Debris-flow runout predictions based on the average channel slope (ACS)

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Abstract

Prediction of the runout distance of a debris flow is an important element in the delineation of potentially hazardous areas on alluvial fans and for the siting of mitigation structures. Existing runout estimation methods rely on input parameters that are often difficult to estimate, including volume, velocity, and frictional factors. In order to provide a simple method for preliminary estimates of debris-flow runout distances, we developed a model that provides runout predictions based on the average channel slope (ACS model) for non-volcanic debris flows that emanate from confined channels and deposit on well-defined alluvial fans. This model was developed from 20 debris-flow events in the western United States and British Columbia. Based on a runout estimation method developed for snow avalanches, this model predicts debris-flow runout as an angle of reach from a fixed point in the drainage channel to the end of the runout zone. The best fixed point was found to be the mid-point elevation of the drainage channel, measured from the apex of the alluvial fan to the top of the drainage basin. Predicted runout lengths were more consistent than those obtained from existing angle-of-reach estimation methods. Results of the model compared well with those of laboratory flume tests performed using the same range of channel slopes. The robustness of this model was tested by applying it to three debris-flow events not used in its development: predicted runout ranged from 82 to 131% of the actual runout for these three events. Prediction interval multipliers were also developed so that the user may calculate predicted runout within specified confidence limits.

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1. Introduction

Debris-flow runout estimations are important for the delineation of potentially hazardous areas on alluvial fans and for the siting of mitigation structures. Existing runout estimation methods require input parameters that can be difficult to accurately estimate. The purpose of this work was to develop a simple method for preliminary estimates of debris-flow runout distances that would be applicable for both fire-related and non-fire-related debris flows that emanate from confined channels and deposit on well-defined alluvial fans. The scope of work was to: (1) develop a model to estimate debris-flow runout distance from easily measured topographic parameters, (2) test the model using information from debris flow events independent of those used in its development, (3) provide the model user with multipliers to the model output in order to obtain a desired level of nonexceedance, (4) compare the accuracy of the model to that of existing runout estimation methods, and (5) compare the consistency of the model results to those from scaled flume experiments.

2. Background

Most runout estimation methods for debris flows and other mass movements fall into one of three categories: volume-based models, dynamic models, and models based on topographic parameters. These runout estimation methods have the limitation of requiring uncertain input parameters. This limitation is discussed in the following sections.
2.1. Volume-based models

As a first approximation, it had been proposed that debris-flow runout distance could be related to event volume and deposit geometry (Hung et al., 1984; Hung et al., 1987; VanDine, 1996; Lo, 2000). Several authors have related the angle of reach of a mass movement to its volume (Heim, 1932; Scheidegger, 1973; Corominas, 1996). A mass movement’s angle of reach is the declination of a line that connects the head of the failed mass to the distal end of the deposit (Corominas, 1996). Rickenmann (1999) developed an empirical relationship to relate a debris flow’s total horizontal travel distance \( L \) to its volume \( V \) and the elevation loss along the travel path \( H \) (Fig. 1). Ikeya (1981, 1989) developed empirical relationships to estimate debris-flow-runout length from event volume and channel slope. Schilling and Iverson (1997), Iverson et al. (1998), Griswold (2004), and Berti and Simoni (2007) developed relationships between mass-movement volumes and the inundated cross-sectional and planimetric areas. Cannon (1989) and Fannin and Wise (2001) proposed that 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.

Volume-based models allow the likelihood of different debris-flow runout lengths to be estimated through frequency–magnitude relationships. While it would be beneficial to map hazard zones as a function of event volume, difficulties can arise in the estimation of a probable range of flow volumes for a given channel. Hung et al. (1984) suggested that volume may be estimated through a unit yield rate per length of channel or per area of the drainage basin. However, generalized values for these yield rates can be quite variable. For five debris-flow events in British Columbia, the channel yield rate varied by a factor of 3 and the area yield varied by a factor of 5 (Hung et al., 1984). A commonly advocated dynamic model to calculate debris-flow runout is the leading-edge model (Takahashi, 1981, 1991; Hung et al., 1984; VanDine, 1996; Lo, 2000):

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

where:

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

In addition to uncertainty in event volume, angle of reach and channel yield rate estimations have the additional difficulty that an initiation point of the debris flow must be predicted. Not all debris flows initiate from a single failed landslide mass. In basins recently burned by wildfires, rills and gullies contribute sediment to the channel and subsequent scour and bulking of material can occur over much of the channel length (Cannon et al., 2003). This debris-flow initiation mode would make choosing a single point of initiation impossible.

2.2. Dynamic models

A commonly advocated dynamic model to calculate debris-flow runout is the leading-edge model (Takahashi, 1981, 1991; Hung et al., 1984; VanDine, 1996; Lo, 2000):

\[
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- \( x_L \): runout distance,
- \( v_0 \): debris velocity,
- \( \theta_0 \): entrance slope angle (channel slope),
- \( g \): acceleration of gravity,
- \( S_f \): friction slope, and
- \( h_0 \): debris flow depth, all in consistent units.

Other dynamic models are also presented by Cannon and Savage (1988), Kang (1997), Lo (2000), Rickenmann (2005), and Van Gassen and Cruden (1989). Dynamic models require two parameters that can be difficult to accurately estimate, namely the flow velocity and the frictional parameter. Flow velocity may be back-calculated from previous events (Johnson, 1984) or predicted using flow equations. Velocity back-calculations require an estimate of a channel’s radius of curvature. This estimate can be subjective and dependent on the method of analysis (Prochaska et al., in review), although a reasonable estimate of the radius of curvature may be obtained. Velocity predictions require the selection of an appropriate rheological model and its input parameters. Rickenmann (2005) suggested that the frictional parameter \( S_f \) could be estimated to be slightly larger than the tangent of the fan slope. However, as \( S_f \) approaches the tangent of the fan slope in Eq. (1), the denominator approaches zero and this equation becomes increasingly sensitive to \( S_f \). Sassa (1988) described the calculation of a frictional parameter through the measurement of the friction angle and pore pressure during shearing in a ring shear apparatus. This method has the disadvantages of the scarceness of ring shear devices and limitations on the maximum particle size that may be tested.

Numerical models also exist for the analysis of debris flows. These models treat the flowing debris as either a continuum (e.g. O’Brien et al., 1993; Hung, 1995; McDougall and Hung, 2003; McArdell et al., 2007) or as distinct elements (e.g. Asmar et al., 2003; González et al., 2003; Miyazawa et al., 2003). González
et al. (2003) discuss the advantages and limitations of continuum and distinct element modeling techniques. Continuum models have faster computational times and are better suited to model viscous flows and pore pressure effects, while distinct element models can better model particle segregation and active and passive pressures. Although generalized calibration factors have been obtained for numerical models (e.g. Ayotte and Hungr, 2000), these factors can be highly variable, even for different debris flows from a single channel (McArdell et al., 2007). This would present difficulties when applying these models in a predictive sense. Numerical runout simulations are also limited by the quality of the topographic data used and difficulties associated with modeling the entrainment and deposition of debris along the travel path (McArdell et al., 2007). Non-uniqueness of a solution is also a problem during the back-analysis of an event.

With the use of the correct input parameters, dynamic models have the potential to provide accurate runout lengths. They also provide additional information, such as the flow velocity along the runout path, the area of flow, and the peak discharge. However, these models also require the most sophistication during data collection and analysis in order to estimate appropriate input parameters. The cost of these detailed analyses may not be warranted for preliminary hazard assessments.

2.3. Topographic parameters

To avoid the use of uncertain and highly variable input parameters required in the classical avalanche runout equation (Voellmy, 1955), snow avalanche runout estimations have been made through a method that used easily measured topographic parameters (Lied and Bakkehøi, 1980; Bakkehøi et al., 1983; Lied and Toppe, 1989). This method predicted the angle of reach, \( \alpha \), of an avalanche as a linear function of the average slope of the travel path, \( \beta \). \( \alpha \) and \( \beta \) were both referenced from the head of the failed snow mass (Fig. 1). Bathurst et al. (1997) obtained encouraging results when this method was used to estimate the delivery of debris-flow sediment into streams.

Although this runout estimation method avoids the prediction of event volume, velocity, and frictional parameters, it still has the disadvantage discussed previously of requiring knowledge of the event initiation point, since the \( \alpha \) and \( \beta \) angles are referenced from the head of the failed mass.

3. Data sets

3.1. Field data set

Mapped debris-flow deposits described in the technical literature were used to develop, test, and analyze the runout model. A summary of the data set is shown in Table 1. The majority of the debris-flow events in the field data set were single events that emanated from confined channels and terminated in natural lobate deposits on well-defined fans. Events were excluded from the data set if they deposited within a steep channel, or if they deposited in, along, or against an obstruction such as a river, an opposing bank of a higher-order stream, or a road embankment. Excluding events that deposit within channels may bias the data set towards longer-runout debris flows, however flows that reach alluvial fans are generally more hazardous to developments than those that deposit within channels. A larger data set would have been desirable, but published values of accurately measured, unimpeded debris-flow runout were rare.

The heavy horizontal lines on Table 1 divide the field data set into four subsets based on geology, burn condition, and location. Basins where a debris-flow event occurred more than three years after a forest fire were categorized as being unburned, since most fire-related debris flows occur in the first few years following a fire before the vegetation becomes reestablished (Cannon and Gartner, 2005). Debris flows from the burned basins were run-off-generated, and material was entrained over much of the channel length. While debris flows from the unburned basins also may have entrained material along their travel paths, these events were generated from discrete landslides.

The first field data subset in Table 1 contains ten debris-flow events from burned basins underlain by sedimentary materials in Utah and Colorado. The second subset contains six debris-flow events from unburned basins underlain by sedimentary materials in California and British Columbia. The third subset contains four events from unburned basins underlain by metamorphic and plutonic materials in British Columbia, California, and Colorado. The fourth subset contains two events from burned basins underlain by metamorphic and plutonic materials from Wyoming and Montana, and one unburned basin underlain by metamorphic and plutonic materials in Idaho. The first three data subsets were used to develop the runout estimation model. The fourth subset was withheld from model development in order to provide a geographically independent test of the model.

3.2. Flume data set

Flume data collected from several sources in the technical literature were compared to the developed model. Chau et al. (2000) performed 10 tests on sand in a 3-meter-long flume that was inclined between 26 and 32°. Runout slopes were either 0 or 10°, gravimetric water contents ranged from 25.5 to 31.2%, and runout distances ranged from 18 to 170 cm.

Shieh and Tsai (1997) performed 69 tests on sand and gravel in an 8-meter-long flume that was inclined between 15 and 21°. The flume bed was roughened by gluing sand to it. Runout slopes were 2 or 5°, gravimetric water contents ranged from 35 to 88%, test volumes ranged from 3600 to 51,300 cm³, and runout distances ranged from 29 to 125 cm.

Various sources report the results of experiments conducted by the U.S. Geological Survey (USGS) in their large-scale (95-meter-long) debris-flow flume (Iverson, 1997; Major and Iverson, 1999; Iverson et al., 2000; Iverson, 2003; Iverson, 2005). This flume is inclined at 31° and can accommodate as much as 20 m³ of up to gravel-sized material. Runout occurs on a 3-degree pad;
runout lengths of the eight tests used in this study ranged from 11.9 to 31.6 m.

4. Methods

4.1. Development of the ACS model

Similar to the model shown on Fig. 1, the ACS model predicts the runout angle ($\alpha$) from the fanhead angle ($\beta$). However, rather than attempting to identify a point of initiation for each event, we selected the point from which to reference the $\alpha$ and $\beta$ angles as the point on the stream profile that is halfway (vertically) between the onset of deposition (which corresponds to the fanhead point at the apex of the alluvial fan) and the drainage divide, as shown on Fig. 2. This reference point is an objective, reproducible location that attempts to provide a center-of-mass characterization of fire-related debris flows that initiate through progressive sediment bulking along much of

![Fig. 2. Location of the point from which $\alpha$ and $\beta$ were referenced in the ACS model.](image)
their channel length. While the erosion along the path of a fire-related debris flow (not necessarily from a completely burned basin) may not be homogeneous and its initiation is difficult to predict, the basin’s midpoint elevation provides a simple approximation. This reference point may have no physical meaning in other cases, and it was lower in the basin than the initiating landslides for the unburned debris-flow events. Several different reference points were investigated before the one shown on Fig. 2 was decided upon. The use of these other points was decided against because of subjectivity in identification of their locations, sensitivity in their use, or less of a physical basis to their placement.

For each debris-flow event in the field data set, topographic maps were used to construct a profile of the basin along the length of the main channel. 1:24,000 scale topographic maps were used for debris-flow events within the United States and 1:50,000 scale topographic maps were used for events in Canada. These are the largest-scale maps that are commercially available, and we consider them sufficiently accurate for drainage-basin-scale analyses. This profile was extended down the fan beyond the farthest extent of the mapped runout and up to the drainage divide directly above the head of the basin’s main channel. The extents of the mapped deposit were also located along the profile. The β angle was identified for each basin by measuring the declination of a line that connected the reference point to the farthest extent of the mapped runout and up to the drainage divide directly above the head of the basin’s main channel. The extents of the mapped deposit were also located along the profile. The β angle was identified for each basin by measuring the declination of a line that connected the reference point to the farthest extent of runout on the profile.

The accuracy of the data used in the model development is limited by the amount of mapping detail and scale used by the authors of the original references. Runout distance can be a subjective measurement that varies between investigators based on the specific facies or thickness of deposit that is used to define the extent of runout (Jakob, 2005). Hungr et al. (1987) reported that the limit of runout is a gradational process. They advocated that the extent of runout should be defined as the farthest extent of debris surge travel, downstream of which no large-scale debris movement will occur. For studies that mapped different deposit facies (e.g. Meyer and Wells, 1997), we interpreted runout as the farthest extent of deposits mapped as being debris-flow deposits. For sources that mapped different levels of impact within the deposit (e.g. Jakob et al., 2000), runout was interpreted to be the farthest extent of the direct impact zone. For sources that did not map different facies or impact zones, runout was interpreted as the farthest extent of the mapped deposit.

Regression analyses of α versus β were performed. Dummy variables, $D_A$ and $D_B$, (Wonnacott and Wonnacott, 1990) were used to code for the first three field data subsets through binary independent variables. If regression analyses show that $D_A$ and $D_B$ are both statistically insignificant, then the regression equations to the individual data subsets share a common intercept. For the burned sedimentary subset, $D_A$ and $D_B$ were both set equal to zero. For the unburned sedimentary subset, $D_A$ was set equal to one and $D_B$ was set equal to zero. For the plutonic and metamorphic subset, $D_A$ was set equal to zero and $D_B$ was set equal to one. Best-fit linear regression equations were obtained for each of the first three field data subsets. ANOVA and t-tests were performed using MINITAB (statistical analysis software) to investigate the statistical significance of the regression equations as a whole and of the individual terms of these equations. After a statistically significant regression equation was obtained for each of the first three field data subsets, tests were performed to identify whether these regression equations were statistically similar (Crow et al., 1960). The data used to develop statistically similar regression equations were combined and a new regression equation was calculated for the unified field data sets.

4.2. Test of the ACS model

The fourth field data subset was withheld from the model development in order to be a geographically independent test of the developed model. For the debris-flow events in this subset, the runout (α) angles that were predicted from the basins’ fanhead (β) angles (using Eq. (3)) were used to calculate predicted runout lengths from the basin profiles. These predicted runout lengths were compared to the actual mapped deposit extents and were reported as percentages of the actual runout.

4.3. Flume tests

For the flume data collected from the literature, actual runout (α) angles and fanhead (β) angles were calculated trigonometrically based on the reported runout length, runout slope, flume slope, and flume length for each test. To remain consistent with the methodology of the field data set, α and β angles were referenced from half-way up the length of the flume. However, flume tests differ from field events, in that debris is released from the head of the flume and no entrainment of material occurs along the flow path. In most cases, the β angle was equal to the flume slope since the flume was linear. The curved profile
of the USGS flume was modeled as being three linear segments: a 75-meter section inclined at 31°, a 7-meter section inclined at 17°, and a runout section inclined at 3°. The 17-degree inclined section was chosen as the intermediate angle between the other two sections in order to represent the curved bottom of the flume (Iverson et al., 1992). The \( \beta \) angle was referenced to the junction of the 17-degree section and the 3-degree runout pad. For tests where an additional length of confinement had been added along the runout section, the \( \beta \) angle was referenced to the farthest extent of the confinement.

### 5. Results

#### 5.1. Development of the ACS model

Table 1 shows the measured fanhead (\( \beta \)) and runout (\( \alpha \)) angles for each debris-flow event in the field data set. Using the dummy variables, the best-fit regression equation to the first three field data subsets was (with \( \alpha \) and \( \beta \) expressed in degrees):

\[
\alpha = 0.80 + 0.84\beta + 0.06D_A - 0.42D_B \\
R^2 = 0.97
\]  

(2)

Fig. 4 shows the best-fit regression lines and equations corresponding to the first three field data subsets. Table 2 summarizes the results of the ANOVA and \( t \)-tests to test for the significance of the regression equations shown on Fig. 4. The low \( P \)-values in Table 2 indicate that each best-fit regression equation is statistically significant, and that the slopes of each of these equations are also statistically significant. However, the high \( P \)-values on \( D_A, D_B \), and the intercept indicate that there is not a statistically significant difference between the intercepts of the three field data subsets, and also that the intercepts of the best-fit regression lines are not statistically significant. Therefore, the regression equations for the first three field data subsets were recalculated while forcing the intercepts to zero, and \( t \)-tests showed no significant differences (at a significance level of 0.005) between the slopes of the three regression lines. As a result, the three field data subsets were then combined into a single regression equation with an intercept of zero, which is plotted on Fig. 5:

\[
\alpha = 0.88\beta \\
R^2 = 0.96
\]  

(3)

The standard error of the slope of Eq (3) is 0.01, and \( \alpha \) and \( \beta \) are again expressed in degrees.

Forcing the intercept through zero makes physical sense as well, so that \( \alpha \) does not exceed \( \beta \) for basins with small \( \beta \) angles. Fig. 5 also shows bounding lines \( \alpha = \beta \) and \( \alpha = 0.80\beta \). The line \( \alpha = \beta \) is a physical upper-bound to the data representing no runout, because by definition the runout angle \( \alpha \) must be less than the fanhead angle \( \beta \) (Fig. 2). The line \( \alpha = 0.80\beta \) has no physical or statistical basis, but is a convenient lower-bound encompassing the data set. By representing a lower-bound to the declination data, the equation \( \alpha = 0.80\beta \) actually represents an upper bound to the corresponding runout distances.

#### 5.2. Test of the ACS model

The three data points withheld from model development to permit an independent test are shown on Fig. 5. The runouts predicted by Eq (3) ranged from 82 to 131% of the actual runouts for these three events, as summarized in Table 3.

#### 5.3. Confidence in prediction

The ACS model regression equation shown as Eq. (3) was bounded by two sets of limits: prediction limits and confidence
limits. For the regression equation to be used as a predictive tool, the prediction limits are of interest because prediction limits define the expected range of the response (z) for a new observation (β) at a given confidence level. For confidence levels of 65 to 95% in 5-percent increments, MINITAB was used to identify the responses (α values) at the prediction limits for the actual β values of the field data set. These α values were drawn through the reference points of the appropriate basin profiles and the runout lengths predicted by the prediction-limit regression equation was plotted versus the confidence level for each basin; this graph was then summarized by producing box and whisker plots at each confidence level.

Fig. 6 shows multipliers that can be applied to predicted runout lengths of the field data set to achieve desired confidence levels. The graph is used by selecting a desired confidence level, runout obtained from the prediction-limit α value as a percentage of the runout obtained from the regression equation was plotted versus the confidence level for each basin; this graph was then summarized by producing box and whisker plots at each confidence level.

5.4. Comparison to existing runout models

Predicted runout lengths for six events within the field data set were compared to runout lengths that would be predicted by other runout estimation methods. The two estimation methods used for comparison were those presented by Corominas (1996) and Rickenmann (1999, 2005) that relate a debris flow’s angle of reach to its volume:

\[
\log (H/L) = -0.105 \log V - 0.012
\]  
(Corominas, 1996)

\[
L = 1.9 V^{0.16} H^{0.83}
\]  
(Rickenmann 1999, 2005)

where:

- \(H\) elevation loss along the travel path (Fig. 1) (m),
- \(L\) total horizontal travel distance (Fig. 1) (m), and
- \(V\) event volume (m³).

The six debris-flow events chosen for comparison had initiating landslides from which to reference \(H\) and \(L\) whose locations were accurately described in their respective reference: Gulley #1, Gulley #2, Hummingbird Creek, Mayflower Gulch, Pilot Ridge, and Jughead. Event volumes and mobility characteristics for these six debris flows are presented in Table 4.

For each of the debris flows listed in Table 4, the event volume was used to calculate a predicted angle of reach using both Eqs. (4) and (5). Lines with declinations equal to these angles were drawn through the location of the initiating landslide on the basin profile for each event; debris-flow travel was predicted to cease where these angle-of-reach lines intersected the basin profile. Table 5 summarizes the mobilities for these six events that were predicted using Eqs. (4) and (5). For three of these events, the predicted angle of reach was steeper than, and thus fell below, the basin profile. For comparison, the runout lengths predicted by Eq. (3) would need to be multiplied by 1.5.

5.5. Volume effects on debris mobility

Previous research has shown that debris-flow mobility and inundation areas increase with an increase in event volume (Heim, 1932; Corominas, 1996; Schilling and Iverson, 1997; Iverson et al., 1998; Griswold, 2004; Rickenmann, 1999, 2005). Thus, the possibility of including event volume to improve the predictive capabilities of Eq. (3) was explored. Using the data

---

**Table 3**

Results of the test of the ACS model

<table>
<thead>
<tr>
<th>Basin</th>
<th>β (deg)</th>
<th>Actual runout (m)</th>
<th>Predicted runout (m)</th>
<th>Predicted/actual runout (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twelve</td>
<td>10.7</td>
<td>9.4</td>
<td>475</td>
<td>480</td>
</tr>
<tr>
<td>Slough R.S.</td>
<td>17.2</td>
<td>15.8</td>
<td>400</td>
<td>525</td>
</tr>
<tr>
<td>Jughead</td>
<td>14.1</td>
<td>11.7</td>
<td>180</td>
<td>148</td>
</tr>
</tbody>
</table>

**Table 4**

Volumes and mobility characteristics for the debris-flow events used in the comparative analysis

<table>
<thead>
<tr>
<th>Basin name</th>
<th>Volume (m³)</th>
<th>Actual H (m)</th>
<th>Actual L (m)</th>
<th>Actual runout (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulley #1</td>
<td>22,000</td>
<td>650</td>
<td>1560</td>
<td>368</td>
</tr>
<tr>
<td>Gulley #2</td>
<td>4500</td>
<td>660</td>
<td>1420</td>
<td>305</td>
</tr>
<tr>
<td>Hummingbird Creek</td>
<td>92,000</td>
<td>1370</td>
<td>5540</td>
<td>420</td>
</tr>
<tr>
<td>Mayflower Gulch</td>
<td>17,000</td>
<td>370</td>
<td>800</td>
<td>181</td>
</tr>
<tr>
<td>Pilot Ridge</td>
<td>460</td>
<td>240</td>
<td>770</td>
<td>142</td>
</tr>
<tr>
<td>Jughead</td>
<td>14,600</td>
<td>230</td>
<td>1130</td>
<td>180</td>
</tr>
</tbody>
</table>

* Horizontal distance from the fanhead point to the distal end of the deposit.
from the field data set (Table 1), regressions of different mobility characteristics versus volume were investigated. For debris-flow events where a range of volumes had been reported, the average value was used. Power law regressions were examined, based on trends observed by others (Corominas, 1996; Rickenmann, 1999, 2005). Regression results are summarized in Table 6.

5.6. Flume tests

Fig. 7 shows how the flume test results compare to the field data set results on a plot of $\alpha$ versus $\beta$. Also shown on Fig. 7 are the linear relationships previously shown on Fig. 5. Details of this comparison are provided in the discussion section below.

6. Discussion of results

6.1. Development of the ACS model

The fact that no statistical difference was found between the regressions to the burned sedimentary field data subset and the unburned sedimentary field data subset indicates that both fire-related and non-fire-related debris flows within the field data set had similar mobility characteristics. It tentatively appears that a distinct runout length can be identified for debris flows, regardless of whether those flows are initiated by progressive sediment bulking or by a single failed landslide mass. In addition, since no statistical difference was observed between sedimentary basins and metamorphic and plutonic basins, this tentatively indicates that debris flows within the field data set had similar mobility characteristics regardless of geology. Unfortunately, the analyzed field data set did not include any recently burned metamorphic and plutonic basins; however, we would anticipate runout behavior similar to the unburned basins. The ACS model provides an average runout length based on the ranges of material properties represented within the field data set. Data scatter around the predictive model (Fig. 5) is likely due to different material properties and event volumes between the individual events.

For the field data set, Eq. (3) approximately quantifies the relationship between landscape degradation and construction through the process of debris-flow deposition. The wedge-shaped region on Fig. 5 bounded by the lines $\alpha = \beta$ and $\alpha = 0.80\beta$ shows that runout ($\alpha$) angles within the field data set become more variable as basins become steeper. This does not necessarily mean that actual runout lengths vary more widely, though, because a variation in $\alpha$ for steep basins produces less of a change in the runout length than the same variation in $\alpha$ for shallow basins (Fig. 8). For example, the runout lengths for the two debris-flow events on Fig. 5 near $\beta = 7^\circ$ differ by over 2500 m, while the runout lengths for the three events shown on Fig. 5 at $\beta = 23$ only vary by less than 600 m. These runout differences between individual basins are not the predictive error of the ACS model, as the conversion of an $\alpha$ angle to a runout distance will also depend on the site-specific topography.

6.2. ACS model applicability and limitations

The ACS model was developed from modest-sized debris flows (Size Class 3 and 4, (Jakob, 2005)) that emanated from confined channels with simple geometries and deposited on well-defined alluvial fans, and thus it would be applicable to only...
events matching these criteria. The model would not be applicable to more complex situations such as canyons that have been glacially oversteepened or where a fanhead location can not be clearly identified. Depending on fan morphology, the fanhead point may not be easily identifiable and large errors may result. In cases such as these, application of the ACS model would be much more subjective and could result in anomalous results. The ACS model provides an average runout length based on the ranges of material properties represented within the field data set. However, only a modest data set was available for development of the ACS model. If this model is applied to a more diverse population of debris-flow events, certain other geographic, geologic, or material property exclusions may appear.

The ACS model does not account for debris-flow volume, and thus does not consider the frequency–magnitude relationship of debris flows. It has been shown that debris-flow travel lengths and inundation areas increase with event volume (Heim, 1932; Corominas, 1996; Schilling and Iverson, 1997; Iverson et al., 1998; Griswold, 2004), and for a given topography a large debris-flow event would be expected to runout farther than a small event. Therefore, the ACS model may significantly underestimate the runout length for events larger than those used in its development.

The ACS model also does not account for 3-D topography. The model was developed based only on the maximum runout length for each event. For alluvial fans where lateral debris spreading or channel avulsions would be suspected, a conservative estimate of the hazard zone could be delineated by swinging an arc across the fan with a radius equal to the predicted runout length and its center located at the fanhead point. This hazard zone would be applicable for large events where fan inundation is expected. For smaller events where local topography and confinement will control runout, a more sophisticated model that accounts for 3-D topography may provide more accurate runout estimations.

The ACS model was based on a limited data set that does not contain the variability inherent to debris-flow processes. Thus, scatter could be greater than that shown within the available data. However, the data are also constrained physically by an upper-bound line of $\alpha = \beta$ and a lower-bound of $(\beta, \alpha) = (0, 0)$ since the angle $\alpha$ must be smaller than the angle $\beta$ and can not be negative. The geometry of the ACS model makes it sensitive to small changes between $\alpha$ and $\beta$, especially for low-gradient channels, which may result in the variability of predicted runout lengths. Uncertainty in $\beta$ (and thus in the calculated $\alpha$) will depend on the certainty with which the fanhead point can be identified and the steepness of the basin profile, which can not easily be quantified. Since the ACS model is empirical rather than physically based, variability will also be introduced through the inherent complexity of debris-flow processes.

6.3. Confidence in prediction

Fig. 6 was based on the actual field data used to develop and test the ACS model. The results shown in the graph are dependent on site-specific geometries, because the conversions between runout ($\alpha$) angles and actual runout lengths are dependent on basin profile shapes. The information shown on Fig. 6 would be applicable to drainage basins within the range of geometries used to develop the data. The field data set had $\beta$ angles that ranged from 7.1 to 26.5° and alluvial fan slopes that were less than 12°. The use of a small data set to develop this information is accounted for statistically by increasing the width of the confidence interval band.

The user of Fig. 6 is free to choose whichever confidence level and percentage of the data set is deemed appropriate. This choice would likely result from a cost-benefit analysis depending on the hazard and risk associated with the site in question. As an alternative to Fig. 6, the relationship $\alpha = 0.80\beta$ may be used, which represents an upper-bound to the runout distances observed in the field data set (Fig. 5). Due to the scatter present in the field data set, more rigorous investigations and analyses may be warranted to provide improved runout predictions on a site-by-site basis.

6.4. Comparison to existing runout models

The angles of reach predicted by Eqs. (4) and (5) were steeper than, and thus fell below, the basin profile for three of the debris flows listed in Table 5. This can be explained by the physical attributes of these three flows and their drainage basins. The gradient of Hummingbird Creek is very low for a debris-flow-transporting basin (Jakob et al., 2000), and thus the predicted angle of reach could likely be steeper than it. The small volume of the Pilot Ridge debris flow (Table 4) would have resulted in the prediction of a steep angle of reach.

For the three debris flows in Table 5 for which the angles of reach predicted by Eqs. (4) and (5) could be used to estimate a runout length, the predicted runout lengths ranged from 184 to 408% of the actual runout lengths. This over-estimation can be explained by the sources of the event volumes. During angle of reach calculations using Eqs. (4) and (5), the entire event volume was assumed to have originated at the initiating landslide. Although these events were initiated by discrete landslide masses, considerable material was scoured from the channel along the debris-flow path (Nasmith and Mercer, 1979) and multiple initiation points were present (Curry, 1966). Thus, applying the
entire event volume to a single initiation point would overestimate the actual volume present at that location, and a lower (more conservative) angle of reach would result. From a physical sense, this error results from the large discrepancies between the heads of the initiating landslides and the centers of mass of the source areas, making angle-of-reach estimations questionable.

For the six debris flows listed in Table 5, the ACS model predicted runouts that were 64 to 130% of the actual runouts, with an average prediction of 91%. For these six events, the ACS model provides more accurate runout lengths than do Eqs. (4) and (5). This should be expected, since many of the events listed in Table 5 were used to develop the ACS model.

6.5. Volume effects on debris mobility

The low P-value for Eq. (6) (Table 6) shows that there is a statistically significant relationship between increasing runout lengths and increasing event volumes for the field data set. However, this trend is not present when the runout lengths are converted to their α and β components. The high P-values for Eqs. (7) and (8) (Table 6) indicate that there are not statistically significant relationships between event volumes and either the angles of reach (as defined by the ACS model) or channel slopes, respectively, for events within the field data set. The high P-value for Eq. (9) (Table 6) shows that no statistically significant relationship exists between the predictive capability of Eq (3) and event volume for events within the field data set. Thus, we concluded that Eq (3) could not be improved upon by including event volume.

6.6. Flume tests

Fig. 7 shows that the field data are comparably tight with respect to the flume data within the same range of β angles. The flume tests by Shieh and Tsai (1997) were conducted in a roughened flume at slope angles within the range of slopes included in the field data set; these results also fit well with the ACS model best-fit regression of \( \alpha = 0.88 \beta \). The flume tests conducted by the USGS and Chau et al. (2000) were performed at β angles higher than most of those found in the field data set. Many of these tests also had runout (α) angles that were considerably lower than the trend indicated by the field data, which means the runouts for these tests were unexpectedly long. It is presumed that these longer runouts are caused by increased velocities due to travel paths that are steeper than those found in the field data set. Additionally, flume tests are subjected to unnatural boundary conditions and limitations to the maximum particle size that may be tested. It is believed that the ACS model would not be applicable to these steeper flume inclinations, since it was developed from events with shallower β angles.

7. Summary and conclusions

A model has been developed to provide preliminary runout predictions from the average channel slope (ACS model) for modest-sized debris flows that emanate from confined channels and have unobstructed deposition on well-defined alluvial fans. A debris flow’s runout angle, \( \alpha \), is predicted from the fanhead angle (the average slope of the travel path), \( \beta \), through the relationship \( \alpha = 0.88 \beta \). Both of these angles are referenced from the location along the basin’s main channel that is at an elevation half-way between the fan apex (representing the onset of deposition) and the drainage divide. This model has been developed from and tested on debris-flow events in basins underlain by non-volcanic rocks across western North America. The model appears to work equally well for both fire-related and non-fire-related debris-flow events. The model was tested using three debris-flow events from locations independent of those used in its development; the predicted runout lengths ranged from 82 to 131% of the actual runout lengths. The model also compared well with laboratory flume tests within the same range of channel slopes. The user of the model is provided with prediction interval multipliers so that predicted runout can be calculated within specified confidence limits.

The ACS model does not account for material properties, event volume, or 3-D topography, and thus other rigorous analyses may be required to provide more accurate estimates of runout distance. The ACS model should not be applied to lahars or to drainage basins other than those where confined channels have unobstructed debris-flow deposition on well-defined alluvial fans. The variability of ACS model results will depend on the accuracy of the chosen fanhead location, small changes between the α and β angles (especially for low-gradient channels), and physical debris-flow processes.

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