slope classification angles for unconfined, confined and transitional reaches have been updated since the initial work presented by Wise and Fannin (2001). The online UBCDFLOW application follows the logical flow statement or general framework as detailed in Figure 9. This is consistent with the method of analysis’s performed for the Klapperhorm Mountain Study area (Lan et al., 2008) and at the Blueberry Creek site (Fannin et al., 2006) which is presented in section 4.2. The primary difference from the current slope bounds versus the origionally proposed slope bounds is, that for slope values less than 55° the upper bounds for each mode of flow have been increased by 0.5° while the lower slope angle bounds have been reduced by 0.5°. These bounds define which regression equation to utilize, thus to remove some ambiguity in data interpretation, as well as to more accurately predict and model which mode of flow dominates in a given reach, the originally proposed (2001) bounds were adjusted.

3.3.2 User Considerations

From utilization of UBCDFLOW, to perform the analyses presented in this report, a few computational traits of the online application became apparent (as of April, 2010). The primary key attributes observed with the online application that users should be made aware/consider are as follows:
i. After the output values are calculated, based on the user inputs, the visual output displays a cumulative volume versus travel distance plot. The UBCDFLOW online application however, does not plot values which go below zero. By forcing the negative terms to zero, the travel distance values that cross the x-intercept (the slightly skewed, as the true intercept can no longer be extrapolated. Typically it was found that the travel distance values found with the UBCDFLOW online model were slightly increased. This increased travel distance value was typically increased by a portion of the terminating reach length, thus providing a slightly upward estimate of the predicted travel distance.

ii. When initially launching the online UBCDFLOW model, the user will typically load a .csv file or input a default value for length, width, slope and azimuth. After the online UBCDFLOW model is launched the user is asked for an initial volume in m³. There are two subsequent attributes that the user should be aware of.

1. Firstly, if an initial volume as well as the reach dimensions is used to calculate the cumulative volumes then, as the initial volume is typically determined from or defined by the first reach, then the value for the first reach (or initial volume) will be double calculated. This double calculation will typically result in larger maximum cumulative volumes being calculated and therefore larger travel distances being predicted. If it is desirable to avoid this issue of ‘doubling’ then a user can either specify an initial volume of 1.0 m³, or
alternately an initial volume can be specified and the reach values for the first reach can be set to zero for width ($W$) and the slope angle ($TH$).

2. Secondly, if the user wishes to use the ‘Visualization of input data’ feature, then a positive value for all the reach input parameters is required (positive and non zero for width). i.e., if the user is using the guidelines set above to avoid ‘doubling’ the initial volume, then a separate iteration might have to be completed to ensure that a proper visualization and schematic representation of the reaches are outputted.

iii. In the ‘visualization of input data’ option, the reported ‘total travel distance’ can be misleading. This reported distance is merely a sum of the input data (typically field survey data) and does not display the same values as the UBCDFLOW regression equation calculations (e.g., predicted ‘travel distance’ which is determined when the cumulative volume, as calculated by UBCDFLOW, reaches zero). This reported ‘total travel distance’ would/could be more accurately reported as the ‘sum of inputted reach lengths.’

These model attributes do not have a significant effect on the behaviors modeled by the online UBCDFLOW application however, users should take into consideration these characteristics when further utilizing or analyzing online model outputs.
4.0 LITERARY REVIEW

Rapid debris flows are among the most damaging and dangerous of all landslide phenomena. Their potential for destruction often cannot practically be reduced by stabilization of the source areas. Engineering risk analyses are then needed, including prediction of runout (Hungr, 1995).

This section provides a summary of a portion of the literature available on debris flows and provides further background information for debris flows in steep forested terrain. In addition, previous analysis’s completed using the UBCDFLOW model are presented. This literary review assists in the completion of a more complete and technical critique of UBCDFLOW.

4.1 Quantitative Estimates of Travel Distance –Non UBCDFLOW

In order to perform a hazard analysis in steep forested terrain or to design protective measures against debris flows, it is necessary to estimate important parameters of debris flows. Important parameters to consider include: debris volume, mean flow velocity, peak discharge, and runout distance (Rickenmann, 1999). The primary focus of this report is on methods and simple empirical relationships posed to estimate runout or travel distance of debris flows.

Two current approaches for the analysis of debris flows exist; these approaches may be classified as semi-empirical and empirical. The semi-empirical or semi-quantitative approach is based on a quantitative evaluation of field observations, taking into
consideration the rheological behavior and associated physical properties (Fannin and Rollerson, 1993). The empirical approach on the other hand is based on a qualitative evaluation of field observations in addition to basic quantitative analyses based on engineering principles (Fannin and Rollerson, 1993). Due to the complexity of the debris-flow process, numerical simulation models of debris flows are still limited with regard to practical applications (Rickenmann, 1999). Further, as a result of the large variety of site and soil conditions the assessment of the debris flow hazard potential has to rely on semi-quantitative methods (Rickenmann, 1999).

Semi-empirical relationships to determine event magnitude, discharge, velocity, angle of deposition, runout distance, superelevation and impact for on defense structures have been proposed by Hungr et al. (1984). In the latter relationships an emphasis becomes apparent which explains that the analytical procedures typically require further calibrations. Brenda and Cundy (1990) have proposed a simple empirical model for predicting travel distance and deposition of debris in confined channels. In the Brenda and Cundy (1990) model however, rheological properties have been avoided and inputs are based on topography alone (Fannin and Rollerson, 1993).

Corominas (1996) further discussed additional formulae which volume (V) directly with the reach angle (α). This correlation works by simplifly the graphical determination of the maximum runout. Here Corominas (1996) compares a dataset of 52 debris flows, debris slides and debris avalanches that occurred in the Pyrenees to 19 worldwide events.
(Hürlimann et al., 2008). The empirical correlation proposed by Corominas (1996) can be written as:

\[ \tan \alpha = \frac{H_e}{L_{\text{max}}} = 0.97V^{0.105} \]

Rickenmann (1999) shows (Figure 10) that a dependence to travel distance \( (L) \) on \( H_e \) and \( M \) exists. Here \( H_e \) is the elevation difference between the starting point and the lowest point of deposition of the mass movement and \( M \) is material volume. In this relationship \( M \) and \( H_e \) can be considered as energy potential of the mass movement. This relationship is based on a data set of approximately 232 events, of which 154 of these events are debris flows. It should be noted that Rickenmann’s (1999) data is comprised mainly of debris flow data however there are also a few occurrences of mudflows and rockfalls/sturzstroms included. These data were derived from, listed in order by areas contributing the largest number of events to the data base: the Swiss Alps, Nevado del Ruiz, USGS flume experiments, the Canadian Cordillera, Japan and the U.S.A..

Figure 10: Total travel distance \( (L) \) of mass movements in relation to an expression for the
energy potential, the product of material volume (M) and elevation difference (He). Also shown is
the semi-theoretical relationship satisfying Froude or geometric similarity. (Rickenmann, 1999)

As found by Rickenmann (1999) the relationship satisfying Froude, or geometric, scaling
can be given by the following semi-theoretical relationship,

\[ L_* = 30(MH_e)^{1/4} \]; where the constant A6=30 was selected to approximate the average
L values for the debris flow field data. Appendix B, extracted from Rickenmann’s 1999
paper, presents a more detailed derivation of the scaling equations utilized in deriving this
semi-theoretical relationship.

B going one step further the following regression equation was derived from debris flow
field data between \( L, M \) and \( H_e \):

\[ L_* = 1.9M^{0.16}H_e^{0.83} \]. Figure 11 shows a visual representation of Rickenmann’s (1999)
regression equation in relation to the data set utilized.

![Figure 11: Total travel distance (L) of mass movements in relation to an expression obtained from a regression calculation using debris flow field data only. Also shown is the line of the regression equation. (Rickenmann, 1999)](image-url)
Now if we take Rickenmann’s (1999) regression equation and apply log/natural log rules to it, we can rearrange this equation into the form (see Appendix C for proof):

\[
\ln M = 6.25 \ln(L) - 5.188 \ln(H_e) - 4.0125.
\]

This above equation is referred to herein as the transformed Rickenmann’s equation.

Further investigation shows that the above transformed version of Rickenmann’s regression formula is of a similar form to that of the UBCDFLOW regression formula (see Table 3). Note that both equations utilize a logarithm transformation to achieve normality after regression, thus allowing for the relation to be approximated by a linear response. In the transformed Rickenmann’s equation \( M \) can be thought of as somewhat analogous to the \( dV_i \) term in the UBCDFLOW equations. Further, \( H_e \), the elevation difference, could be somewhat thought of as a function of \( TH_i \) (slope) and \( L_i \) (length), with constants dictated by site/soil conditions inherent in each respective model database.

Cannon (1989) has proposed a subsequent volume-based model with concepts again similar to those of Fannin and Wise (2001). In Cannon’s volume based model, the initial volume of a debris flow and the rate at which material is entrained or deposited along its travel path could be used to estimate the total travel distance (Prochaska et al., 2008).

As detailed by Prochaska et al. (2008 paper) a commonly advocated dynamic model used to calculate debris flow runout is the leading-edge model (Takahashi, 1981, 1991; Hungr et al., 1984; VanDine, 1996; Lo, 2000):
This report aims to focus more on volume-based models as they better compare/contrast to the UBCDFLOW model. Further, often these dynamic models require two parameters that can be difficult to accurately estimate, namely the flow velocity and the frictional parameter (Prochaska et al., 2008).

At the present there are no rigorous methods which would allow for a strict assessment to determine an exact probability of debris-flow occurrence, be it based either on physically measured characteristics of a catchment or by statistical analysis (Rickenmann, 1999). If information is available on past debris flow events, then this data is often viewed as the most reliable indicators of system trends (Rickenmann, 1999). As UBCDFLOW has been developed from a fairly large dataset it shows promise in providing order of magnitude estimates of debris flow travel distance in steep forested terrain under various initial conditions. Past analyses completed with UBCDFLOW are presented in the next section to better investigate and constrain the confidence at which the model can be utilized.

\[
x_L = \frac{v_0^2 \cos^2 (\theta_0 - \theta)}{g(S_f \cos \theta \sin \theta)} \left( 1 + \frac{gh_0 \cos \theta_0}{2v_0^2} \right)^2
\]

where:

- \(x_L\) runout distance,
- \(v_0\) debris velocity,
- \(\theta_0\) entrance slope angle (channel slope),
- \(\theta\) runout slope angle (fan slope),
- \(g\) acceleration of gravity,
- \(S_f\) friction slope, and
- \(h_0\) debris flow depth, all in consistent units.
4.2 Illustrative Applications of UBCDFLOW

Through literary review, some analysis’s can be found which further compare modeled UBCDFLOW travel distances against field observations (Eliadorani et al, 2003; Fannin et al, 2004; Fannin et al., 2006, Lan et al., 2008). Preliminary sensitivity analyses have been previously completed to examine the sensitivity of the UBCDFLOW model to uncertainty in initial volumes and event path width size (Fannin et al., 2006). In fact, the online UBCDFLOW application incorporates in an option to vary the initial volume as well as the entire event path width so that a basic sensitivity analysis can readily be performed.

4.2.1 Blueberry Creek, B.C. (UBC Analysis)

Application of the UBCDFLOW model for back analysis (Eliadorani et al., 2003; Fannin et al., 2006) and a sensitivity analysis (Fannin et al., 2006) have been performed for a site at Blueberry Creek, British Columbia. The Blueberry Creek Event is so named because of its location within the watershed. This site is 17 km west-southwest of Castlegar, B.C. in a forest clear cut (Fannin et al., 2006), and is within the same Columbia Mountain region as the events later detailed in section 5.0.

The cutblock where the flow initiated (#14-11), is 38 ha in size and is located on an east facing 55-60% gradient slope. The Blueberry Creek landslide event occurred in May 1993 and initiated at elevation 1600m (Fannin et al., 2006).
This event started as a small landslide at a subtle break in slope below a culvert.

Blueberry Creek is a Type 3 event (see section 3.2) as this event traveled in a gentler gully system (Fannin et al, 2003). The event occurred in the forest clearcut with an initial volume of 130 m$^3$, travelling 1580 m to the point of terminal deposition. This event continued as a large debris flow which nearly reached the Blueberry Creek. A cross-drain culvert had been placed about 10 m to one side of a natural drainage hollow, in order to coincide with a low spot in the road. This failure behaviour is typical of many slides which occur below poorly-placed culverts or cross-ditches, and illustrates how flow diversions of only a few meters can initiate large mass movements.

Figure 12 shows sketches illustrating the two main causes of gentle-over-steep landslides; concentration and diversion of runoff by roads and increase snowmelt in clearcuts above a point of landslide initiation (Jordan and Nicol, 2002).

Figure 13, shows site photographs of the Blueberry Creek slide.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{blueberry_creek.png}
\caption{Illustrations of the two main causes of gentle-over-steep landslides, concentration and diversion of runoff by roads and increase snowmelt in clearcuts above a point of landslide initiation (Jordan and Nicol, 2002)}
\end{figure}
Figure 13: Site photographs of the Blueberry Creek 1993 event (Jordan and Nicol, 2002, also presented at http://www.civil.ubc.ca/ubcdflow).

Eliadorani et al. (2003) published transverse data for the event which was used both for the UBCDFLOW sensitivity and back-analysis. A schematic representation of the travel distance and flow behavior in each reach is provided in Figure 14 (Fannin et al., 2006). Results of the UBCDFLOW back analysis are reported as a cumulative volume curve in Figure 15. The material volume balance has been based on field observation and forensic estimates and is shown for comparison. As show in Figure 15 the estimated travel distance was found to correctly model the mode of flow. Through inspection of Figure 15 it can seen that the estimated UBCDFLOW travel distance calculated is approximately 2.6% greater than the actual travel distance (1580m) recorded for the Blueberry Creek event (Fannin et al., 2006). A back analysis of the Blueberry Creek event with the online UBCDFLOW was performed to initially the online UBCDFLOW application. In
completing this calibration it was found that the UBCDFLOW analysis’s completed by Eliadorani et al. (2003) and Fannin et al (2006) were completed by using forensically informed simulations where solely the reach width corresponding to the dominant flow behavior was inputted into the model (e.g. the larger of $W_e$ or $W_d$ were utilized in the reaches where evidence of entrainment and deposition occurring in a reach can be found, see Section 5 for further details).

Figure 14: Schematic of Blueberry Creek debris flow UBCDFLOW back analysis. Note that the travel distance and reach widths are on different scales. (Fannin et al., 2006)
Figure 15: UBCDFLOW back analysis of the Blueberry Creek debris flow (Fannin et al., 2006).

Figure 16 shows a comparison between the UBCDFLOW model and the empirical model of Benda and Cundy (1990). In the Benda Cundy (1990) model, deposition is predicted based on the channel-junction angle with the point of deposition at the point of 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 is then multiplied by an assigned average channel yield rate of 8m³/m plus the initial failure volume to give an estimate of the volume at termination. Inspection of Figure 16 shows that UBCDFLOW more closely follows the flow mode, as determined from field inspections. (Eliadorani et al., 2003)
As found by Fannin et al (2006) the back-analysis of the Blueberry Creek event, using the UBCDFLOW model, shows the debris flow travel distance to be insensitive to the initial failure volume (Figure 17). In addition, the back analysis reveals the cumulative flow volume to be insensitive to fluctuations in initial volume.

Travel distance was found somewhat sensitive to the width of the event path, but not
overly so (Figure 18). However, the cumulative flow volumes, and hence overall magnitude of the event, proved very sensitive to the width of the event path. (Fannin et al., 2006)

![Figure 18: UBCDFLOW back analysis, change in cumulative volume for different widths of deposition and scour at Blueberry Creek (Fannin et al., 2006).](image)

These findings suggest that the UBCDFLOW model provides a useful means of establishing travel distance, for similar types of debris flow (Fannin et al., 2006).

### 4.2.2 Klapperhorn Mountain, BC/AB Border (UofA Analysis)

Lan et al. (2008) performed a back analysis, through the use of UBCDFLOW, on an event in the Yellowhead Pass in the Canadian Rocky Mountains. The study area is located on Klapperhorn Mountain near the border between Alberta and British Columbia. Debris flows occurring on Klapperhorn Mountain pose a significant hazard to railway operations at the base of the mountain. The study area and the two railways operated by Canadian National Railway (Albreda and Robson subdivisions) are running parallel at the base of the mountain as shown in Figure 19. As observed in Figure 19 three kilometer
long section of both railways have been impacted by debris flow events. Figure 20 shows a photographic overview of the study area with the corresponding drainage basin labels shown. Generally the site is within the Rocky Mountains Proterozoic Middle Miette Group, this includes feldspathic sandstones, granule and pebble conglomerate, siltstone and argillite. (Lan et al, 2008)

Figure 19: Study area of Klapperhorn Mountain. Existing debris flow channels are marked by red lines. Five drainage basins are identified. The Albreda (upper) and Robson (lower) railway subdivisions along the base of the Klapperhorn are also shown. (Lan et al., 2008)
Figure 20: Photo showing the overview of the study area. The main creek in the foreground is Mile 54.3 of the Albreda Subdivision (Lan et al., 2008).

Airphoto interpretation and GIS analysis, together with field work were undertaken at two debris flow events located at track mileage 54.0 and 54.3. Characteristics of these two debris flow events were analyzed, including debris flow path morphology and event behaviours. The sizes and travel distances were estimated with the empirical-statistical UBCDFLOW model under different initial conditions. Based on the gathered information the hydrologic analysis functions were used to delineate drainage basins using digital elevation models in the study area. (Lan et al., 2008)

Input parameters for the UBCDFLOW model were determined by using the spatial tools within GIS software, performed on a digital elevation model, together with the detailed field survey including inspection of scarps, scour lines, lateral deposition and path morphology (Lan et al, 2008). Based on the results of the UBCDFLOW model the potential impacts on the railway bridges were evaluated. Figure 21 shows a plan view,
broken into reaches, for debris flows 54.0 and 54.3.

![Plan view of debris flow 54.0 and 54.3](image)

**Figure 21:** Plan view of debris flow 54.0 and 54.3 (Lan et al., 2008).

Typically the channel slope in the upper portion of the M54.0 event ranged from 30° to 40° and that the M54.3 event ranged from 40° to 60° (Lan et al., 2008). Both events were observed to deposit below the Robson subdivision.

As observed in the field, the debris flows in the study area initiated near the top of the colluvial. Typically it was found that less than 2m of this colluvial lay on bedrock. Figure 22 shows the flow volume changes versus debris flow travel distance for the two events as simulated by the UBCDFLOW model. As observed in Figure 22 one can see that by using different initiation depths that different initial volumes were inspected.
Figure 22: Estimated size and travel distance for debris flow M54(a) and M54.3 (b) as predicted by UBCDFLOW (Lan et al., 2008).

As shown in Figure 22 the simulated maximum accumulated volume for event M54 is around 2,000 m$^3$ and event M54.3 is around 20,000 m$^3$. Debris flow M54 reaches the bridge at the Albreda subdivision before it reaches a maximum flow volume where M54.3 reaches the bridge location right after the maximum flow volume is reached. Although event M54 yields a lower flow volume and shorter travel distance it is not well channelized and occurs frequently and thus has a greater potential for impacting the railway bridge in question. The UBCDFLOW simulated events for event M54 and M54.3 show that both debris flow event pose significant threats to railway infrastructure, since they both reach the track level with large flow volumes. (Lan et al., 2008)

Further Lan et al., go on to show that with a simple bridge blockage ratio, defined as the possible debris accumulation depth under the bridge open area to the depth of bridge open, the potential impact of future events reoccurring along the historic paths can be evaluated. Figure 23 shows a track bridge crossing the M54.3 debris channel while
Figure 24 shows the simple method used to analyze the blockage potential hazard to the bridge.

*Figure 23: Track bridge crossing the M54.3 debris channel (left) and Figure 24: schematic map for calculating ht bridge blockage ration by debris flow (right) (Ref: Lan et al., 2008).*

As observed in the above case study the empirical-statistical UBCDFLOW model shows potential to offer a practical approach for estimating a debris flows size and travel distance in the study area and assist in better defining variables in risk analysis for a given debris flow hazard.

### 4.3 Additional UBCDFLOW Dataset

Dr. Jonathan Fannin with the assistance of research student has previous performed an additional back analysis, through the use of UBCDFLOW, on an event in Col du Sabot France. This analysis offers another opportunity to reflect on the application of UBCDFLOW for back-analysis purposes.

#### 4.3.1 Col du Sabot, France (Unpublished Analysis)

The Col du Sabot debris flow event occurred in the southeastern portion of France within a region of the French Alps. Figure 25 shows the location of this event.
Similar to the Blueberry Creek back analysis, the Col du Sabot event was a forensically informed UBCDFLOW back analysis simulation in which the modeled the mode of flow generally agreed with what was recorded by the site field survey. To further investigate this event a sensitivity analysis was performed through use of the online UBCDFLOW application to investigate the model sensitivity to again initial volume and reach width uncertainty. Figure 26 shows the initial volume uncertainty sensitivity analysis and Figure 27 shows the reach width uncertainty analysis for done for the Col du Sabot event.
From the Col du Sabot back-analysis, the debris flow travel distance was again observed to be insensitive to the initial failure volume. Further, the cumulative flow volumes and overall magnitude of the event are observed to be very sensitive to the width of the event path. The travel distance appears only mildly sensitive to the width of the event path, note that this trend is somewhat masked in Figure 26 as the online UBCDFLOW application does not plot below zero, slightly effecting the true extrapolated values at the x-intercept (travel distance).
5.0 ANALYSIS/RESULTS

The UBCDFLOW model was further assessed through performing a back analysis of five events from the Kootenay-Columbia area. All data were collected by Jordan (2001) during a Ministry of Forestry study of landslides caused by forest roads and timber-harvesting in the Kootenay-Columbia region. The field data are post-event measurements and observations of debris movement (Fannin et al., 2003). The analysis is limited by the
difficulty of accurately describing an event some years after it has taken place (Fannin et al., 2003).

5.1 UBCDFLOW Simulations

To further critique the UBCDFLOW model it was decided that the method of inputting the survey data would be inspected. It has been recognized and reported that some reaches along an event path experience both entrainment and deposition (Fannin and Rollerson, 1993; Fannin and Wise, 2001). As a result, when the UBCDFLOW model was developed it was designed to model the dominant behaviour in any reach by applying a filter, or logical rule flow net, to the data set (see Figure 8). Two dominant methods of inputting the survey data into UBCDFLOW became apparent:

1) **Forensically-informed Simulation** (Simulation 1): where the governing mode of flow in a reach was observed in the field and thus known beforehand. For this simulation back-analysis is performed based on forensic measurement of all input parameters; i.e. the width of entrainment ($W_e$) and/or the width of deposition ($W_d$) is known in addition to $L_i, AZ_i, TH_i$ and the initial volume. Therefore, by knowing if entrainment or deposition prevails, $W_e$ or $W_d$ can be inputted.

2) **Path-informed Simulation** (Simulation 2): where the mode of flow is not known and/or the benefits of knowing the mode of flow are not realized. This simulation is more likely to be implemented if reach width can not be be forensically constrained and/or only preliminary estimates of overall reach width are
obtainable. In this case \( W_c \) and or \( W_d \) are not individually know or \( W \) is imported without regard for entainment or deposition prevailing. In this case it is assumed that \( L_i, AZ_i, TH_i \) and the initial volume can still be constrained/estimated.

This yields a comparison of the observed mode of flow to the simulated mode of flow.

Figure 28 presents the developed, generalized decision framework for implementing survey reach widths into the UBCDFLOW model.

Figure 28: Generalized decision framework for reach width implementation.

After establishment of the decision framework it was decided that a sensivity analysis would be performed on UBCDFLOW for the five randomly selected Kooteny-Columbia events.
The corresponding latter two calculated cumulative volume cases were compared against the field survey. To further the sensitivity analysis done by Fannin et. al., 2004 the UBCDFLOW website was utilized to further assess the effects of implementing changes to initial volume and overall event path width. These further sensitivity analyses were performed through use of the online UBCDFLOW website. For all initial volume and overall event path reach width sensitivity analysis the Case 2 (size informed) reach width values were utilized. In the UBCDFLOW model, as discussed in subsection 5.1.1.1, the initial volume was inputted online and the first reach was forced to not model a flow behavior (as this is accounted for in the initial volume). Further, in order to perform the sensitivity analysis on the initial failure volume, the model was run with different initial volumes while keeping each of the other input variables unchanged, this is consistent with the procedure used by Fannin et al., 2006. A similar approach to the aforementioned was utilized for the sensitivity analysis on the width of the event.

A discussion of each event, along with figures corresponding to the performed analysis is presented below. Note that as the online UBCDFLOW does not generate cumulative volume values below zero, thus the figures shown below exhibit this same characteristic.

**5.1.1 Shannon Creek #5004 – Landslide Event**

The Shannon Creek event occurred in June 1999 and illustrates some of the common causes of landslides below roads and cutblocks. The slide started as a fill failure in an old skid trail, below a culvert on a recently reconstructed road. The culvert was placed about 40 m down-road from the centre of a gully. The ditch and culvert intercepted subsurface
flow from the gully and diverted to the failure point. Diversion of water by old skid trails was also a factor. As about 90% of the drainage area upslope is clearcut, with the recent large cutblock logged in 1979, increased snowmelt was probably also a factor. (Jordan, 2002)

Shannon Creek is a Type 2 event (see Section 3.1). Type 2 events may initiate on open slopes or gully headwalls, and travel down a relatively steep, confined channel (Fannin et. al, 2003). Figure 29 below shows field notes and photographs of this debris flow area. As outlined above, the event started on an open slope. The flow continued down the channel with occasional transitional flows until ending on a fan at the base of the gully (Fannin et al., 2003). There are 13 reaches for this event.

Figure 29: Field notes and photograph of the Shannon Creek Landslide event (The landslide is on the left of the photo. The feature on the right is a snow avalanche which originated in the cutblock) (Jordan, 2002).
Figure 30 presents a schematic representation of how the Shannon Creek #5004 event was evaluated with the UBCDFLOW model and Table 4 provides basic reach characteristic which established the simulated UBCDFLOW mode of flow.

![Schematic diagram](image)

**Figure 30:** Schematic of Shannon Creek debris flow UBCDFLOW back analysis. Note this figure was generated through the use of the UBCDFLOW website. Unconfined flow is shown in green, confined flow is shown in blue and transitional flow is shown in red (reach widths have been multiplied by a factor of 10 for visualization of the data).

**And**

**Table 4:** Basic reach characteristics of the Shannon Creek #500 event.

<table>
<thead>
<tr>
<th>Reach Number</th>
<th>Slope angle ($^\circ$)$^1$</th>
<th>UBCDFLOW morphology$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.2</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>38.0</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>31.0</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>T</td>
</tr>
<tr>
<td>5</td>
<td>31.0</td>
<td>C</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>T</td>
</tr>
<tr>
<td>7</td>
<td>32.2</td>
<td>C</td>
</tr>
<tr>
<td>8</td>
<td>35.0</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>26.6</td>
<td>C</td>
</tr>
<tr>
<td>10</td>
<td>26.6</td>
<td>C</td>
</tr>
<tr>
<td>11</td>
<td>10.2</td>
<td>C</td>
</tr>
<tr>
<td>12</td>
<td>0.0</td>
<td>T</td>
</tr>
<tr>
<td>13</td>
<td>16.7</td>
<td>U</td>
</tr>
</tbody>
</table>

$^1$ from field measurements in %  
$^2$ U: Unconfined - open slope, C: Confined, T: Transitional
5.1.1.1 Simulation Results

**Shannon Creek #5004**
Cumulative Volume Comparison

![Cumulative Volume Comparison Graph](image1)

*Figure 31:* UBCDFLOW back analysis of the Shannon Creek debris flow.

**Shannon Creek #5004**
Initial Volume Sensitivity

![Initial Volume Sensitivity Graph](image2)

*Figure 32:* UBCDFLOW initial volume sensitivity analysis, performed using online application for the Shannon Creek #5004 event.
Figure 33: UBCDFLOW event path width sensitivity analysis, performed using online application for the Shannon Creek #5004 event.

The UBCDFLOW calculated flow volumes for the back analysis are comparable to the cumulative volume as determined by the field survey. The first portion of entrainment is in especially good agreement. However, as the slope angles are generally high (>30°) in the entainment zone, the model entrains at a higher rate than the observed data (Fannin et al., 2003).

Between Simulation 1 (forensically informed) and Simulation 2 (path informed), only minor difference were observed between cumulative volume and the simulated travel distance. By comparing the travel distance recorded in the field survey to the UBCDFLOW simulation is observed to overestimate the travel distance by around 7% (or ~35m).
The Shannon Creek #5004 event showed little change in the travel distance and cumulative flow volume over the range of initial volumes modeled, with the event being observed to be quite insensitive to changes in the initial failure volume. The difference between the curves appears to be nearly constant for the entrainment reaches while slightly more converging for the depositional reaches. Overall the flow volumes generated by UBCDFLOW at Shannon Creek #5004 are observed to be moderately sensitive to a change in the event width however the predicted travel distance is not and remains relatively unchanged.

5.1.2 Bigmouth #11 – Landslide Event

Figure 34 presents a schematic plan view representation the UBCDFLOW modeled debris flow geometry for Bigmouth #11. This type 1 event occurred on an open slope and consists of 12 reaches. Table 5 provides the basic reach characteristic for this event.

![Schematic of Bigmouth #11 debris flow UBCDFLOW back analysis. Note this figure was generated through the use of the UBCDFLOW website. Unconfined flow is shown in green, confined flow is shown in blue and transitional flow is shown in red (reach widths have been multiplied by a factor of 10 for visualization of the data).](image-url)
<table>
<thead>
<tr>
<th>Reach Number</th>
<th>Slope angle $(\theta)$</th>
<th>UBCDFLOW morphology $^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39.4</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>31.8</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>27.9</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>33.0</td>
<td>U</td>
</tr>
<tr>
<td>5</td>
<td>26.6</td>
<td>U</td>
</tr>
<tr>
<td>6</td>
<td>31.0</td>
<td>U</td>
</tr>
<tr>
<td>7</td>
<td>24.7</td>
<td>U</td>
</tr>
<tr>
<td>8</td>
<td>23.3</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>14.0</td>
<td>T</td>
</tr>
<tr>
<td>10</td>
<td>14.0</td>
<td>U</td>
</tr>
<tr>
<td>11</td>
<td>15.6</td>
<td>U</td>
</tr>
<tr>
<td>12</td>
<td>14.0</td>
<td>U</td>
</tr>
</tbody>
</table>

$^1$ from field measurements in %
$^2$ U: Unconfined - open slope, C: Confined, T: Transitional

Table 5: Basic reach characteristics of the Bigmouth #11 event.

5.1.2.1 Simulation Results

![Cumulative Volume Comparison](image-url)
Figure 35: UBCDFLOW back analysis of the Bigmouth #11 debris flow.

Figure 36: UBCDFLOW initial volume sensitivity analysis, performed using online application for the Bigmouth #11 event.

Figure 37: UBCDFLOW event path width sensitivity analysis, performed using online application for the Bigmouth #11 event.
As shown in Figure 35, simulations yielded a approximately 76-110% larger maximum cumulative volume than the observed filed survey measurements. In addition, for this event the travel distance is overestimated by the UBCDFLOW simulations, by about 4.0-5.4%. Thus, for the Bigmouth #1 event there was a moderate difference observed when comparing Simulation 1 versus Simulation 2.

Overall this event was observed to be fairly insensitive to changes in the initial failure volume to both cumulative volume and travel distance. The flow volumes generated by UBCDFLOW at Bigmouth #11 are moderately sensitive to a change of the event widths (values ranging from approximately -50 to + 50%) however, the predicted travel distance is deemed relatively insensitive.

5.1.3 Tindale-Airy Creek #1620 – Landslide Event

Airy Creek #1260 is an 11 reach event, type one event which occurred on an open slope. Figure 38 presents a schematic plan view representation the UBCDFLOW modeled debris flow geometry for the Airy Creek #1620 event while Table 6 presents characteristics of the event reaches.

![Figure 38: Schematic of Airy Creek #1620 debris flow UBCDFLOW back analysis. Note this](image-url)
figure was generated through the use of the UBCDFLOW website. Unconfined flow is shown in green, confined flow is shown in blue and transitional flow is shown in red (reach widths have been multiplied by a factor of 10 for visualization of the data).

<table>
<thead>
<tr>
<th>Reach Number</th>
<th>Slope angle ($^\circ$)$^1$</th>
<th>UBCDFLOW morphology$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33.8</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>31.0</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>35.0</td>
<td>T</td>
</tr>
<tr>
<td>4</td>
<td>28.4</td>
<td>U</td>
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<td>5</td>
<td>0.0</td>
<td>U</td>
</tr>
<tr>
<td>6</td>
<td>28.8</td>
<td>U</td>
</tr>
<tr>
<td>7</td>
<td>28.8</td>
<td>U</td>
</tr>
<tr>
<td>8</td>
<td>26.6</td>
<td>U</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
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<tr>
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<td>35.0</td>
<td>U</td>
</tr>
<tr>
<td>11</td>
<td>8.5</td>
<td>U</td>
</tr>
</tbody>
</table>

$^1$ from field measurements in %  
$^2$ U: Unconfined - open slope, C: Confined, T: Transitional

Table 6: Basic reach characteristics of the Airy Creek #1620 event.

5.1.3.1 Simulation Results

Figure 39: UBCDFLOW back analysis of the Airy Creek #1620 debris flow.
**Figure 40:** UBCDFLOW initial volume sensitivity analysis, performed using online application for the Airy Creek #1620 event.

**Figure 41:** UBCDFLOW event path width sensitivity analysis, performed using online application for the Airy Creek #1620 event.
As shown in Figure 39 there was only a minor difference observed between implementing Simulation 1 and Simulation 2 for the Airy Creek #1620 event, with both simulation maximum cumulative volumes around 200% larger than the survey data measurements. For this event the UBCDFLOW model predicts a significantly larger maximum cumulative volume than what was recorded in field inspections.

By extending the final linear trending portion of the UBCDFLOW cumulative volume plot for this example, highly speculative as there is only one data point for deposition after the maximum cumulative volume peak has been reach, it can be observed that the UBCDFLOW model overestimates the observed travel distance (on the order of magnitude of +30%).

From this range of initial values, the magnitude of the cumulative flow volume at each reach did not change significantly, nor did the simulated travel distance (±1%). The investigation of the widths of entrainment and deposition for the Airy Creek #1620 event, shows that the percent variation in cumulative flow volume varied by approximately ±50%. Overall the flow volumes generated by UBCDFLOW at Bigmouth #11 we observed to be moderately sensitive to a change in the event width while the predicted travel distance was observed to be relatively insensitive.
Figure 42 presents a schematic plan view representation of the UBCDFLOW modeled debris flow geometry for the Airy Creek #1621 event. Table 7 outlines some reach characteristics of this type 2 event.

Table 7: Basic reach characteristics of the Airy Creek #1621 event.

<table>
<thead>
<tr>
<th>Reach Number</th>
<th>Slope angle (°)</th>
<th>UBCDFLOW morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.2</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>34.2</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>33.0</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>35.0</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td>31.8</td>
<td>C</td>
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<tr>
<td>6</td>
<td>30.1</td>
<td>C</td>
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<tr>
<td>7</td>
<td>26.6</td>
<td>C</td>
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<tr>
<td>8</td>
<td>24.7</td>
<td>C</td>
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<tr>
<td>9</td>
<td>23.3</td>
<td>C</td>
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<tr>
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<td>17.2</td>
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<tr>
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<td>5.1</td>
<td>U</td>
</tr>
<tr>
<td>12</td>
<td>9.1</td>
<td>U</td>
</tr>
</tbody>
</table>

1 from field measurements in %
2 U: Unconfined - open slope, C: Confined, T: Transitional

Figure 42: Schematic of Airy Creek #1621 debris flow UBCDFLOW back analysis. Note this figure was generated through the use of the UBCDFLOW website. Unconfined flow is shown in green, confined flow is shown in blue and transitional flow is shown in red (reach widths have been multiplied by a factor of 10 for visualization of the data).
5.1.4.1 Simulation Results

**Figure 43:** UBCDFLOW back analysis of the Airy Creek #1621 debris flow.

**Figure 44:** UBCDFLOW initial volume sensitivity analysis, performed using online application for the Airy Creek #1621 event.
The mode of flow for all 12 reaches are modelled as predicted by the observed filed data, with only slight deviations being observed for Simulation 1 and Simulation 2. Overall UBCDFLOW models moderately smaller values for the maximum cumulative volume and slightly underestimates (by ~3%) the travel distances for this event.

The Airy Creek #1621 event showed characteristics very similar to Shannon Creek #5004 in regards to initial volume sensitivity. Little change resulted to the travel distance and cumulative flow volume over the range of initial volumes. For this event the calculated and predicted travel distance values were near identical. This event was observed to be insensitive to a change in the initial failure volume. Finally, the flow volumes generated by UBCDFLOW for Airy Creek #1621 are observed to be moderately sensitive to changes in the event width, while the predicted travel distance remains insensitive.

Figure 45: UBCDFLOW event path width sensitivity analysis, performed using online application for the Airy Creek #1621 event.
5.1.5 Airy Creek #3017 – Landslide Event

Figure 46 presents a schematic plan view representation the UBCDFLOW modeled debris flow geometry for the Airy Creek #3017 event. Table 8 shows some characteristics of the events reaches for the type 2 event.

![Diagram of Airy Creek #3017 debris flow UBCDFLOW back analysis.](image)

<table>
<thead>
<tr>
<th>Reach Number</th>
<th>Slope angle ($^\circ$)</th>
<th>UBCDFLOW morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.9</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>31.0</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>33.0</td>
<td>U</td>
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<tr>
<td>4</td>
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<td>5</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>30.1</td>
<td>C</td>
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<tr>
<td>8</td>
<td>24.2</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>U</td>
</tr>
<tr>
<td>10</td>
<td>20.8</td>
<td>C</td>
</tr>
<tr>
<td>11</td>
<td>0.0</td>
<td>U</td>
</tr>
<tr>
<td>12</td>
<td>17.2</td>
<td>U</td>
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<tr>
<td>13</td>
<td>9.6</td>
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<tr>
<td>14</td>
<td>8.5</td>
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<td>5.7</td>
<td>U</td>
</tr>
<tr>
<td>16</td>
<td>2.9</td>
<td>U</td>
</tr>
</tbody>
</table>

1 from field measurements in %  
2 U: Unconfined - open slope, C: Confined, T: Transitional

*Figure 46: Schematic of Airy Creek #3017 debris flow UBCDFLOW back analysis. Note this figure was generated through the use of the UBCDFLOW website. Unconfined flow is shown in green, confined flow is shown in blue and transitional flow is shown in red (reach widths have been multiplied by a factor of 10 for visualization of the data).*

*Table 8: Basic reach characteristics of the Airy Creek #3017 event.*
5.1.5.1 Simulation Results

**Figure 47:** UBCDFLOW back analysis of the Airy Creek #3017 debris flow.

**Figure 48:** UBCDFLOW initial volume sensitivity analysis, performed using online application for the Airy Creek #3017 event.
Simulation 1 and 2 yield maximum cumulative volumes that are similar to the observed field data. Difference between the two simulations are primarily observed with the rate of deposition, where Simulation 2 models a slightly quicker rate of deposition. Further the UBCDFLOW simulates a travel distance that correlates well with the field data.

The Airy Creek #3017 event showed similarities to the Blueberry Creek analysis completed by Fannin et al., 2006. The cumulative flow volumes at each reach and overall travel distance was observed to be insensitive to variances in initial volume.

Investigation of fluctuations in reach width for the Airy Creek #3017 event, shows that the percent variation in cumulative flow volume varied by up ±50%. Therefore the flow
volumes generated by UBCDFLOW at Airy Creek #3017 are moderately sensitive to a change in the event width, however, the predicted travel distances are again deemed relatively insensitive.

6.0 DISCUSSION

UBCDFLOW is intended primarily to assist the user to a better understanding of the factors influencing the travel distance of debris flows (www.civil.ubc.ca/ubcdflow). The factors which influence travel distance are examined in this report by means of sensitivity analyses and through a comparison of modeled UBCDFLOW travel distances with the actual field surveyed/measured distances. This allows for comments to be made, assisting to further develop the model and better constrain the confidence with which UBCDFLOW can be used.

6.1 Climatic Limitation – UBCFLOW Model

UBCDFLOW is not able to consider the changes in weather conditions. It is commonly observed that debris flows occur after or during periods of heavy rainfall or during spring months when snow melts rapidly in a drainage basin (Lan et al., 2008). UBCDLOW is limited due to the aforementioned however as it was created from a database of debris flows occurring in B.C.. UBCDFLOW appears to prove applicable to steep forested terrains expected to experience similar weather conditions to the Queen Charlotte Islands and more generally similar to B.C.. Therefore it can be stated that the UBCDFLOW model is expected to be most accurate in predicting debris flow events in mountainous regions experiencing more temperate climate.
6.2 Interpretation of Results / Findings

Table 9 summarizes the findings of the UBCDFLOW simulations for the Shannon Creek #5004, Bigmouth #11, Airy Creek #1620, Airy Creek #1621 and Airy Creek #3017 event.

<table>
<thead>
<tr>
<th>Event</th>
<th>UBCDFLOW vs. Observed</th>
<th>Simulation 1 vs. Simulation 2</th>
<th>Initial Volume Uncertainty</th>
<th>Reach Width Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shannon Creek #5004</td>
<td>Δ Cumulative Volume</td>
<td>Overestimated</td>
<td>Simulation 2 smaller (~10% lower maximum value)</td>
<td>Insensitive</td>
</tr>
<tr>
<td></td>
<td>Travel Distance</td>
<td>Similar/overestimate. (overall good agreement)</td>
<td>Relatively unchanged</td>
<td>Insensitive</td>
</tr>
<tr>
<td>Bigmouth #11</td>
<td>Δ Cumulative Volume</td>
<td>Overestimated</td>
<td>Simulation 2 moderately larger</td>
<td>Relatively insensitive</td>
</tr>
<tr>
<td></td>
<td>Travel Distance</td>
<td>Underestimated</td>
<td>Simulation 2 slightly larger</td>
<td>Relatively insensitive</td>
</tr>
<tr>
<td>Airy Creek #1620</td>
<td>Δ Cumulative Volume</td>
<td>Considerable overestimation</td>
<td>Simulation 2 moderately larger</td>
<td>Insensitive</td>
</tr>
<tr>
<td></td>
<td>Travel Distance</td>
<td>Overestimation (overall not good)</td>
<td>Simulation 2 slightly larger</td>
<td>Insensitive</td>
</tr>
<tr>
<td>Airy Creek #1621</td>
<td>Δ Cumulative Volume</td>
<td>Overestimated</td>
<td>Similar. Simulation 2 slightly larger</td>
<td>Relatively insensitive</td>
</tr>
<tr>
<td></td>
<td>Travel Distance</td>
<td>Estimates appear in good agreement.</td>
<td>Negligible differences</td>
<td>Negligible differences</td>
</tr>
<tr>
<td>Airy Creek #3017</td>
<td>Δ Cumulative Volume</td>
<td>Overestimated</td>
<td>Simulation 2 smaller (primarily in deposition)</td>
<td>Insensitive</td>
</tr>
<tr>
<td></td>
<td>Travel Distance</td>
<td>Underestimated</td>
<td>Relatively unchanged</td>
<td>Insensitive</td>
</tr>
</tbody>
</table>

*Table 9: Summary of select, Kootenay-Columbia, UBCDFLOW simulations*
Generally the UBCDFLOW simulations exhibited the following observed trends:

i. The modelled mode of flow was in good agreement with the observed/recorded field data.

ii. Travel distances determined by the UBCDFLOW model were similar to those that were recorded in the forensic field surveys (approximately $< \pm 10\%$).

iii. When forensically informed UBCDFLOW simulations were compared to the path informed simulations it was observed that, due to the variances in entrainment and deposition widths, minor fluctuations in cumulative volume resulted. The difference between the curves appears to be nearly constant for the entrainment reaches and slightly more converging for the depositional reaches. This being stated, no significant variances in travel distance were observed between simulations 1 and 2.

iv. Further sensitivity analysis shows that the UBCDFLOW regression equations are observed to be relatively insensitive to variations in initial volume.

v. Sensitivity analyses assist in showing that wider event path widths typically yield larger magnitude changes in cumulative volume, for both entrainment and deposition reaches. As observed in the plots in section 5.0 entrainment appears to be slightly more sensitive to these changes in reach width.
vi. Travel distance was relatively insensitive to changes in event path width. On a couple occurrences deviations from field data moved slightly towards greater overestimation.

vii. The Airy Creek #1620 event showed the poorest modeled backanalysis flow behaviour. The predicted UBCDFLOW results for this event were too conservative in terms of estimating the travel distance. The main reason that this larger deviation of the UBCDFLOW calculated volumes from the surveyed volumes exist can likely be attributed to the fact that UBCDFLOW only reports entrainment or deposition while the field survey indicated a bifurcation of flow (dual flow in this case).

6.4 Online UBCDFLOW Model

The online UBCDFLOW model is a useful and powerful tool however, as is the same with all geotechnical modeling, the output values are only as good as the inputs. The input parameters must be understood to properly confirm that that model is responding appropriately to the recorded or observed parameters.

As accurately described by Eberhardt (2003), when properly completed, modeling can significantly assist in the design process by providing key insight into potential stability problems and failure mechanisms. Yet it must also be emphasized that modeling is a tool and not a substitute for critical thinking and judgment. As such, numerical modeling is most effective when applied by an experienced and cautious user.
7.0 Conclusion

Hazard assessments require that an understanding of landslide behaviors be developed. As a component of many hazard assessments, simulations/predictions of runout distance are completed. Through coupling engineering principles with a quantitative evaluation of field observations, a further understanding of the parameters governing observed strength loss mechanism can be developed. Only then through an understanding of the governing strength loss mechanism can models be developed.

The UBCDFLOW regression equations have been examined to further assist in constraining the confidence with which the model can be used. It has been found that little differences in cumulative volume and travel distance are observed when back-analyses are completed based on forensically informed (reach width of dominant flow behavior utilized) versus size informed data (the dominant flow behaviors are not known or utilized). Sensitivity analysis shows that the cumulative volumes and travel distances are relatively insensitive to changes to initial volumes. Further, cumulative volume was observed to be moderately sensitive to deviations in the event width, while travel distance was found somewhat sensitive to the width of the event path, but not significantly.

Generally, UBCDFLOW appears to offers a practical means of predicting the behavior/mode of flow while providing a better understanding of the factors influencing the travel distance of debris flows.
As displayed in the illustrative applications, as well as in the completed simulations, UBCDFLOW appears to be a reasonable tool to assist with back-analysis and simulation. This appears to be especially true for events may reoccur in a given event path (in areas of likely reoccurring landslide activity). The primarily limitation of the UBCDFLOW model was observed in events experiencing bifurcation of flow. In conclusion UBCDFLOW shows potential as a decision-support tool and appears to trend towards overestimation of cumulative volume and travel distance.
8.0 RECOMMENDATIONS FOR FURTHER WORK

As outlined in Section 3.3 ‘UBCDFLOW Website’, the online UBCDFLOW application has a few traits which warrant comment. Updates to the UBCDFLOW website which would contribute to better informing a use would allow for a more enhanced understanding. This could be simply be addressed by including a section on the UBCDFLOW website which outlines user considerations. Alternatively to possibility of further development of the way the website handles regression equation inputs, outputs and visuals, could be examined.

The largest source of error in the completed UBCDFLOW simulations appears to be connected to branching or splitting of debris flow reaches. Further investigation into ways of incorporating bifurcation of flow into the UBCDFLOW model could allow for more representative simulation results. Determining how to deal with this splitting of reach flow appears difficult. A possible solution, which could be further researched, would be to create a ratio by assume fluid like behaviours and approximating the channel and flow as broad-crested weirs subject to the same flow elevation/depth. This ratio might then be utilized to guide the division of the cumulative flow volume. Once the flow in a reach had been divided, individual simulations could be run and summed.
ACKNOWLEDGMENTS

My advisor, Jonathan Fannin, recommended this topic for my thesis, which in the end was tremendously fulfilling and interesting to work on. I am also grateful for our meeting and all the valuable feedback he has provided me. His reviews and recommendations have greatly contributed to this thesis. I would like to thank Peter Jordan who, through Dr. Fannin, provided me with the field data from previous field work. Finally, I would like to acknowledge my friends and family that supported and encouraged me over the course of composing this thesis and throughout my undergraduate degree.
REFERENCES


Debris flows are a type of landslide activity that commonly occur on steep mountainous terrain. UBCDFLOW is a model that may be used to evaluate the likely travel distance of a debris flow. Travel distance is an important component of any landslide risk analysis.

UBCDFLOW is intended primarily to assist the user better understand factors influencing the travel distance of debris flows. Accordingly, it is a decision-support tool, intended to supplement judgement and experience. For an assumed initial failure volume, changes in event magnitude arising from volumetric entrainment and deposition along the downslope path of movement are used to establish total travel distance. Equations on which the model is based are reported, together with a glossary of terms, and a list of published references on development and application of the model.

The UBCDFLOW user guide describes how to run a simulation, and includes a tutorial exercise for illustrative purposes. The UBCDFLOW model is launched from this site.

UBDFLOW was developed using field survey data from debris flow activity on the Queen Charlotte Islands, British Columbia, using an empirical-statistical approach. Accordingly, it should only be used where the terrain is similar and where its suitability can be demonstrated through experience.

For more information please contact Jonathan Fannin, Ph.D., P.Eng. Professor, Geotechnical Engineering Research Group.
Landslides comprising soil, rock and organic material are termed debris slides or debris flows, with a distinction made largely to recognize the form of movement along the event path. Where initial movement occurs as a slide, it often progresses quickly to a flow. Debris flows are a common natural hazard in mountainous terrain.

The path of a debris flow comprises an initiation zone, a transportation zone and a zone of terminal deposition. The initiation zone, where the onset of failure occurs, is typically found within a gully channel or on an open hillslope. In the case of a gully, it may occur at the headwall, on a steep side slope, or within the steep bed of the gully channel. In the case of an open hillslope, it may take the form of shallow sliding on a translational plane of slip, else it may initiate at a discrete point of quasi-liquefied flow. Often, the initial failure volume is small in comparison to the peak magnitude of the resulting event. Travel distance commences at the point of origin of the event. Downslope movement occurs through a transportation zone. Events that initiate in a gully typically remain within it. Events that initiate on an open slope may remain on the slope, or may enter a gully as a consequence of topographic constraints. Three modes of flow are considered in UBCDFLOW: unconfined flow (UF) on an open slope; confined flow (CF) in a gully channel; and transition flow (TF) deemed to occur immediately upon exiting a gully channel onto an open slope. Movement is rapid and may, on occasion, involve more than one surge of debris. It is accompanied by processes of erosion, entrainment, transport and deposition, resulting in a cumulative flow volume that tends to increase with distance travelled.

Typically entrainment dominates on steeper slopes and deposition on gentler slopes. The zone of terminal deposition is distinguished by the onset of major deposition, typically in response to encountering a relatively gentle slope angle, experiencing a loss of confinement, or a combination of both influences. The cumulative flow volume diminishes with continued runout distance, as debris is deposited and the event comes to a halt. Total travel distance is measured from the point of origin to the end of this terminal deposit, where the event volume diminishes to zero.
Debris flow activity is a natural hazard, with potential to cause loss of life, to inflict property damage, and to impact the environment. A landslide risk analysis requires the hazard be identified, and the nature of these consequences be established with respect to injury or loss. The probability of occurrence is the hazard. Consequence is governed by the potential for the debris flow event to reach a location of interest, and the likelihood it impacts an element of interest at that time. Travel distance of a debris flow is therefore important to any risk analysis because, given an event that may occur, it describes the potential to reach a location along the expected path of movement.

For more information please contact Jonathan Fannin, Ph.D., P.Eng. Professor, Geotechnical Engineering Research Group.
Regression Equations

The volume-based approach of the model involves the following controls. Initiation occurs for a user-defined initial failure volume in the first reach of the event. Thereafter, the morphology of each subsequent reach determines the flow behaviour (UF, CF or TF), and slope angle of the reach determines the mode of flow (entrainment +dV, or deposition -dV). The volume of entrainment and (or) deposition is calculated using regression equations.

Accordingly, the cumulative flow volume $\Sigma V_i$ at each reach $i$ can be determined from the reach morphology (unconfined, confined, or transition flow), and a set of measured and derived predictor variables for the reach.

The measured predictor variables are:

- Length of the reach, $L_i$
- Width of the entrainment or deposition, $W_i$
- Slope angle of the reach, $TH_i$

The derived predictor variables are:

- Incoming flow volume, $\Sigma V_{i-1}$
- Bend-angle function, $BAF_i$

The $BAF_i$ is determined by:

$$BAF_i = \cos(dTH_i) \cos(dAZ_i) \ln(\Sigma V_{i-1})$$

where,

$$dTH_i = |TH_i - TH_{i-1}|$$

$$dAZ_i = |AZ_i - AZ_{i-1}|$$
The change in flow volume is determined by one of five equations, depending on the slope angle and flow type. Each equation determines the change in volume for a reach $i$. This change is **negative** in the case of deposition (flow volume decreases) and **positive** in the case of entrainment (flow volume increases).

### Unconfined flow (UF)

For unconfined flow on a slope angle between 29.5° and 55°, the flow will **entrain** a volume $dV_i$, where $dV_i$ can be determined from:

$$dV_i = \frac{A_Z L_i}{f}$$
For unconfined flow on a slope angle between 18.5° and 29.5°, the flow will **entrain** a volume $dV_i$, where $dV_i$ can be determined from:

$$\ln(dV_i) = 0.728 + 1.31\ln(W_i) + 0.742\ln(L_i) - 0.0464(TH_i)$$

For unconfined flow on a slope angle less than 18.5°, the flow will **deposit** a volume $dV_i$, where $dV_i$ can be determined from:

$$\ln(dV_i) = 1.13\ln(W_i) + 0.787\ln(L_i) - 0.0636\ln(\sum V_{i-1})$$

For unconfined flow on a slope angle between 10.5° and 55°, the flow will **entrain** a volume $dV_i$, where $dV_i$ can be determined from:

$$\ln(dV_i) = 0.344 + 0.851\ln(W_i) + 0.898\ln(L_i) - 0.0162(TH_i)$$

For unconfined flow on a slope angle less than 10.5°, there is no change in flow volume (neither deposition nor entrainment).

**Transition flow (TF)**

For transition flow on a slope angle greater than 20.5°, there is no change in flow volume (neither deposition nor entrainment).

For transition flow on a slope angle less than 20.5°, the flow will **deposit** a volume $dV_i$, where $dV_i$ can be determined from:

$$\ln(dV_i) = 1.54\ln(W_i) + 0.901\ln(L_i) - 0.123(BAF_i)$$

For more information please contact [Jonathan Fannin](mailto:jfannin@bcc.mcgill.ca), Ph.D., P.Eng, Professor, Geotechnical Engineering Research Group.

The Blueberry Creek flow began with an unconfined flow on an open slope, and then became a confined flow once it entered the forested area.
**Glossary**

**bend-angle function (BAF)**: A function of change in slope angle ($dTH_i$), change in path azimuth ($dAZ_i$), and incoming flow volume ($V_{i-1}$) for a given reach $i$ defined by:

$$BAF_i = \cos(dTH_i) \cos(dAZ_i) \ln(\Sigma V_{i-1})$$

**confined flow (CF)**: Flow within a gully channel (width of the flow is constrained by hillslope topography).

**cumulative flow volume**: Total volume of the event at a given reach along the debris flow path.

**debris fan**: Deposition zone of a debris flow which occurs as a result of a reduction in the slope angle, and a transition from confined to unconfined flow behaviour.

**debris yield rate ($m^3/m$)**: Volume of material deposited in the terminal deposition area ($m^3$) per unit distance (m) from point of origin to onset of terminal deposition.

**deposition**: Loss of material leading to a decrease in cumulative flow volume.

**entrainment**: Accumulation of material by a process of erosion, leading to an increase in cumulative flow volume.
A debris flow showing entrainment followed by deposition in a debris fan.

**initial [failure] volume \( (m^3) \)**: User-defined volume at the onset of failure.

**length \( (L (m)) \)**: Slope length of a reach.

**mode of flow**: Unconfined flow, confined flow, or transition flow.

**path azimuth \( (AZ (\degree)) \)**: Angle (in degrees) of the lengthwise axis of a reach (measured facing down the slope, in degrees clockwise from north).

Point of origin of Blueberry Creek.

**point of origin**: Location of the onset of failure.

**point of terminal deposition**: Location of the front of the debris flow, where it comes to a halt.

**reach**: portion of an event path having a distinctive morphology, length, width, and orientation.

**slope angle \( (TH (\degree)) \)**: Angle (in degrees) of the slope of a reach (measured up from the
transition flow (TF) : Flow on the first open-slope reach after a confined reach (typically occurs on the apex of a fan, but may also occur where a confined event crosses a road.

travel distance : Slope distance along the travel path, from point of origin to point of terminal deposition.

unconfined flow (UF) : Flow on an open-slope reach, including the headwall, sidewall, or fan of a gully or a road.

width (W (m)) : Width of a reach, established with reference to the occurrence of entrainment or deposition along the path of the event.

Reach 17 of Blueberry Creek, a reach of confined flow.

For more information please contact Jonathan Fannin, Ph.D., P.Eng. Professor, Geotechnical Engineering Research Group.
References


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User Guide & Tutorial

This guide takes you through each step to run a debris flow simulation with UBCDFLOW. For this example, we will use data for the Blueberry Creek debris flow. Download Blueberry Creek data.

1) Launching UBCDFLOW
2) Setting initialization values
3) Setting reach values
4) Changing the number of reaches
5) Schematic views
6) Calculating results
7) Errors and warnings
8) Saving results

1) Launching UBCDFLOW

UBCDFLOW can be launched in two ways, either using default data values, or using supplied values from a data file. In either case, you can change any of the values from within UBCDFLOW, and repeat the simulation.

(Note: the default values are as follows: Number of reaches : 5, Initial volume : 1.0 m³, Uncertainties (initial volume and widths) : 0%, Lengths/widths : 1.0 m³, Slopes/azimuths : 1.0°, Flow type : Unconfined)

To launch UBCDFLOW using your own data, supply a .csv file with the following format:

reach_number,length,width,slope_angle,path_azimuth,flow_type

where length and width are in metres, slope_angle and path_azimuth are in degrees, and flow_type is either u, c, or t for unconfined, confined, and transition flows accordingly. Your file should not include column headings, and there should be no spaces between values (just commas), eg.:

1,35,6,25.6,46,u
2,46,3,24.2,40,u
3,21,4,26.6,55,u
4,104,3,26.6,36,c

To run UBCDFLOW with the default values, click "Launch UBCDFLOW!"; to run UBCDFLOW with your data, browse for the file then click "Launch UBCDFLOW!". The main UBCDFLOW window will then load.
2) Setting initialization values

The top of the UBCDFLOW tool contains three input parameters, the initial volume, the uncertainty in initial volume, and the uncertainty in width.

The initial volume is the failure volume at the start of the debris flow. The uncertainty in initial volume and uncertainty in width are percent uncertainties that you can use to calculate three sets of results. (See Calculating Results for more details on using uncertainties.

Blueberry Creek had an initial failure volume of 129.6 m$^3$. Let's set the uncertainties to 50% to see what effect they have on our calculations.
3) Setting reach values

Each reach has 5 values which can be independently controlled. These are the **length** and **width** of the reach in metres, the **slope angle (TH)** in degrees, the **path azimuth (AZ)** in degrees clockwise from north, and the **flow type** (either **unconfined**, **confined**, or **transition**). These parameters determine which regression equation is used to calculate the change in volume (either positive in the case of entrainment or negative in the case of deposition) for this reach.

**Note**: All values must be positive. The slope angle must be between 0 and 55 degrees, and the path azimuth angle must be between 0 and 360 degrees. If the chosen parameters of slope and flow type will result in no change in volume, a warning will display. The calculation can still be done in this case, but no change in volume will be calculated for this reach.

In this example, we have loaded in values from a file, so we do not have to change any values. If we wish to see what effect a change in these parameters would make, we can edit them and run the calculations again.

4) Changing the number of reaches

The number of reaches can be increased or decreased. Reaches are added or removed from the **end** of the flow (i.e. if you have 7 reaches, and you click "Remove a reach", the 7th reach is removed). Any reaches added to the flow are added with the default values (see Launching UBCDFLOW for default values).
When loading values from a file, the number of reaches will be set to the number of rows of values in the .csv file. If you wish to run the calculation with fewer or greater reaches than your file provided, you can change this with the add/remove buttons once you are running UBCDFLOW.

5) Schematic views

You may view your reach parameters in graphical form by clicking "Visualisation of input data".

The top graphic shows a top-down Schematic plan view of the reach morphology, allowing you to view your input reach lengths, widths and path azimuths.

The bottom panel shows a Schematic cross-section view of the slope angles (TH) of your reach inputs.

Also included in this display are the Total reach distance (the sum of the lengths of all reaches), the Horizontal projected distance ("map" distance), and the Vertical drop. Note that these calculations use all the reaches defined by the input data, although the final calculation may indicate that the flow volume would drop below zero (thus ending the debris flow) earlier that the last input reach.

6) Calculating results

Three options are provided for calculating results. Calculating with no uncertainty simply calculates one set of results using your input data as defined in the main applet window.

Results are calculated from the user-defined input values using the regression equations. From these results we can see that the flow volume does not fall to 0 within the specified number of reaches. We can also determine that the maximum flow volume during these reaches was 2459 m$^3$.

Calculating with initial volume uncertainty first applies the uncertainty positively and negatively to the initial volume, then runs the calculation for all three initial volumes (regular, positive, and negative). For example, with a 50% uncertainty in initial volume on the Blueberry Creek flow, we calculated the results using:

1) 129.6 m$^3$
2) $129.6 - 0.5 \times 129.6 = 64.8$ m$^3$
3) $129.6 + 0.5 \times 129.6 = 194.4$ m$^3$

Again, we can see that the flow volume does not reach 0, for any of these three sets of results.

Next, we calculate three sets of results using the uncertainty in width. When using width uncertainty, the results are first calculated with the user-defined reach widths, then with widths modified both positively and negatively by the user-defined width uncertainty. For example, given a flow with 4 reaches with a width uncertainty of 50% and reach widths 6.0 m, 3.0 m, 4.0 m, 3.0 m

One set of results would be calculated using those widths, one set would be calculated using the widths:

3.0 m, 1.5 m, 2.0 m, 1.5 m

and one set of results would be calculated using the widths:

9.0 m, 4.5 m, 6.0 m, 4.5 m
Calculating results for Blueberry Creek with a 50% uncertainty in the reach widths gives a wider range in flow distances. Although the unmodified and negatively modified reach widths still result in a travel distance which is greater than the user-defined number of reaches, the positively modified reach widths cause the flow to end in the 24th reach. Further "tweaking" of this final reach's length could determine the precise travel distance.

7) Errors and warnings

If any of your input values (either file input data or manually entered values) are faulty, i.e. you input a non-numeric value, or a negative value, or an angle that exceeds the maximum for slope (55°) or azimuth (360°), you will see an error message. All input errors must be resolved before you can calculate your results.

Some valid reach input values will result in a zero change in flow volume for that reach. In this case, you will see a warning letting you know which reaches have a zero change in flow volume.

You can run calculations with reaches that cause zero change in flow volume.

8) Saving results

If you wish, you can save the results that you generated into a .csv file, which you can later view in Microsoft Excel, OpenOffice, or another spreadsheet program. As in your calculation, select the uncertainty type and then click Save Results. You will be presented with a set of data formatted for use in a .csv file.

Copy the data and paste it into a text file and save the file with the file extension .csv. You can then view your results in Excel.

For more information please contact Jonathan Fannin, Ph.D., P.Eng. Professor, Geotechnical Engineering Research Group.
Running the UBCDFLOW application

The UBCDFLOW application can be run either with input data in .csv format, or with default values.

**Using default values:**

To run UBCDFLOW using the default values, simply click "Launch UBCDFLOW!".

**Loading data from a file:**

You may supply a .csv (comma-separated value) file in the following format:

reach_number,length,width,slope_angle,azimuth,flow_type

where length and width are in metres, slope_angle and azimuth are in degrees, and flow_type is either u, c, or t for unconfined, confined, and transition flows accordingly. Your file should not include column headings, and there should be no spaces between values (just commas), eg.:

```
1,35,6,25.6,46,u
2,46,3,24.2,40,u
3,21,4,26.6,55,u
4,104,3,26.6,36,c
```

Please see the sample data file for format.

Upload data from a .csv file (optional): [Browse...]

Launch UBCDFLOW!  Download sample .csv file: [Blueberry Creek Data]

For more information please contact Jonathan Fannin, Ph.D., P.Eng, Professor, Geotechnical Engineering Research Group.
The UBCDFLOW model was originally developed with financial support from the B.C. Science Council and with supplemental funding from Golder Associates and the B.C. Ministry of Forests, Vancouver Forest Region. The UBCDFLOW website was developed with additional support from the B.C. Ministry of Forests and Range, Northern Interior Forest Region.

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APPENDIX B

Rickenmann (1999) - Derivation of Scaling Equations
Appendix: Derivation of Scaling Equations

For the derivation of the scaling equations it is assumed that Froude similarity must be satisfied for the flow process of debris flows. Froude similarity is considered a necessary requirement since debris flows are a gravitational process with a fluid-like flow behavior and having a free surface. The index \( s \) is used here to denote the ratio of two variables of the same kind but of different magnitude, e.g., \( \lambda_s = \lambda_1/\lambda_2 \), where the indices 1 and 2 refer for example to prototype and laboratory flows and \( \lambda \) is a characteristic length scale. For Froude scaling (e.g., Henderson 1966) we have to satisfy the relationships:

\[
Q_s = Q_{p2}/Q_{p1} \sim \lambda_s^{5/2}, \quad (A1)
\]

\[
M_s = M_2/M_1 \sim \lambda_s^3, \quad (A2)
\]

Combining (A1) and (A2) we obtain a theoretical relationship between peak discharge \( Q_p \) and debris-flow volume \( M \) for debris flows of different size:

\[
Q_s \sim (M_s^{1/3})^{5/2} \sim M_s^{5/6} \quad (A3a)
\]

or

\[
Q_s = A_1 M_s^{5/6}, \quad (A3b)
\]

where \( A_1 \) is an empirical constant.

Considering similar relationships between other parameters, we can base the analysis on the respective Froude scaling relationships for the dimensions of time \([s]\), length \([m]\), and mass \([kg]\) involved in the parameters of interest. For these dimensions we have to satisfy the relationships:

\[
[s] \sim \lambda_s^{1/2}, \quad (A4)
\]

\[
[m] \sim \lambda_s^1, \quad (A5)
\]

\[
[kg] \sim \rho_s \lambda_s^3 = \lambda_s^3, \quad (A6)
\]

where \( \rho \) is the density of the fluid or solids, and \( \rho_s = 1 \) is assumed.

Considering Newtonian laminar flow, and postulating that Reynolds’s similarity should be satisfied beside Froude similarity, we find for the scaling of the dynamic viscosity:

\[
\mu_s \sim [kg/s m] \sim \lambda_s^3/(\lambda_s^{1/2} \lambda_s^1) = \lambda_s^{3/2}. \quad (A7)
\]

Combining (A7) and (A1) we can write

\[
\mu_s \sim (Q_s^{2/5})^{3/2} = Q_s^{3/5} \quad (A8a)
\]

or

\[
\mu_s = A_2 Q_s^{3/5}, \quad (A8b)
\]
where $A_2$ is an empirical constant.

Considering dilatant inertial flow, and postulating that Froude similarity should be satisfied beside keeping the Bagnold’s number (e.g., Takahashi 1991) constant, we can find for the scaling of the parameter $\xi$

$$\xi_s \sim 1/[s \, m^{1/2}] \sim 1/(\lambda_s^{1/2} \lambda_s^{1/2}) = \lambda_s^{-1}. \quad \text{(A9)}$$

Combining (A9) and (A1) we can write

$$\xi_s \sim 1/(Q_s^{2/5}) \sim Q_s^{-2/5} \quad \text{(A10a)}$$

or

$$\xi_s = A_3 Q_s^{-2/5}. \quad \text{(A10b)}$$

where $A_3$ is an empirical constant.

For Manning’s $n$ we have

$$n_s \sim \sqrt{s} / [m^{1/3}] \sim \lambda_s^{1/2} / \lambda_s^{1/3} = \lambda_s^{1/6}. \quad \text{(A11)}$$

Combining (A11) and (A1) we can write

$$n_s \sim (Q_s^{2/5})^{1/6} \sim Q_s^{1/15} \quad \text{(A12a)}$$

or

$$n_s = A_4 Q_s^{1/15}, \quad \text{(A12b)}$$

where $A_4$ is an empirical constant.

For Chezy $C$ we have

$$C_s \sim [m^{1/2}] / [s] \sim \lambda_s^{1/2} / \lambda_s^{1/2} = 1 \quad \text{(A13a)}$$

or

$$C_s = \text{const.} \quad \text{(A13b)}$$

From (A13) we conclude that the flow resistance parameter $C_s$ should show no dependence on $Q_s$ for debris flows having the same material properties.

Considering the mean velocity Equation (14), and postulating that Froude similarity should be satisfied, we can find for the scaling of the flow resistance parameter $C_1$:

$$C_{1s} \sim [m^{0.7} / s] \sim (\lambda_s^{0.7} / \lambda_s^{0.5}) = \lambda_s^{0.2}. \quad \text{(A14)}$$
Combining (A14) and (A1) we can write

\[ C_{1\alpha} \sim (Q_{\alpha}^{2/5})^{1/5} = Q_{\alpha}^{2/25} \]  
(A15a)

or

\[ C_{1\alpha} = A_{5} Q_{\alpha}^{2/25} \]  
(A15b)

where \( A_{5} \) is an empirical constant.

For the total travel distance \( L \) we can write

\[ L_{\alpha} \sim \lambda_{\alpha} \]  
(A16)

\[ (MH)_{\alpha} \sim \lambda_{\alpha}^{3} \lambda_{\alpha} = \lambda_{\alpha}^{4} \]  
(A17)

Combining (A16) and (A17) we obtain a theoretical relationship between travel distance \( L \) and the energy potential \( MH \) for debris flows of different size:

\[ L_{\alpha} \sim (MH)_{\alpha}^{1/4} \]  
(A18a)

or

\[ L_{\alpha} = A_{6} (MH)_{\alpha}^{1/4} \]  
(A18b)

where \( A_{6} \) is an empirical constant.

For the runout distance \( L_{f} \) on the fan we can write

\[ L_{f\alpha} \sim \lambda_{\alpha} \]  
(A19)

\[ M_{\alpha} \sim \lambda_{\alpha}^{3} \]  
(A2)

Combining (A19) and (A2) we obtain a theoretical relationship runout distance and the debris-flow volume for debris flows of different size:

\[ L_{f\alpha} \sim M_{\alpha}^{1/3} \]  
(A20a)

or

\[ L_{f\alpha} = A_{7} M_{\alpha}^{1/3} \]  
(A20b)

where \( A_{7} \) is an empirical constant.
APPENDIX C


\[ L = 1.9M^{0.16}H_e^{0.83} \]  
(Rickenmann’s Regression Eqn, original form)  
\[ \frac{L}{H_e^{0.83}} = 1.9M^{0.16} \]  
\[ \frac{L}{1.9H_e^{0.83}} = M^{0.16} \]  
\[ \ln\left(\frac{L}{1.9H_e^{0.83}}\right) = \ln M^{0.16} \]  
\[ \ln\left(\frac{0.526L}{H_e^{0.83}}\right) = \ln M^{0.16} \]  
\[ \ln\left(\frac{L}{H_e^{0.83}}\right) - 0.642 = 0.16\ln M \]  
\[ \ln(L) - 0.83\ln(H_e) - 0.642 = 0.16\ln M \]  
\[ 6.25\ln(L) - 5.188\ln(H_e) - 4.013 = \ln M \]  
\[ \ln M = 6.25\ln(L) - 5.188\ln(H_e) - 4.013 \]  
(Similar to UBCDFLOW form)