CONTROLS ON DEBRIS-FLOW AVULSIONS: WHITE MOUNTAINS OF CALIFORNIA AND NEVADA

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ABSTRACT

The process by which debris flows shift from an active channel and branch out into new transport or depositional areas is termed "avulsion." They pose serious risks for structures and populations on debris-flow fans, yet avulsion mechanisms are relatively unknown and unaccounted for in hazard assessments, as compared to avulsions of rivers and streams, which are better understood. This study analyzes six debris-flow fans in the White Mountains of California and Nevada to identify relationships between avulsion locations and channel characteristics, constrain the controlling factors on avulsion, assess the probability that avulsion will occur at specified locations, and develop a method to predict avulsion locations. A database of avulsion locations and their channel characteristics was compiled in the field. These were compared to the characteristics of other positions on the fan surface that show evidence of debris flows that did not avulse through stepwise, binary logistic regression. Results indicate that two-thirds of avulsion likelihood can be attributed to the percentage of boulders at the site, slope angle, channel width, and the ratio between flow thickness and average slope at the avulsion location. The accuracy of this model can be improved when it accounts for the presence of a coarse channel plug, which increases the likelihood of avulsion. Application of the model is demonstrated by runout simulations with forced avulsions from modeled channel plugs.

Keywords: debris flow, avulsion, fan, channel

1 – INTRODUCTION

The process by which debris flows shift from an active channel and branch out into new channels or areas is termed "avulsion." Debris-flow avulsion poses serious risks for structures and populations residing on debris-flow fans, yet avulsion mechanisms are relatively unknown and unaccounted for in hazard assessments, as compared to avulsions of rivers or streams, which are better understood. Until relatively recently, studies of debris flow largely neglected avulsion hazards, and modeling of avulsion processes followed the better constrained mechanics controlling fluvial avulsions. However, these methods do not account for differences in flow content and viscosity for debris flows, and long-term studies on debris flows are somewhat sparse because of long recurrence intervals (de Haas et al. 2018). More recent avulsion studies have speculated that avulsion has long-term compensational tendencies with strong dependence on channel plugs (Pederson et al. 2015; Santi et al. 2017; Hawie et al. 2018; Densmore et al. 2019). Generalized models for evaluating landslide hazards such as debris flows exist, but thus far these have not been adapted to identify a robust set of parameters for predicting avulsion locations (Jakob et al. 2005).

Because of the great risk posed by debris-flow avulsions in a variety of settings, climates, and fan surface conditions, avulsions are a critical factor for geohazard management. Understanding these hazards is difficult because of the apparently abrupt and random behavior displayed by avulsions, which are caused by seemingly unobservable changes on the fan surface. Study of debris-flow avulsions is also a relatively new field, making databases of field findings, evidence of controls on their occurrence, and literature on the topic somewhat sparse. As a result, new case studies building on existing theory and the development of a broader body of knowledge on the topic are highly valuable. In particular, identification of controlling mechanisms to aid in the prediction of avulsion locations will allow incorporation of avulsion into hazard assessments.

This paper seeks to identify relationships between channel and avulsion characteristics, constrain the controlling factors on avulsion, assess the probability that avulsion will occur at predictable locations, and develop a method to predict these locations.

2- STUDY SITE

We focus here on a set of debris-flow fans along the western flank of the White Mountains in eastern California (Fig. 1), where evidence for past debris flows is well-preserved on the fan surfaces (Hubert and Filipov, 1988). The White Mountains are bounded on the west by the White Mountains Fault Zone, which serves as an upper boundary of an apron of debris-flow fans. This high-angle fault zone accommodates about 8 kilometers of displacement and is associated with right-lateral and normal fault movement from the Walker Lane belt (Stockli et al., 2003). The range is underlain by sedimentary, metamorphic, and volcanic rocks with the addition of granitic plutons in some, but not all, of the catchments draining the western flank (Beaty 1963). Notably within these units is the Bishop Tuff, which directly underlies all the debris-flow fans, leading Hubert and Filipov (1988) to conclude that the construction of these fans has taken at least 700,000 years, the age of the tuff. This geological variability leads to differences in lithologies exposed within each catchment, and thus to differences in the composition and grain-size distribution of sediments supplied to the fans.

Because of the arid climate, the White Mountains receive the majority of their precipitation during cloudbursts in spring and summer months, with a mean annual precipitation of 150 mm (Hubert and Filipov, 1988). The most intense recorded cloudburst released about 250 mm of precipitation in the span of two hours in July of 1955, recorded near White Mountain Peak (Hubert and Filipov, 1988). The White Mountains are flanked by at least ten debris-flow fans along their western flank. The mountains actively produce debris flows during rainfall events, recorded as recently as 1952, 1955, 1958, and 1964 (Hubert and Filipov, 1988), with field evidence of previous flows still preserved on the fan surfaces. The fans on the flanks of the White Mountains are an ideal study area for debris-flow avulsion because of the evidence of previous and ongoing avulsion events, the availability of high-resolution topographic data, the consistency in climate and weathering regime for the alluvial fans, and the lack of vegetation cover on the fan surfaces. These characteristics also make it easier to reconstruct the flow deposits and cross-cutting relationships. This project focuses on a subset of six of these active debris-flow fans that have evidence of previous avulsions, high potential for future avulsions, and good accessibility.

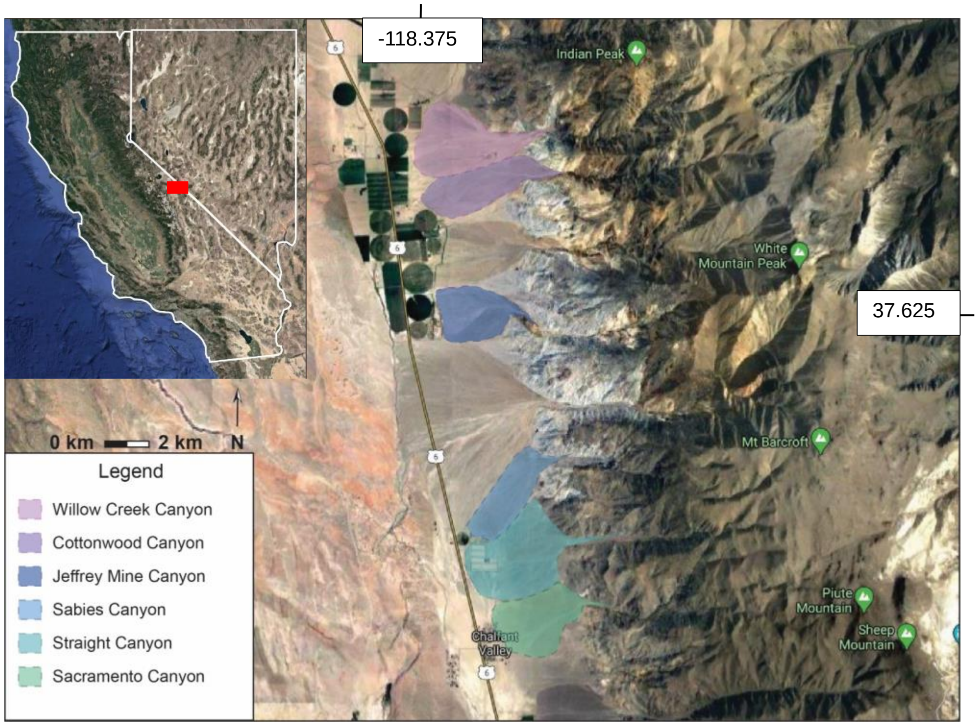

Fig 1 Location map of White Mountains study site, with inset map of broader region (study site location shown with red box). Six debris-flow fans of key interest are visible to the right of Highway 6.

The six debris fans chosen for the project are shown on Figure 1. Incised channels from several of these fans were previously evaluated by Hubert and Filipov (1988) in an effort to interpret the history and nature of the debris-flow deposits. Their work provided insight into the bedrock geology of the region and preliminary field descriptions of the debris-flow beds. Based on the results of their study, there is evidence of previous avulsion activity in several of the studied channels. Generally, these fans range in width from 1.5-5 kilometers, and in length from 5-8 kilometers.

Each of the six alluvial fans chosen for field work has unique characteristics and varying underlying lithologies. Regionally, the fans share a climatic regime and tectonic history that reduces some of the influencing variables and allows for their comparison in this study. General features and history of the six canyons chosen for this study are as follows:

- *Willow Creek Canyon (WC)* is the northernmost drainage in the study site, which most recently experienced a debris flow in 1956 (Hubert and Filipov, 1989). This catchment has an area of 9.06 km^2 above the mountain front and a total relief of ~580 m from ridge crest to outlet. A privately-owned farm is located on the distal fan, and a homeowner's property also lies directly on the medial fan, making certain parts of the fan inaccessible for field work.
- *Cottonwood Canyon (CC)* most recently experienced a debris flow in 1952 (Hubert and Filipov, 1989). The catchment has an area of 11.9 km^2 and a total relief of ~530 m from ridge crest to outlet. The fan crosses a privately-owned farm at the base.
- *Jeffrey Mine Canyon (JM)* shows evidence of at least four recent debris flows in several sections, and shallow paleochannels similar to the active channels show evidence of avulsion during previous debris-flow events. The most recent flow recorded on this fan occurred in 1958 (Hubert and Filipov, 1989). The catchment has an area of 8.03 km^2 and a total relief of ~270 m from ridge crest to outlet. A privately-owned farm is located on the distal fan.
- *Sabies Canyon (SabC)* also shows evidence of at least four relatively recent debris flows, with the most recent having occurred in 1918, and is characterized by debris-flow deposits that are considerably thicker than most other fans (Hubert and Filipov, 1989). The fan has an area of 10.9 km^2 and a total relief of ~470 m from ridge crest to outlet.
- *Straight Canyon (SC)*, like Sabies Canyon, exposes four distinct recent debris flows in the incised channel near its apex, and was also affected by a flow in 1918 (Hubert and Filipov, 1989). The fan has an area of 10.1 km^2 and a total relief of ~340 m from ridge crest to toe.
- *Sacramento Canyon (SacC)* is the southernmost drainage in the study site. Based on our field observations, the fan shows evidence of three recent debris flows at the surface. The catchment has an area of 22.8 km^2 and a total relief of ~380 m from ridge crest to toe. The White Mountain Estates neighborhood and a local landfill are built on the distal fan.

3 – PREVIOUS WORK

Fans in the White Mountains and neighboring Sierra Nevada have been the subject of a number of previous debris-flow and avulsion studies. Rigorous field mapping and analysis of stratigraphic sections and soil samples by Hubert and Filipov (1988) resulted in a detailed understanding of exposed debris-flow beds in the region. Whipple and Dunne (1992) used similar deposits from fans bounding the Sierra Nevada to describe how the rheology of debris-flow deposits impact the formation of debris-flow landforms, using shear stress, yield strength, fines content, and slope angle, among other measured and estimated variables. A change in depositional slope from debris levees on the proximal fan to lobes on the distal fan was speculated to be a function of boulder loss moving outward from the fan apex (Blair and McPherson 1998). Although they were working farther south in the Owens Valley, Blair and McPherson (1998) also suggested that lobe creation is more likely following the movement of boulders and other coarse material in the proximal fan. More recent study of debris-flow fans bounding the Inyo Mountains, the southern continuation of the White Mountains, has suggested that channel plugging may play the key role in avulsion in this setting, rather than gradual aggradation, provided that the thickness of the channel plug is larger than the channel depth and median debris lobe thickness (de Haas et al. 2019).

Avulsions have been well-studied in braided river systems and a general understanding of the mechanisms that contribute to their occurrence can be gleaned from these efforts. These differ, however, from debris-flow avulsions, given notable differences in rheology, setting, and dynamics (Reitz and Jerolmack 2012). Debris-flow avulsions have more recently been the subject of several field and laboratory studies attempting to characterize and understand their occurrence (Pederson et al. 2015; de Haas et al. 2018a, b). These studies reveal that over geologic time scales, avulsions often lead to compensational stacking (progressive filling of topographic lows) as a function of the availability of topographic lows on the debris-flow fan and sediment aggradation within active channels. The avulsions and related hazards are understood to be a function of the debris-flow fan morphology, sediment supply over time, and the volume of each debris-flow event (Bryant et al. 1995; Reitz and Jerolmack 2012; de Haas et al. 2016). Avulsion requires the presence of a viable path outside of the main channel, and is therefore also a function of the fan topography and thus the number of potential channel pathways present on the fan (Jerolmack and Mohrig 2007; Densmore et al. 2019). Additionally, insight into debris-flow avulsions can be gained from literature on subaqueous debris flows. Subaqueous debris-flow lobe development has been shown to be a function of topographic confinement, channel dimensions, and flow dimensions, in which avulsions occur in surging events that compensate for lows in topography over time (Locat and Lee 2002; Pettinga et al. 2018; Hawie et al. 2018).

A number of variables that might influence debris-flow avulsion have been identified from field observations, and are often modeled in flume experiments or tested through database statistics. These variables will serve as a starting point for the statistical analysis for this research. First, increasing distance from the fan apex is suggested to be associated with lower sediment concentrations and therefore a lowered likelihood for avulsion (Whipple and Dunne 1992; Iverson et al. 1998). Focused more on alluvial systems, Reitz and Jerolmack (2012), related the morphology of the active channel to sediment aggradation over time through the measurement of slope angles at avulsion sites and hinge points separating the angle at avulsed lobe sectors and the angle upslope of these features. Slope angles were also seen to contribute to a positive relationship between sediment supply and frequency of channel avulsion in braided river systems (Ashworth et al. 2004; Reitz and Jerolmack 2012).

A study performed by Wood and Mize-Spansky (2009) demonstrates that debris levee heights and widths tend to increase downslope at locations with lower slope angles, further showing that these variables are strongly linked. The width and depth of the active channel was also used to infer avulsion frequency, and the ratio between them has been used in part of an estimation of mobility for both fluvial and debris-flow dominated systsems (Whipple and Dunne 1992; Jerolmack and Mohrig 2007; Straub et al. 2009; Reitz and Jerolmack 2012; de Haas et al. 2015). Systems with large mobility based on this ratio were associated with low avulsion frequencies in these studies, and vice versa. Additionally, combinations of active channel geometry variables have been used to estimate parameters such as normal stress, shear stress, mobility, and yield strength, which were then correlated to runout distances, time scales for avulsion, and rheological properties of debris flows and also systems with more of an alluvial component (Parker et al. 1998; Whipple and Dunne 1992; Dade 2000; McArdell et al. 2007; Reitz and Jerolmack 2012). Because debris-flow behavior on a fan is dependent on the material available, debris flow and avulsion studies frequently include characterizations of grain size distributions. The amount of coarse material has been related directly to fan roughness and was also connected to avulsion frequency (Savenjie 2003; Reitz and Jerolmack 2012; Chen et al. 2022). Finally, channel plugs resulting from the deposition of thick debris lobes have been proven to cause avulsion at locations where other factors such as channel-bed superelevation were not present. Some studies have suggested that channel plugs are connected to the amount of coarse material at the snout of debris-flow surges, forcing avulsion (Blair and McPherson 1998; Zanuttigh and Lamberti 2007; de Haas et al., 2019).

4 - METHODOLOGY

4.1 Design of Field Investigation

Preparation for field work involved the identification of avulsion locations on each of the six debris-flow fans. The heads of previous avulsions were generally visible using satellite imagery on Google Earth Pro, identified as the point in the channel centerline at the highest upstream point where flow departs from the principal channel, forming a new active channel or depositing material outward (Figure 2). This method of identification followed Densmore et al. (2019). Fan sectors were also mapped as topographically-distinct areas of the fan surface, separated in most but not all cases by recognizable avulsions. We separate sectors from the deposits associated with individual flows or surges, which we here term lobes following Densmore et al. (2019).

Avulsions can be characterized by a number of different dimensions, including topographic and morphologic factors (Figure 3). The selected sites (Figure 1) were located on public land and were accessible in the field. Additional sites were identified to include, in order to expand the dataset, but were inaccessible because of difficult terrain, limited road access, and their location on private property.

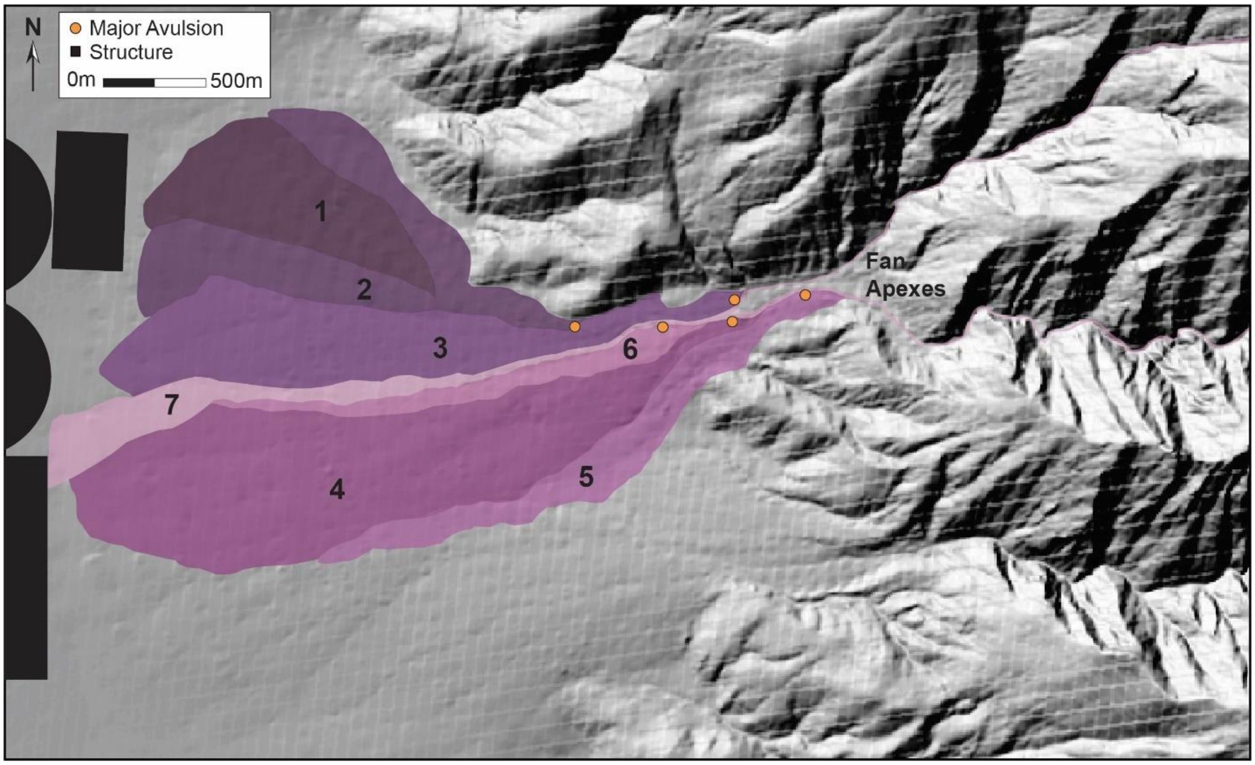

Fig 2 Willow Creek Canyon fan sectors built by successive debris flows, illustrated from oldest to most recent as numbers 1-7, respectively. Major avulsion sites are marked where they split from an active channel into new fan sectors

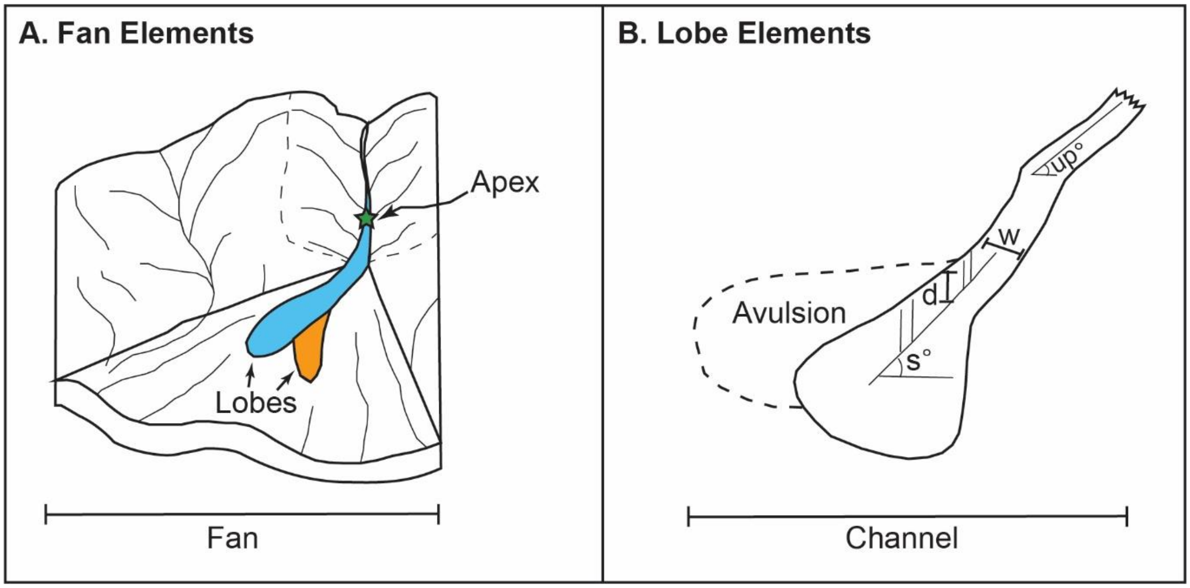

Fig 3 Two scales displaying terminology used within the study are shown. **A**: At the fan scale, avulsions cause shifts between different sectors that are active for a period of time, but also lead to the formation of individual lobes. **B**: At the lobe scale, avulsions cause departure from the channel axis and establishment of a new channel or deposition of material. Dimensional variables are illustrated here and defined in Table 1: w = channel width, d = channel depth, s^0 = slope angle, and up^0 = upslope angle

At each avulsion location, a variety of morphologic characteristics were recorded as shown in Table 1 (more detailed descriptions are given in Herbert, 2021) Characteristics were chosen on the basis of their demonstrated importance in studies indicated in the "Previous Work" section, their ability to be estimated using GIS and Google Earth images, and the ease in observing them in the field. "Non-avulsion sites" were also identified for logistic regression comparison, using criteria described in more detail below. In addition, "candidate sites" were identified as locations where avulsion may occur in the future due to a favorable combination of the potential avulsion factors. These sites were identified for use in logistic regression analysis as potential avulsion locations to compare to past avulsion locations.

Table 1: Measurements, methods, and justification for channel variables measured at avulsions

Characteristic	Justification	Measurement Method
% Boulders (%)	The percent of boulders at a location is indicative of the relative quantity of coarse debris carried by the channel to that point	Measured in the field as the percentage of cobbles and boulders (>64 and >256 mm, respectively) on the fan surface at the avulsion site, recorded within a representative 10m x 10m area at the site.
Slope Angle (degrees)	Because slope angle varies throughout each fan, slope angle at avulsion sites may show specific trends and control deposition of channel plugs	Measured in the field or on Google Earth, as the average values of three angle measurements in increments of 10-20m: upstream, downstream, and at the point of avulsion. Upslope angle is the measurement upstream of the point of avulsion.
Upslope Angle (degrees)	Angle upslope of the avulsion site may provide indication of greater trends in the particular segment of fan, whether slope is steady or changing	
Change in Slope (degrees)	A significant difference between the slope angle and upslope angle could cause debris slow and spread laterally or change paths	Difference between measured slope and upslope angles. Recognize that this angle is a smoothed value since it relies on measurement over a distance rather than at a single point.
Channel Width (m)	Wider channels may inhibit avulsion likelihood, giving flow space to spread, whereas narrower channels may promote avulsion	In the field, the channel width measurement was taken perpendicular to the channel from one edge to the other. The channel depth measurement was taken from the top of the channel bank or levee top to the base, simulating a bank-full condition. These parameters were estimated in the office for the non-avulsion sites, which were selected after field work was completed, using Google Earth satellite view and an elevation profile of channel cross-sections taken length- and width-wise.
Channel Depth (m)	Deeper channels may inhibit avulsion because they can accommodate a greater volume of debris, whereas shallower channels may promote avulsion by overflow	
Width/Depth Ratio	A certain threshold for the relationship between channel width and depth may need to be met for avulsion to occur	Ratio of measured channel width and depth.
Distance from Apex (m)	Avulsions may be more likely to occur closer to the fan apex where the potential energy of the flow is highest and quantity of boulders is greatest	Measured in the office with Google Earth, using avulsion locations marked in the field using GPS. Fan apexes were defined as the point where there is at least a 5-degree decrease in slope angle as the flow path transitions from a confined valley to an open fan.
Presence of Plug (0-1)	Channel-filling plugs may force avulsion even in the absence of other controlling factors	This measurement represents the availability of coarse debris plugs at the site. Defined as zero for non-avulsion or avulsion points that did not show any evidence of plugging, , and as one for avulsion points that showed evidence of plugging
Flow Thickness/Average Slope (m/degrees)	If the thickness of a debris flow is high relative to the slope, avulsion may occur	Ratio between flow thickness and an average slope for the segment of the channel containing the avulsion or non-avulsion site. Flow thickness was approximated as the distance from the top of a debris levee to the base of the incised channel at each avulsion location. The average slope used for this measurement was derived from the average

		slope angle of this segment of the channel, as indicated above.
Shear Stress (degrees/m)	A boundary shear stress threshold may control the likelihood of avulsion from a channel. Higher shear stress may reduce avulsion likelihood as the debris flow may further excavate the channel, rather than avulse out.	The ratio of the average slope to the length of that section of the channel was used as a proxy for shear stress. This measurement was chosen to represent the gravity-driven stress that pulls the flow down parallel to the slope over the particular length of the location of measurement.
Slope/Width Ratio (degrees/m)	If the average slope of the fan segment is high relative to the width of the channel, avulsion may be more likely to occur	Ratio between average slope at a given section of the channel and channel width.
Avulsion (1 or 0)	Response variable measured as a 1 or 0, indicating whether avulsion occurred at a location	This represents the response variable to be regressed upon in statistical analysis.

As soil characteristics may influence avulsion type and occurrence, selected samples of regolith were taken from within the debris-flow levees adjacent to avulsion points. Samples were approximately 4 liters in volume, collected at a depth of five to fifteen centimeters below the surface to minimize the effects of surface winnowing and erosion. Given the frequency of cobbles and boulders throughout the sites, a representative volume of grains larger than 64 mm were included in sampling. A total of 17 samples were collected for laboratory sieve and hydrometer analysis to identify soil type.

4.2 Choice of Measurement Locations

Prior to field work, a total of 29 avulsion locations across the six debris-flow fans were chosen as a reasonable subset of the total number of avulsed locations that are apparent on the debris-flow fans.

In order to demonstrate differences in characteristics between sites along the fan surface where avulsion occurred and sites where avulsion did not occur, 29 additional locations were carefully chosen within close proximity to the avulsion locations, termed “non-avulsion” locations. To minimize sample bias, non-avulsion sites were located within several hundred meters upstream or downstream in the same channel, or in a nearby but parallel channel. For the purpose of demonstrating an avulsion location prediction method, nine “potential avulsion” locations were also chosen in the field at sites where it appeared that avulsion could occur in future debris flows, but where there was no evidence of past avulsion. These were chosen with at locations where large boulders were evident in shallow channels, recognizing in advance the importance of their presence for avulsion. Examples of the locations of avulsion, potential avulsion, and non-avulsion points on debris-flow fans are shown in Figure 4 below.

4.3 Runout Modeling Methods

The modeling program Laharz_py was chosen to simulate current and potential future debris-flow runout pathways on each fan. Laharz_py is a forecasting program used to predict inundation and runout of lahars, debris flows, and rock avalanches, originally developed by Iverson and others (1998) to aid in hazard mapping and refined by Schilling (2014). The goal of this analysis was to show that Laharz_py can be adapted to match the avulsive runout of flows on a debris-flow fan at avulsion locations predicted using the methods developed in this study. The software operates in conjunction with a Geographic Information System (GIS) to delineate hazard areas with user-given volume estimates. The model estimates flow cross-sectional area A and planimetric area B as a function of volume V via a set of semi-empirical scaling relationships, where $A = 0.1V^{2/3}$ and $B = 20V^{2/3}$ (Griswold and Iverson, 2008).

Laharz_py requires the input of a DEM of the site, locations where the runout will begin, and specified volumes of material that will be used in the modeled event. A 10 m-resolution DEM published by the United States Geological Survey (USGS) was used for modeling the six debris-flow fans. At the time of modeling, this was the only resolution publicly available for the area: it also serves to demonstrate that avulsion modeling can be reasonably applied at relatively coarse resolution, with greater accuracy expected at finer resolution.

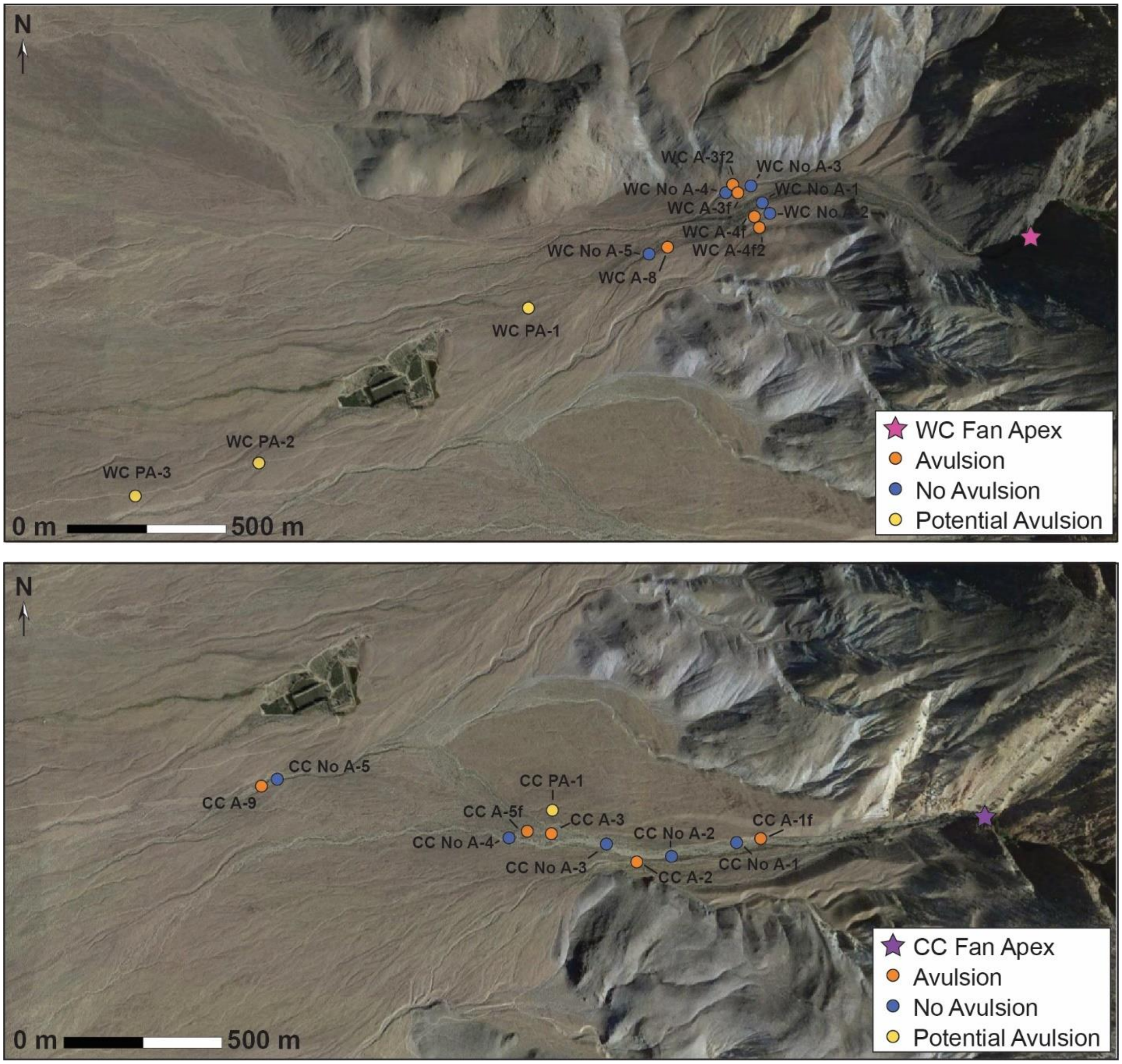

Fig 4 Locations of the analysis sites at Willow Creek Canyon (upper) and Cottonwood Creek Canyon (lower)

Laharz_py was run for three different assumed flow volumes on each of the six fans: an assumed ‘average event’ along with flows of +90% and -90% volume. This range captures potential larger and smaller events and shows a wide range of debris-flow volumes that could occur given a change in rainfall intensity and sediment supply. The assumed ‘average event’ was calculated with the empirical flow volume relationship of Gartner et al. (2014), utilizing peak 60-minute rainfall intensity (i60), total watershed area (A), the total area of the watershed burned by the most recent fire (Bt), time since the most recent fire (T), and the relief of the watershed (R), as seen in Equation 1. Peak rainfall intensity i60 was taken to be 125 mm/yr for all catchments based on the heaviest recorded precipitation near White Mountain Peak, while T was taken to be 100 years as the length of the historical flow record in the White Mountains (Hubert and Filipov, 1989). Other watershed specific values are shown in Table 2.

$$\ln V = 6.07 + 0.71 * \ln i60 + 0.22 * \ln Bt - 0.24 * \ln T + 0.49 * \ln A + 0.03 * \sqrt{R} \qquad (1)$$

Table 2: Estimated average flow volumes for each fan based on the empirical relationship of Gartner et al. (2014)

Fan	**i60 (mm/hr)**	**A (km^2)**	**Bt (km^2)**	**T (years)**	**R (m)**	**Ln(v)**	**Average V (m^3)**
WC	125	9.06	9.06	100	1901	11.27	78000
CC	125	11.91	11.91	100	2205	11.56	105000
JM	125	8.03	8.03	100	2031	11.22	75000
SabC	125	10.88	10.88	100	2182	11.49	98000
SC	125	10.10	10.10	100	2100	11.41	90000
SacC	125	22.79	22.79	100	2200	12.02	170000
Source of Info	Huber and Filipov (1988)	USGS StreamStats			USGS StreamStats	Gartner et al. (2014)	

Avulsion runout can be simulated in Laharz_py by the addition of a channel plug. This is implemented by changing values in the DEM to reflect a higher elevation at locations within the channel, so that the debris-flow runout must avulse around it. Because Laharz_py is not sensitive to small changes in a 10 m-resolution DEM, the height of the DEM at avulsion locations was modified to be several meters above the current elevation. This is similar to how channel plugs affect a debris flow. For this study, seven selected channel plugs, as observed in the field, were simulated to demonstrate the potential for modeling the change in inundated area area caused by avulsions.

4.4 Statistical Modeling

Stepwise binary logistic regression was used to develop a regression equation constraining the controls on avulsion, using Minitab 19 data analytics software. Inputs were identified as continuous independent variables, regressed against the response variable to the alpha level, or significance threshold, of 0.15.

Following the regression, the fit of the model was judged by the R-squared value: values close to one are desirable, as they indicate that a high percentage of the variance in the dataset is explained by the model. Additionally, the coefficients and p-value for each continuous variable in the model were calculated. The coefficients serve as a means to understand the weight that each variable carries in the regression equation. The p-value shows the likelihood of the response variable occurring as a result of random chance. A p-value less than 0.05 is typically required for a parameter to be statistically significant.

5 - RESULTS

The findings of the project include the development of a working statistical model for avulsion likelihood, a method to anticipate future potential avulsion locations, and runout results to demonstrate the impact of debris-flow avulsion in hazard mapping. Data for the project is available upon request from the corresponding author.

5.1 Laboratory Analysis of Soils

No significant differences or trends were noted in the grain size and hydrometer analysis. While samples showed variability in percent gravel, sand, silt, and clay, no canyon had a distinct regolith texture that could be related to the four parameters in the predictive equation.

5.2 Logistic Regression Analysis

Statistical analysis of field-based data variables demonstrated that avulsion likelihood can be anticipated using four of the eleven independent variables suggested as controls, where the probability of avulsion, P(a) is modeled as:

$$P(a) = \exp(Y') / (1 + \exp(Y')) \qquad (2)$$

$$Y' = 6.15 + 0.1524\ \%Boulders - 0.965\ Slope - 0.444\ Channel\ Width + 16.54\ Flow\ Thickness/Average\ Slope \quad (3)$$

The variance in avulsion likelihood that can be attributed to the model input parameters is calculated as an R-squared value of 63.6%. The p-values for each of the four variables are less than 0.05, meaning these variables can be considered statistically significant (Table 3); the other seven variables were not significant. The degrees of freedom (DF) for the regression constant and each variable are also presented, along with the chi-squared value for each.

Table 3: Analysis of variance for regression equation components

Analysis of Variance			
Source	**DF**	**Chi Square**	**p-value**
Regression	4	11.79	0.019
%Boulders	1	5.31	0.021
Slope	1	9.54	0.002
Channel Width	1	11.33	0.001
Flow Thickness/Average Slope	1	10.38	0.001

An illustration of the effects of each of these factors on avulsion can be seen in Figure 5, which shows avulsion likelihood against variations in the model values. These plots cannot be used individually to predict likelihood of avulsion, but are a useful means to visualize how the continuous variables work in tandem to control avulsion. The mean values and interquartile range of each significant variable for each avulsion site can be seen in Figure 6. The results are grouped by fan and indicate variances in these means between fans.

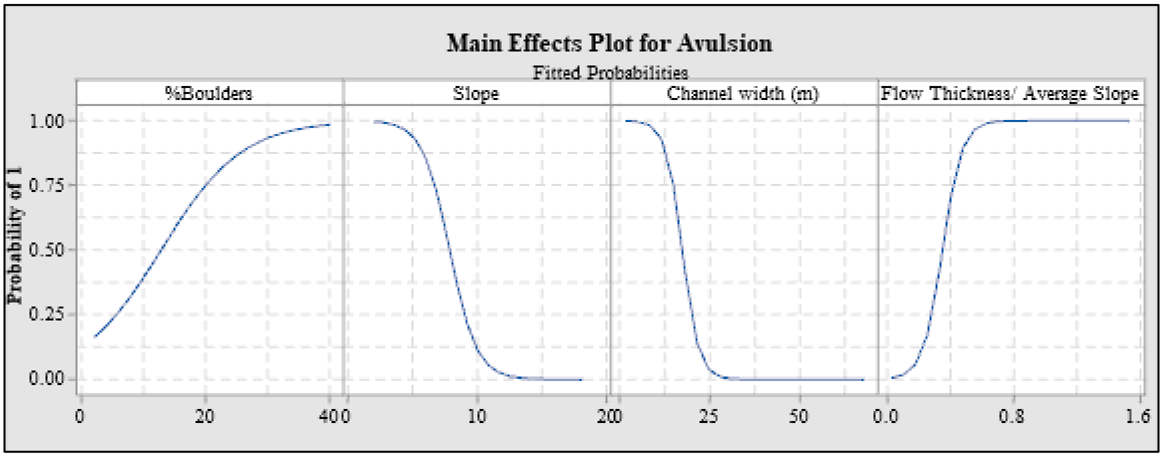

Fig 5 Factorial plots with significant variables from regression shown against avulsion probability

Estimated avulsion probability from equation 2 can be compared to the presence or absence of avulsions at the 58 avulsion and non-avulsion sites across the six fans. Recall that the avulsion sites (n = 29) were used in the regression, but the non-avulsion sites (n = 29) were chosen as nearby locations where there was no evidence of recent avulsion. Not surprisingly, estimated avulsion probability is high at avulsion sites, with 25 sites having $P(a) \geq 0.7$ (Figure 7). Most non-avulsion sites, by contrast, have low estimated probabilities, with 25 sites having $P(a) < 0.4$ (Figure 7). Based on the distribution of probabilities, we group our sites into three categories of avulsion likelihood: low, with $P(a) < 0.4$; medium, with $0.4 \leq P(a) < 0.7$; and high, with $P(a) \geq 0.7$ (Figure 7).

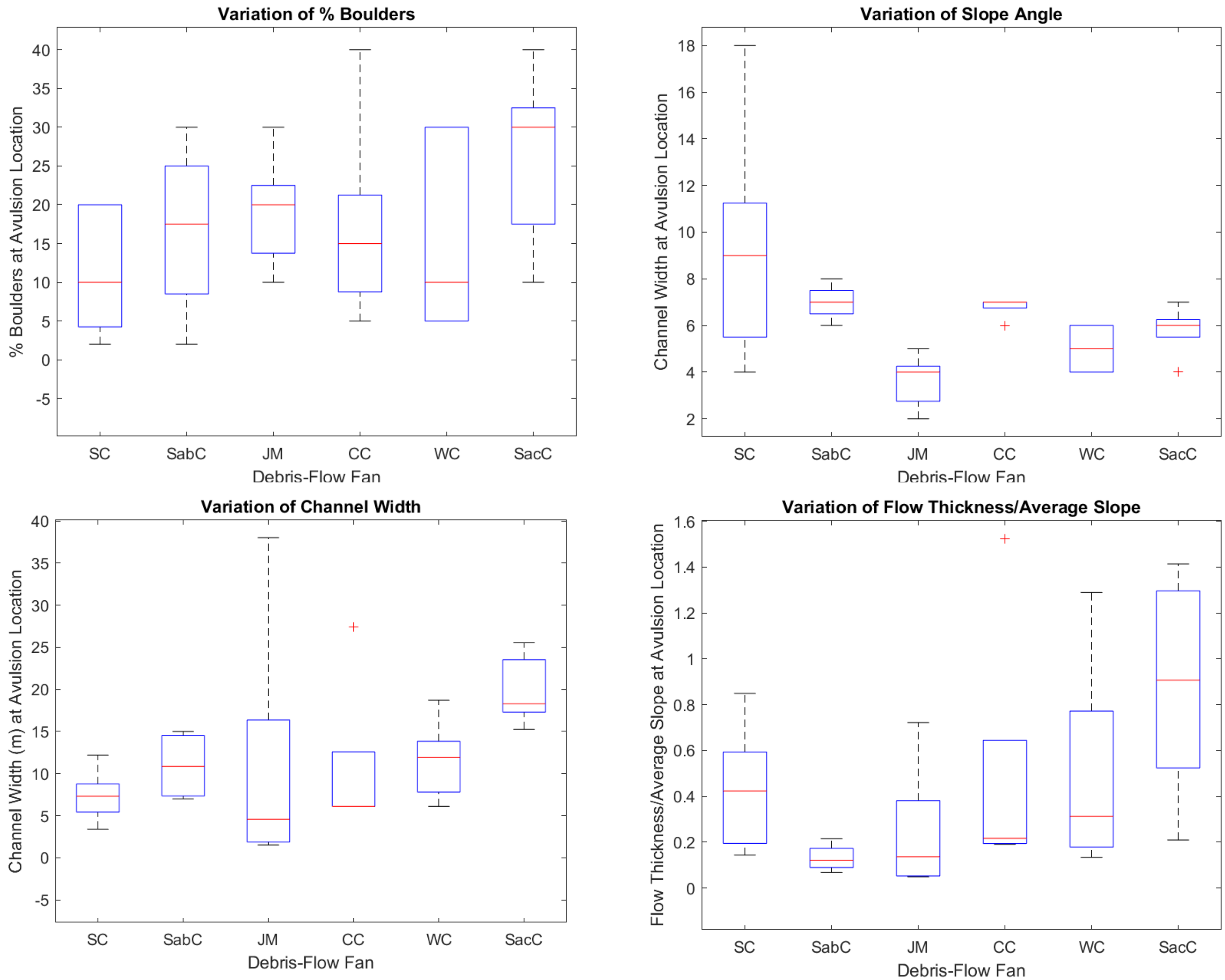

Fig 6 Boxplot presentation of the four significant variables in the avulsion probability regression equation, plotted by fan. Note that there are five data points for all fans but SabC, which has four points

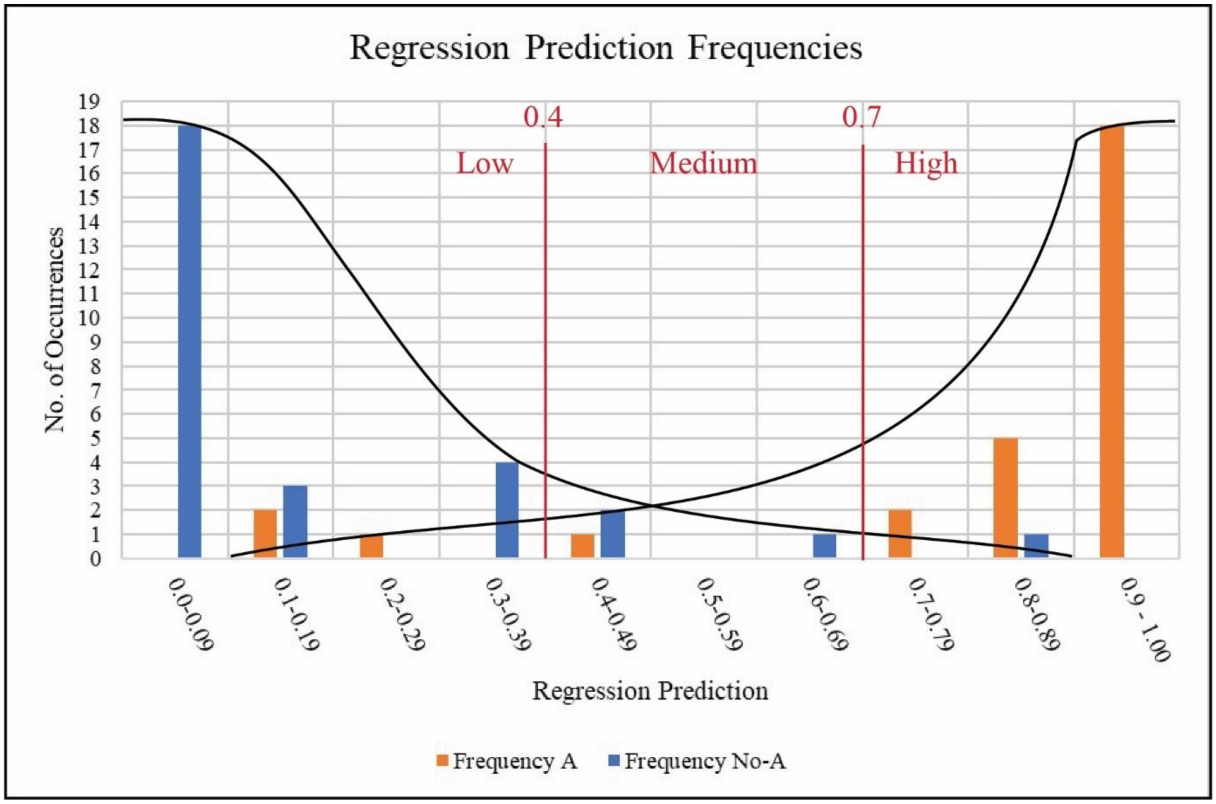

Fig 7 Histogram of estimated avulsion probability, using Equation 2, at all avulsion (A, n =29) and non-avulsion (No-A, n = 29) locations. Vertical lines show proposed division into low, medium, and high categories based on the distribution of values

5.3 **Accounting for Channel Plugs**

The presence of a channel plug also has a high impact on avulsion probability. As observed in the field, various plugs fill different percentages of the channel. The size of a plug is affected by the percent of boulders at the site, the channel width, and the flow thickness (which can be estimated as approximately the channel depth). Channel plugs have also been speculated to be the key factor impacting avulsion in the White Mountains by de Haas et al. (2019).so the effect on avulsion likelihood from a channel plug was incorporated into the avulsion model by estimating a high probability for avulsion at locations that are impacted or may soon be impacted by a channel-filling plug. Should a plug not be present or likely based on site observations, avulsion probability can be ranked as high, medium, or low according to the regression equation. The cutoffs for each of these ranks were determined based on a histogram plot of the avulsion and non-avulsion location probabilities (Figure 7). A few outliers exist in both distribution tails, but the majority of avulsion points have a probability of over 0.7, and the majority of non-avulsion points have a probability of less than 0.4.

The presence of a plug can increase the avulsion likelihood of a site even if low probability is calculated, as is demonstrated in Table 4, in which a select ten of the sites that avulsed were reentered into the regression equation. This shows generally high calculated probabilities, as expected, for sites that avulsed, but also two low, outlying values where avulsion occurred, despite the low estimated probability, as a direct result of the presence of a channel plug. This method was also implemented on the nine potential avulsion locations identified in the field and the results are presented in Table 5. Using these overall results, it is feasible that debris-flow avulsions can be anticipated with at least a 63.6% confidence level, as shown by the R-squared value, for the White Mountains.

5.4 **Modeling of Avulsion**

As a first step, runout was modeled with Laharz_py assuming no channel plugs, using the range of volumes in Table 2 (average, then +90% and -90% to represent upper and lower limits, respectively). The models showed that changing the flow volume affects the length and, to a lesser extent, the width of the runout path, but not the path direction or fan sector that is active. Examples of this are shown in Figure 8.

Next, runout was modeled with plug deposition simulated. In five of the six fans evaluated, the flow diverts onto a different fan sector, as shown on Figure 8, and then follows pre-existing topography. Depending on the fan, the avulsion may lead to an entirely new flow pathway (Figure 8a), or a pathway which rejoins the original channel some distance down-fan (Figure 8b). Changing the flow volume leads to similar changes as for the no-plug case along the new flow pathway. In the sixth fan, for Sacramento Canyon, the flow stays in the same pathway and does not divert to a new sector.

Table 4: Field variable values and calculated avulsion probability P(a) for selected avulsions highlighting range of likelihood values in avulsion events and the effect of channel plugs. Bold text highlights two sites with low calculated avulsion probability P(a), but where avulsions occurred nonetheless as a result of channel plug formation.

ID	% Boulders	Slope (degrees)	Channel Width (m)	Flow Thickness / Average Slope (m/degree)	Calculated Probability, P(a)	Presence of Plug	Estimated Likelihood of Avulsion
SabC A-2	2	8	7.0	0.13	**0.10**	**1**	**High**
CC A-5 f	40	7	27.4	0.35	**0.29**	**1**	**High**
SabC A-3	30	7	14.0	0.11	0.40	0	Medium
SC A-6	10	18	7.3	0.85	0.75	0	High
SabC A-4	20	6	7.7	0.07	0.75	0	High
WC A-8 f	10	4	12.2	0.19	0.83	0	High
SC A-4	5	9	7.6	0.42	0.86	0	High
JM A-1 f	20	2	38.0	0.72	0.91	0	High
SacC A-3 f	40	4	18.0	0.21	0.98	0	High
CC A-1 f	5	7	6.1	1.52	1.00	0	High

Table 5: Variable values and calculated avulsion probability P(a) for nine potential avulsion sites

Potential Avulsion ID (see Figure 4)	% Boulders	Slope (degrees)	Channel Width (m)	Flow Thickness / Average Slope (m/degree)	Calculated Probability, P(a)	Presence of Plug	Estimated Likelihood of Avulsion
WC PA-1	20	9	11.1	0.10	-	1	High
WC PA-2	10	10	7.6	0.04	-	1	High
WC PA-3	15	11	4.8	0.03	0.03	0	Low
CC PA-1	25	8	11.2	0.03	0.11	0	Low
JM PA-1	30	14	8.0	0.03	0.00	0	Low
SabC PA-1	10	9	17.4	0.34	0.04	0	Low
SabC PA-2	10	7	11.5	0.04	0.04	0	Low
SacC PA-1	20	14	10.9	0.06	-	1	High
SacC PA-2	15	12	11.4	0.05	-	1	High

6 - DISCUSSION

The results of field, statistical, and runout analyses have been integrated to develop an initial method for anticipating avulsion occurrence. The methods defined for the White Mountains can be tested on other, similar debris-flow fans in arid mountainous environments. While some significant controlling factors were identified through our analysis, more accurate prediction of the full extent of avulsion hazards is likely to depend on a variety of other, as yet not identified, factors.

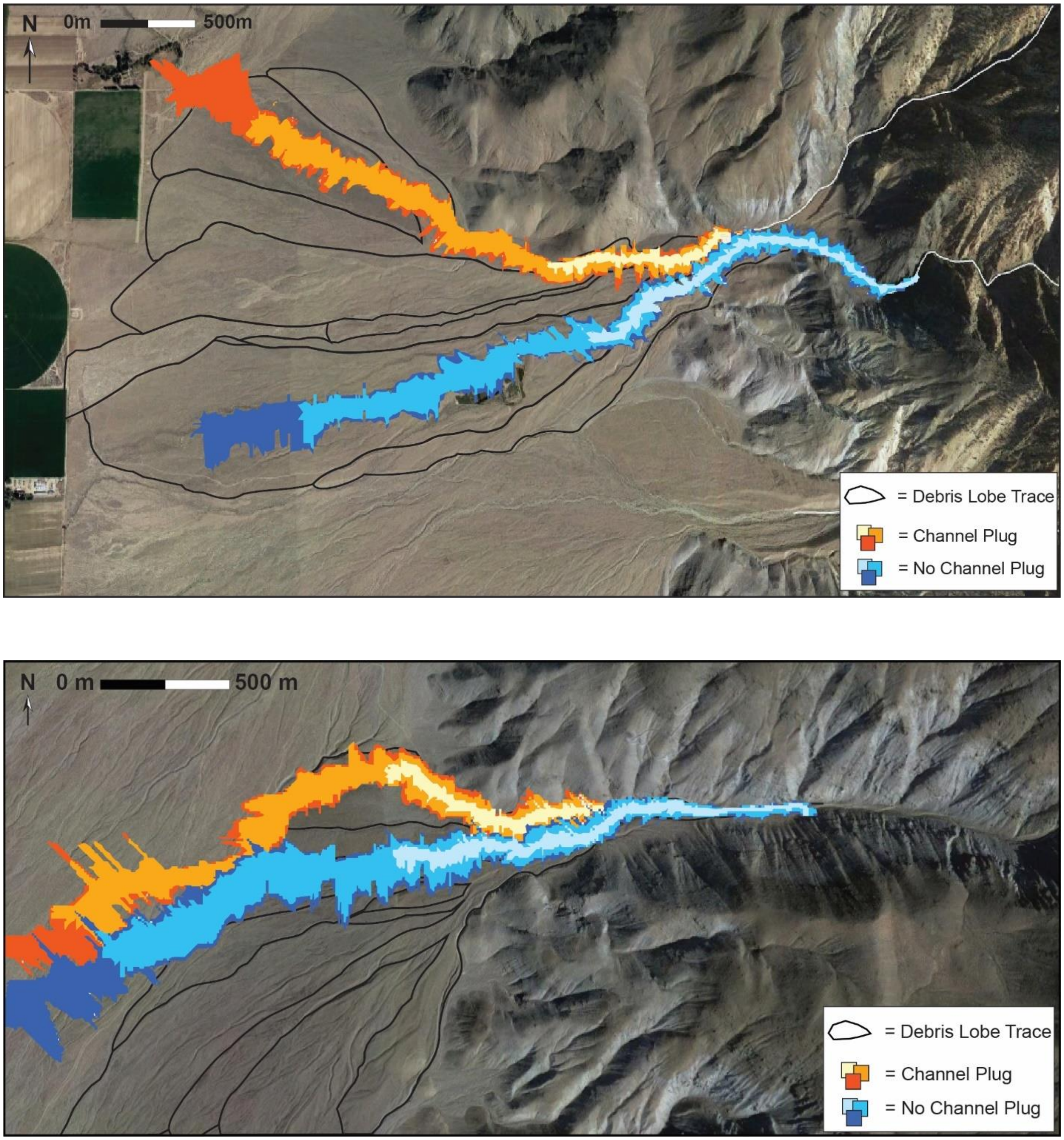

Fig 8 Modeled Laharz_py runout on Willow Creek (A, upper panel) and Sabies (B, lower panel) Canyon fans. Shades of color represent average event volume and +/- 90% volume values (Table 2). Black lines indicate mapped fan sectors. For the Willow Creek fan, the avulsion

followed an entirely new pathway downstream of the imposed avulsion location on an older fan sector. The Sabies Canyon avulsion started on a new path, but lower down rejoined the original fan sector.

The statistical analysis confirms the influence of several factors that may play a role in controlling avulsion. For example, a decrease in slope angle would be expected to slow a debris flow and, all else being equal, allow for lateral spreading of debris material, whereas higher slope angles would increase velocity and reduce the likelihood of avulsion. If a debris flow has a higher percentage of coarse material, there is an expectation that a coarse debris plug could readily form and encourage avulsion. Additionally, a narrower channel increases likelihood of avulsion due to potential chokepoints within the channel, but a wider channel would allow for unrestricted movement. Finally, when the ratio of flow thickness over average slope at the avulsion site is larger, avulsion likelihood increases. Higher flow thickness at a site allows avulsion from overtopping to occur more readily. A higher slope angle might force a debris flow to remain in the active channel, but a lower slope angle, and therefore a larger ratio, allows for departure from the channelized flow. The inherent assumption in this analysis is that these probabilities are calculated using current fan conditions, and over a short time scale, on the order of tens to hundreds of years. We expect that over time, sediment aggradation occurs within channels and channel plugs are deposited, so avulsion probability will increase in the future on a longer timescale, unless there are incision events such as clear water floods, or local uplift.

The results of the regression equations (equations 2 and 3) reproduce debris-flow avulsion with an R-squared value of 64%, but the four factors selected within the model with statistical significance are likely not the sole controls on avulsion. It is very likely that avulsion likelihood is also affected by topographic changes on the fan surface such as interaction with overlap with debris-flow fans on neighboring canyons, or surface deformation associated with movement along the White Mountains Fault Zone. Additionally, the importance of channel plugs cannot be understated. Each measured site containing a coarse debris plug that filled at least part of the channel experienced avulsion. The presence of plugs should be used to supplement the other statistically significant terms in the model to increase the expected likelihood of avulsion. While avulsion can occur without a coarse debris plug, as the other factors can directly influence the possibility, a channel-filling plug is the most direct cause for a debris flow to avulse. Therefore, to calculate the likelihood of avulsion at a specific location, we propose the two-step process shown in Figure 9. The process starts with assessment of the presence or likelihood of a channel plug, following by scoring the likelihood based on Equations 2 and 3, using measurements of percent boulders, slope angle, channel width, and the ratio between flow thickness and average slope.

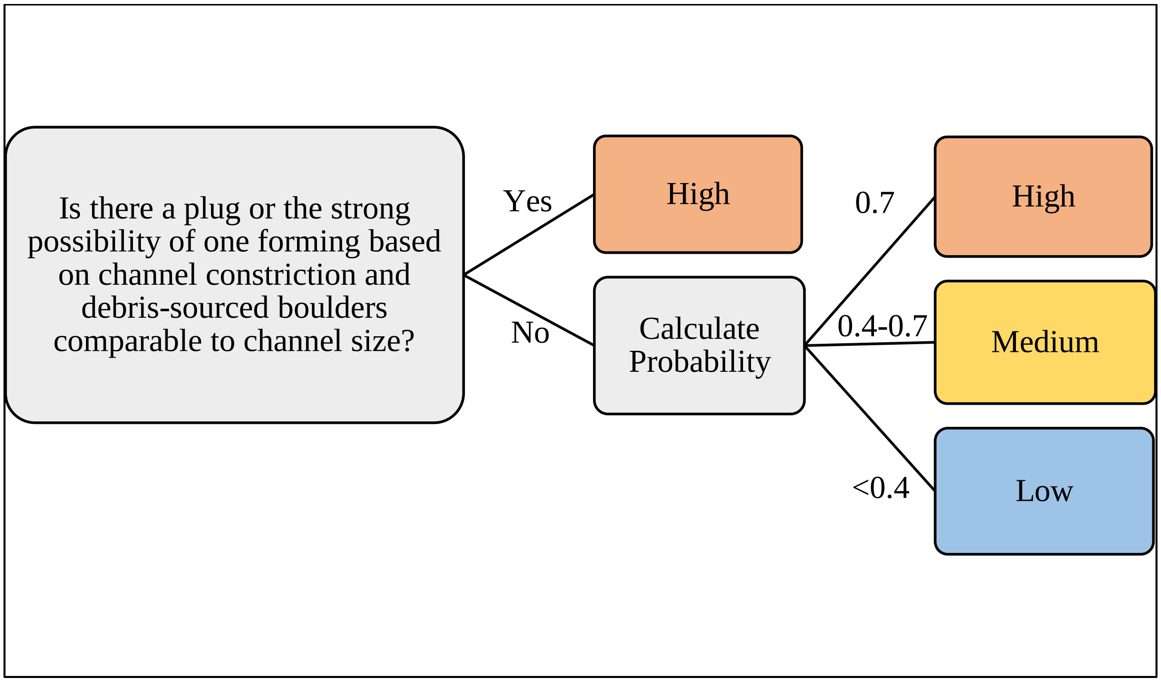

Fig 9 Proposed methodology for anticipating avulsion likelihood depends first on the presence of a channel plug, and can be further estimated using the results of the regression equation to calculate probability based on channel characteristics

Observations of the relative values of the parameters that are part of the predictive equation (shown on Figure 6) may shed some light on debris-flow avulsive behavior. The mean value of *percent boulders* covered a large range, from ~30% for sites on the Sacramento Canyon fan to ~10% for the Sabies and Willow Creek Canyon fans. By contrast, *slope angle* varies much less at the avulsion locations, from ~9 degrees for sites on the Straight Canyon fan to ~4 degrees on the Jeffrey Mine Canyon fan. *Channel width* covered a large range, from ~20 m at Sacramento Canyon to ~5 m at Jeffrey Mine Canyon. Finally, the *ratio of flow thickness to average slope* also had a large range, from ~1.0 for Sacramento Canyon to ~0.19 for Jeffrey Mine and Sabies Canyons. These trends suggest that high (or low) values of the four parameters tend to occur together. Sacramento Canyon is the highest in three of the four, and in the middle range for slope angle. Jeffrey Mine Canyon is the lowest in three of the four, and in the middle range for percent boulders. The other four canyons have mixed rankings, with mostly values in the middle range. Since these values were all measured at points of known avulsion, there is no clear trend to indicate that specific patterns of these values would indicate susceptibility to avulsion.

Having made this observation, however, Equation 3 does indicate which parameters are more influential than others. Since each parameter in the equation covers a different range, and has a different coefficient, their weight can be judged by normalizing, which involves multiplying the coefficient against the middle value of the range. For example, for percent boulders the coefficient is 0.1524 and the middle of the range is ~20%, so the weight would be +3.0 (positive value indicates positive correlation). Similar calculations yield the following weights: slope angle = -6.3, channel width = -5.6, ratio of flow thickness to average slope = +9.9. On this basis, flow thickness to average slope ratio has the strongest influence on the likelihood of avulsion, and percent boulders has the least influence. We should emphasize that all of these parameters have already been shown to be statistically important, but thick debris flows on steep slopes are identified as particularly susceptible to avulsion.

Laharz_py was shown to produce avulsions at specified locations that broadly match patterns of deposition that are seen on the fan, in terms of switching from deposition on one sector to another. Some avulsions return to the original channel farther downfan, and some follow a new fan sector for their entire runout. Modeling of potential avulsion paths is a critical step in hazard assessment. We suggest that multiple realizations are modeled, testing high likelihood locations as identified in Figure 9, and running secondary avulsion models on newly avulsed paths from the primary avulsion models.

We expect that the level of prediction of this model may be improved by the addition of variables not considered in this analysis such as clay content, cross-sectional area of the channel, and the compensational tendencies of avulsion suggested by Pederson et al. (2015), Santi et al. (2017), and de Haas et al. (2018). These may be accounted for, in part, by including the steepest adjacent slope outside of the active channel, which may be indicative of the direction of the next avulsion, or some measure of channel bed elevation relative to the surrounding fan surface. In addition, the direction of avulsions was not specifically addressed within this study, although we suspect that it may be controlled in part by upstream channel conditions. For example, a sharp bend in the channel resulting from a topographic break or interaction with another fan may result in an avulsion downstream that flows straight rather than following the sharp bend. Additionally, the conditions that allow a debris flow to reoccupy a previous pathway or move in a new direction were not directly explored. These may be related to components as diverse as fan roughness at the location, the permanence of a possible channel plug, and volume of the flow. This study also did not address the effect that varying volumes of debris flow would have on avulsion likelihood: with a large enough flow, it is assumed that avulsion is much more likely, even at unexpected locations, because the flow volume will exceed the channel capacity and overflow more readily.

7 – CONCLUSIONS

Debris-flow avulsion is a critical mechanism that amplifies the hazard posed by debris-flow runout in terms of both changes in the position of the active channel and unpredictability of flow direction. The risk of avulsion has not been typically included in hazard analyses because avulsions have historically been under-analyzed. This project sought to develop a method for predicting avulsion likelihood at locations on six debris-flow fans in the White Mountains, based on the characteristics of sites that had avulsed in the past. Following the mapping of avulsion locations and literature review to guide suggested field measurements, a field investigation was completed to gather data at 29 avulsion locations across the six fans. An additional 29 "non-avulsion" locations were chosen for statistical comparison based on their proximity and similarity to the avulsed locations.

Stepwise, binary logistic regression analysis was performed on the database compiled from avulsion and non-avulsion sites. This analysis indicated that the percentage of boulders, slope angle, channel width, and the ratio between flow thickness and average slope play the largest roles in controlling avulsion. The regression equation accounts for 64% of the variance in the dataset. A final flowchart to predict avulsion likelihood combines the regression equation with field indications of a coarse debris plug in the channel that would enhance avulsion. Runout analyses were performed with Laharz_py, simulating debris flows of three different volumes to demonstrate the changes in debris-flow patterns due to avulsions from channel plugs. Modeling of potential avulsion paths is a critical step in hazard assessment, and the results of this study support a hazard management analysis where multiple runout realizations are modeled, including avulsions at locations identified as high likelihood using our recommended workflow, and running secondary avulsion models on newly avulsed paths from the primary avulsion models. The model could be applied to similar areas to identify locations likely to avulse in the future, so that runout modeling can account for the hazards in the new runout areas.

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