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ASSESSMENT OF TOPOGRAPHIC AND DRAINAGE NETWORK CONTROLS ON DEBRIS-FLOW TRAVEL DISTANCE ALONG THE WEST COAST OF THE UNITED STATES

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ABSTRACT

To better understand controls on debris-flow entrainment and travel distance, we examined topographic and drainage network characteristics of initiation locations in two separate debris-flow prone areas located 700 km apart along the west coast of the U.S. One area was located in northern California, the other in southern Oregon. In both areas, debris flows mobilized from slides during large storms, but, when stratified by number of contributing initiation locations, median debris-flow travel distances in Oregon were 5 to 8 times longer than median distances in California. Debris flows in Oregon readily entrained channel material; entrainment in California was minimal. To elucidate this difference, we registered initiation locations to high-resolution airborne LiDAR, and then examined travel distances with respect to values of slope, upslope contributing area, planform curvature, distance from initiation locations to the drainage network, and number of initiation areas that contributed to flows.

Results show distinct differences in the topographic and drainage network characteristics of debris-flow initiation locations between the two study areas. Slope and planform curvature of initiation locations (landslide headscarps), commonly used to predict landslide-prone areas, were not useful for predicting debris-flow travel distances. However, a positive, power-law relation exists between median debris-flow travel distance and the number of contributing debris-flow initiation locations. Moreover, contributing area and the proximity of the initiation locations to the drainage network both influenced travel distances, but proximity to the drainage network was the better predictor of travel distance. In both study areas, flows that interacted with the drainage network flowed significantly farther than those that did not. In California, initiation sites within 60 m of the network were likely to reach the network and generate long-traveled flows; in Oregon, the threshold was 80 m.

Key words: *rainfall, debris flow, travel distance, channel, drainage, contributing area, curvature, initiation, entrainment, LiDAR, California, Oregon*

INTRODUCTION

Prediction of travel distance is a fundamental element of debris-flow hazard assessments. Total volume exerts a primary control over debris-flow travel distance and inundation area (e.g., Iverson *et alii*, 1998; Griswold & Iverson, 2007), and debris flows that grow as they entrain sediment can generate exceptionally large and destructive flows (Hungr *et alii*, 2005).

To help clarify controls on entrainment and travel distance throughout the debris-flow prone west coast of the U.S., we investigated debris flows triggered by two major precipitation events in two separate geographic areas located about 700 km apart. The first area is within the Coast Range of central Alameda County in the San Francisco Bay region of northern Califor-

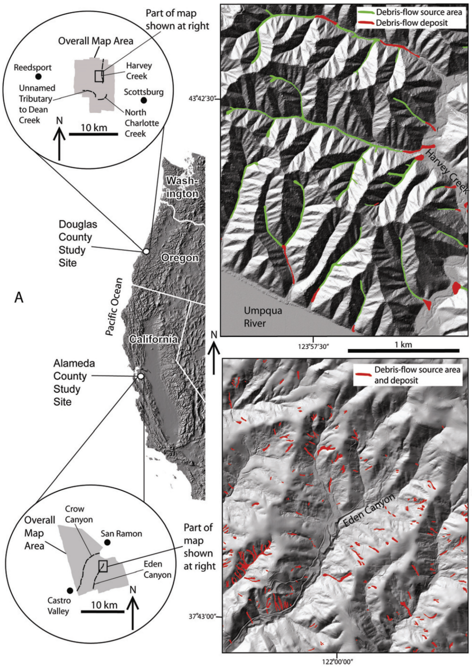

Fig. 1 - A) Map showing study area locations and drainage basins where we computed drainage densities (e.g., Eden Canyon, Harvey Creek, etc.). B) Part of the debris-flow inventory map for Oregon study area. C) Part of the debris-flow inventory map for California study area. Inventory maps are from Coe *et alii (2011) and* Coe *et alii (2004), respectively*

nia (Fig. 1). Here, we examined debris flows triggered by February 1998 rainfall during the 1997/98 El Niño Southern Oscillation, which caused widespread debris flows and flooding throughout California. The second area, located in the Coast Range of western Douglas County in southern Oregon (Fig. 1), contains debris flows that were triggered by rainfall during November 1996. These storms generated flooding and debris flows throughout western Oregon (Robison *et alii*, 1999; Wiley, 2000; Hofmeister, 2000).

In both areas, debris flows mobilized from slides, but entrainment and travel distances of the flows were very different. In California, nearly all debris flows did not entrain material and had relatively short travel distances. In Oregon, nearly every flow entrained material and travel distances were relatively long.

The physical properties of surficial geologic materials, topographic boundary conditions, drainage sinuosity, confinement, and junction angles, and the properties and dynamics of the flows themselves influence entrainment and travel distances (e.g., Benda & Cundy, 1990; Anderson & Sitar, 1995; Iverson *et alii*, 2000; Reid *et alii*, this volume; Silbert *et alii*, 2002; McCoy *et alii*, 2010). However, for regional hazard evaluations, investigators typically have little detailed data on spatially variable material properties or expected flow dynamics, but they often have reliable Digital Elevation Model (DEM) data, as well as hydrologic drainage network data derived directly from DEM data. For this reason, forecasts based on DEM data are appealing and often sought. For example, shallow landslide initiation locations are commonly predicted using topographic and drainage variables such as local slope and upslope contributing area (Montgomery & Dietrich, 1994; Tarboton, 1997; Dietrich *et alii*, 2001). This approach for identifying initiation sites prompts the question: Do the topographic and drainage network characteristics of initiation locations influence the entrainment and travel distance potential of debris flows generated from those sites?

In this paper, we investigate this question by examining the topographic and drainage network characteristics of debris-flow initiation locations in the two study areas using recently available, high resolution, Light Detection And Ranging (LiDAR) topographic data. Specifically, we examine whether values of slope, upslope contributing area, planform curvature, and proximity to the drainage network at debris-flow initiation locations influence resulting debris-flow travel distances. We also assess the effect that multiple numbers of debris-flow initiation locations have on travel distance. Based on the results of our assessment, we present two empirical approaches that can be used to estimate travel distance; one based on the number of contributing initiation locations, and the other based on the proximity of initiation locations to the drainage network.

STUDY SITES

Both study sites are prone to precipitation triggered debris flows. We analyzed topographic and drainage network variables at the two study sites, but there are also non-topographic variables, such as differing geologic units and vegetation, that could potentially impact travel distances. The following sections provide detailed descriptions of the characteristics of each study area.

ALAMEDA COUNTY, NORTHERN CALIFORNIA

The Alameda County study area is about 125 km^2 in size and lies within the northwest-trending Coast Ranges of northern California in the San Francisco

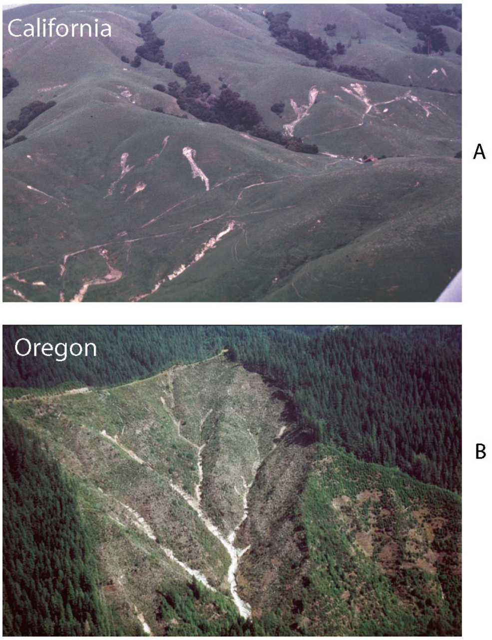

Fig. 2 - Photographs of hillslopes and debris flows in our study areas. A) California study area. Distance from lower left to upper right edges of the photograph is about 2000 m. B) Oregon study area. Distance from left to right edges of the photograph is about 650 m. Oregon photo modified from Stock and Dietrich (2006)

Bay region (Fig. 1). Hillslopes in the area (Fig. 2) have moderate to steep gradients (10°-30º) and are mantled by colluvial soil up to a few meters in thickness. Vegetation is mostly grass but includes some shrubs and deciduous trees. Land use is predominantly livestock grazing, but some areas have been converted to residential use. Elevations reach a maximum of about 600 m. Climate in the area is Mediterranean, with mean annual precipitation of about 460 mm in valleys, and as much as 610 mm along upper flanks of the prominent northwest-trending ridges (Rantz, 1971). The area is underlain by Cretaceous and Tertiary sedimentary rocks of marine and non-marine origin that have been extensively folded and faulted by multiple oblique-slip faults (Graymer *et alii*, 1996). Most of these rocks release clay as they weather (Ellen & Wentworth, 1995).

Landslides occur primarily during the late fall through early spring wet season. Debris flows typically mobilize from small, shallow slides (e.g., see Fig. 2 and Ellen & Fleming, 1987; Wieczorek *et alii*, 1988; Anderson & Sitar, 1995), often in topographically convergent, concave hillslope areas (also called hollows, Reneau & Dietrich, 1987). Debris flows in February 1998 were triggered by about 90 mm of rainfall on February 2-3. Seasonal antecedent rainfall prior to February 2 exceeded 350 mm and antecedent soil moisture conditions were well above the previously defined rainfall-threshold levels (Coe and Godt, 2001). Field observations following the February debris-flow event indicated that nearly all (>99%) of debris flows did not erode or entrain hillslope and channel material.

DOUGLAS COUNTY, SOUTHERN OREGON

Our second study area, in Douglas County, Oregon, is about 94 km^2 in size, lies within the southern Oregon Coast Range, and is transected by the Umpqua River (Fig. 1). Elevations in the map area range from sea level to about 490 m. The area has a maritime climate with wet winters and dry summers. Average annual precipitation ranges from about 1,600 to 2,300 mm. The wet and relatively warm climate results in a coastal rain forest that is dominated by Douglas fir, western hemlock, red alder, and a variety of understory shrubs. Trees are harvested throughout the study area, usually through commercial clear-cut operations.

The area is underlain by Tertiary marine sandstones and siltstones of the Tyee Formation (Walker & McLeod, 1991; Ma *et alii*, 2009). The rocks are gently folded and have a slight westward dip (Kelsey *et alii*, 1996). The drainage network is dense, with a dendritic pattern (e.g., May, 2002) that has often been characterized as highly dissected (e.g., Benda, 1990). Hillslopes (Fig. 2) are short, steep (20-40º), and typically mantled by 0.5 to 3 m of colluvial soil (Reneau & Dietrich, 1991; Montgomery *et alii*, 2002).

Debris flows typically mobilize from slides in concave hillslope areas, and increase in volume by erosion and entrainment of downslope channel sediment (Fig. 2) before depositing material in higher order drainage channels and fans (Benda & Cundy, 1990). Debris flows in 1996 were triggered by about 230 mm of rainfall between November 17 and November 20. Even though debris flows occurred relatively early in the fall/winter wet season, antecedent rainfall in the study area was well above the threshold of 100-280 mm suggested by Wiley (2000). Rainfall in the area between Oct. 1 and November 17, 1996 was about 440 mm. Based on inventory mapping of the November, 1996 debris flows, our best estimate is that about 95% of debris flows in the study area entrained sediment and wood from downslope channels.

METHODS

We used debris-flow inventories and bare-earth LiDAR data to examine topographic and drainage network characteristics of debris-flow initiation locations in both study areas. In California, debris flows were mapped as single polygons that included slide initiation locations, travel paths, and deposition areas from 12:000-scale aerial photographs acquired in May, 1998 (Coe *et alii*, 2004) (Fig. 1). In Oregon, debris flows were mapped from 12:000-scale aerial photographs taken in May, 1997. Unlike California, mapped debris flows in Oregon were divided into two types of polygons, source areas (including slide initiation locations, travel paths, and areas of erosion and entrainment, see Coe *et alii*, 2011 for details) and areas of deposition (Fig. 1). Debris flows in both areas were mapped onto 1:24,000-scale USGS quadrangle maps enlarged to 1:12,000-scale.

Airborne LiDAR data were acquired in California in 2006 and in Oregon in 2008. In California, LiDAR data had an average ground-point spacing of 1.4 m (0.5 points/m^2) and were gridded to a 1.52 m (5 ft.) cell size. In Oregon, LiDAR data had an average density of 0.6 points/m^2 for ground-classified points. Ground-classified data were gridded to a 0.91 m (3 ft.) cell size.

Our analysis consisted of the following steps: 1) transferring and registering inventory data to the LiDAR topographic base, 2) identifying accurate debris-flow initiation locations on the LiDAR base, 3) measuring the travel distance of each flow, 4) determining local slope, upslope contributing area, and planform curvature for each initiation location, 5) identifying the distance from initiation locations to local drainage network, and 6) analyzing the topographic and drainage network characteristics of initiation locations. Below, we discuss our methods for each of these steps.

The process of transferring and registering mapped debris flows to LiDAR-based maps was difficult because the topographic details visible in the LiDAR were often not visible in, or were different from, the more generalized quadrangle-based topography. Nevertheless, when transferring mapped debris flows to the LiDAR bases, we attempted to maintain their original shapes and sizes. Travel distance lengths were not affected during the transfer process, and debris flow widths were minimally affected. However, in many instances, we had to adjust the locations of debris flows, particularly along channels (sometimes by much as 25 m (about 2 mm at 1:12,000-scale)), to properly fit the LiDAR topography.

To determine initiation locations for debris flows, we selected single points located at the approximate center of each slide headscarp. Horizontal travel distances for each flow were measured along the approximate centerline of the flow, progressing from the initiation locations, to the downslope end of the flow. Some debris flows had multiple initiation locations that contributed material to the flow. In these cases, travel distances were measured from each initiation location until they intersected, at which point the remaining downslope distance was measured along the single combined flow path. We extracted slope, upslope contributing area, and planform curvature from the LiDAR DEM grid cell at each initiation location using functions within ESRI's (Environmental Systems Research Institute) ArcMap GIS. Positive planform curvature values indicate a convex (divergent) slope, whereas negative curvature values indicate a concave (convergent) slope.

Determining distances from initiation locations to the drainage network required defining the drainage network for each area. We defined the upslope most extent of the network (i.e., the approximate location of channel heads) using a DEM analysis technique. We first evaluated the drainage density of 2-3 large basins (Figs. 1 and 3) in each DEM. Drainage density is defined as the total length of drainages per unit area. To determine drainage density, we utilized D8 flow direction algorithms (Jenson & Domingue, 1988) implemented in ArcMap to determine flow direction, flow accumulation, and total length of drainages. The total length of drainages was then summed and divided by the drainage area for each of the large basins.

Using these drainage densities, we identified contributing area values where densities rapidly increased, or “feathered” indicating that the local DEM topography was no longer convergent. Feathering occurred when computed drainage paths extended onto planar or divergent hillslopes. We found that contributing areas for this feathering effect for California and Oregon were 2000 m^2 and 1500 m^2, respectively (Fig. 3). These values are similar to those determined by previous work in the San Francisco Bay region (Montgomery & Foufoula-Georgiou, 1993) and the Oregon Coast Range (Miller, 2008).

The contributing area upslope of actual channel heads in a region can be quite variable and a function of both topographic, and non-topographic factors (Montgomery & Dietrich, 1992; Wilson & Gallant, 2000; Tarboton & Ames, 2001). Precise channel head

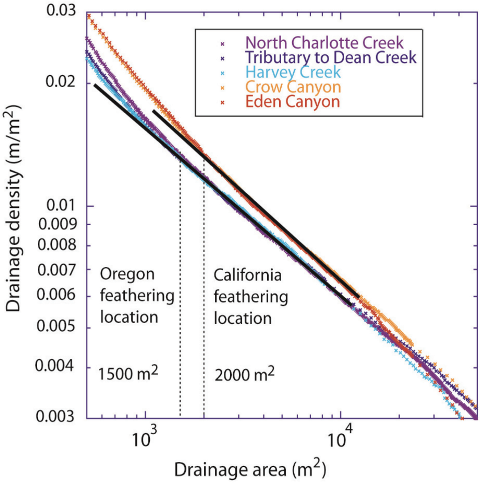

Fig. 3 - *Diagram showing drainage density analysis for the California and Oregon study areas. Drainage areas where feathering occurs (approximate limit of drainage network) are shown*

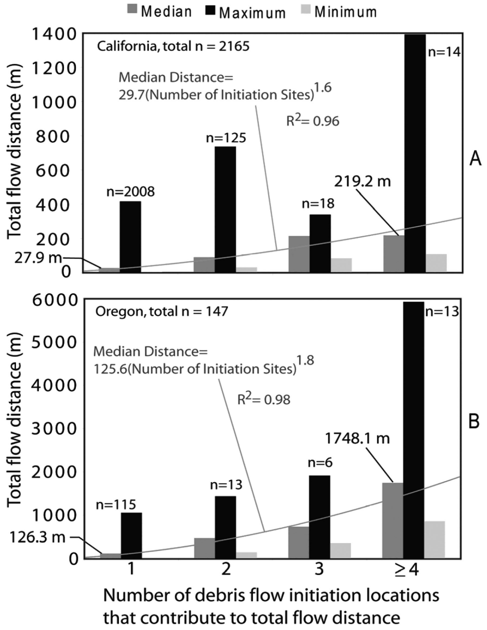

Fig. 4 - *Travel distances of debris flows as a function of the number of initiation locations contributing to the flow. Curves show power-law fits to the median data. A) California. B) Oregon. Travel distances of many flows in Oregon could not be measured because they extended to areas outside the coverage of the inventory map*

locations in each individual basin cannot be determined without extensive fieldwork, which is impractical in large study areas. However, by using the density analysis approach, we were able to objectively determine overall drainage networks.

Once the drainage networks were established, we measured distances from debris-flow initiation locations to the network. These distances were determined by progressively accumulating distances along flow paths from initiation locations to the first intersection with the drainage network using the flow direction methodology of Tarboton (1997). A distance of zero means that an initiation location is within the defined drainage network. Throughout the text, we use the phrase "interact with the drainage network" to describe debris flows that either initiated within the network, or entered the network as they flowed downslope.

We analysed topographic and network characteristics using statistical techniques including histogram analyses, descriptive statistics, regression analyses, probability density analyses, and the Mann-Whitney U test for non-parametric data (Mann & Whitney, 1947). The Mann-Whitney U-Test is a non-parametric test of significance used to determine if differences between two groups of samples are significant. Probability values (p values) from the Mann-Whitney test indicate the probability that the two samples being compared would be truly different from a single large population. For example, a p value of 0.05 (5%) indicates that there is a 95% chance that the two populations are different. By convention, the typical critical value of p used to determine significance is 0.05 (i.e., the null hypothesis that the two groups are from the same population is rejected for p values less than 0.05).

RESULTS

DEBRIS-FLOW TRAVEL DISTANCE

Visually, there is a large difference in typical debris-flow travel distances between the two study areas (Fig. 1). Our travel distance measurements, when stratified by the number of contributing initiation locations, show that median distances for debris flows in Oregon were between 5 and 8 times longer than median distances for debris flows in northern California (Fig. 4). In California, median travel distances were 27 m for flows that originated from single initiation locations, and 219 m for flows that initiated from four or more initiation locations (Fig. 4). In Oregon, median travel distances were 126 m for flows that originated from single initiation locations, and 1748 m for flows that initiated from four or more initiation locations (Fig. 4).

In both study areas, there is a positive, power-law relation between median debris flow travel distance and the number of contributing debris-flow initiation locations (Fig. 4). In California, this relation is defined as $y=29.7x^{1.6}$, where y is median travel distance and x is number of contributing initiation locations. In Oregon, the relation is defined as $y=125.6x^{1.8}$. This same relation holds for maximum and minimum travel distances in Oregon (Fig. 4A), and for minimum travel distances in California (Fig. 4A). Maximum distances in California appear to vary from this pattern (Fig. 4A), but the lack of observed debris flows (<2% of the total number) with more than 2 initiation locations may bias the results.

SLOPE, CONTRIBUTING AREA, AND CURVATURE CHARACTERISTICS OF INITIATION LOCATIONS

There are distinct differences in the slope, contributing area, and planform curvature values of debris-flow initiation locations in California and Oregon (Figs. 5 and 6). In general, Oregon initiation locations have steeper and more convergent slopes with larger upslope contributing areas than initiation locations in California (Figs. 5 and 6). The median slope and upslope contributing area of initiation locations in Oregon are 38° and 1529 m^2, respectively (Fig. 5). In California, the median slope and upslope contributing area of initiation locations are 28° and 42 m^2, respectively. In Oregon, more than 41 percent of initiation locations have planform curvature values less than -10, whereas only about 1 percent of initiation locations in California have curvature values less than -10 (Fig. 6). The median curvature values of initiation locations in Oregon and California are -6.81 and -0.29, respectively.

Because these three topographic variables, and the lengths of travel distances, were distinctly different for the two study areas, we tested each variable as a possible predictor of travel distance using regression analyses. For these analyses, we only used debris flows with single initiation locations. We did not find any significant positive or negative correlation between travel distance and any of the topographic variables, commonly used to identify initiation sites, in either study area.

We investigated the topographic variables further by grouping travel distances of flows from single initiation locations according to important topographic threshold values. For example, travel distances were grouped according to slope values at initiation locations, one group from locations with slopes ≤ 20° and one group from locations with slopes > 20°. Other slope thresholds used were 25º, 30º and 35º. The threshold value used for planform curvature was 0 (convergent vs. divergent slopes) and the threshold values used for contributing area were 2000 m^2 and 1500 m^2 for California and Oregon, respectively. Mann-Whitney U tests of these groupings showed that only contributing area discriminated between different travel distances in both study areas. Travel distances were significantly ($p=0.001$ in California and 0.029 in Oregon) longer for flows that initiated from locations with contributing areas greater than threshold values compared to those that initiated from locations with contributing areas less than the threshold values. In general, Mann-Whitney tests of groups based on slope and planform curvature values did not yield significantly different travel distances. One exception was curvature in California. Here, convergent initiation locations (curvature < 0) produced longer

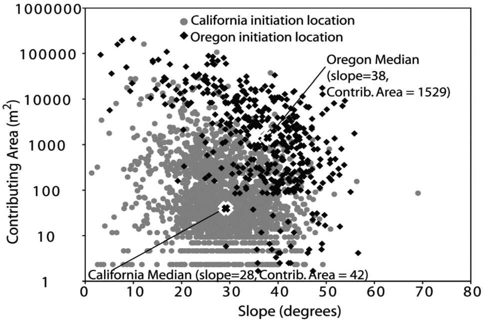

Fig. 5 - Diagram showing slope and contributing area characteristics of initiation locations (landslide headscarps) in California and Oregon. Number of initiation locations was 438 in Oregon and 2400 in California

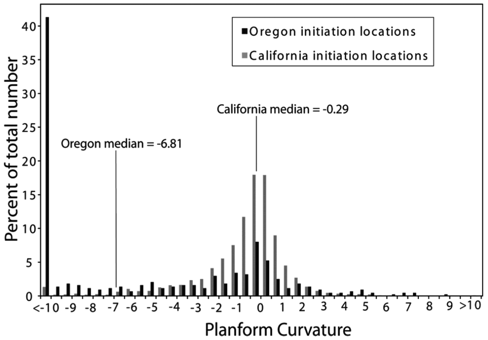

Fig. 6 - Histogram showing planform curvature characteristics of initiation locations in California and Oregon. Number of initiation locations was 438 in Oregon and 2400 in California

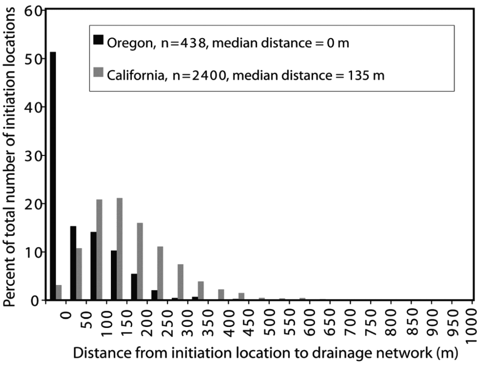

Fig. 7 - Histogram showing distance from initiation locations to drainage network in each study area. Distance values of zero are from sites that initiated within the drainage network. Number of initiation locations was 438 in Oregon and 2400 in California

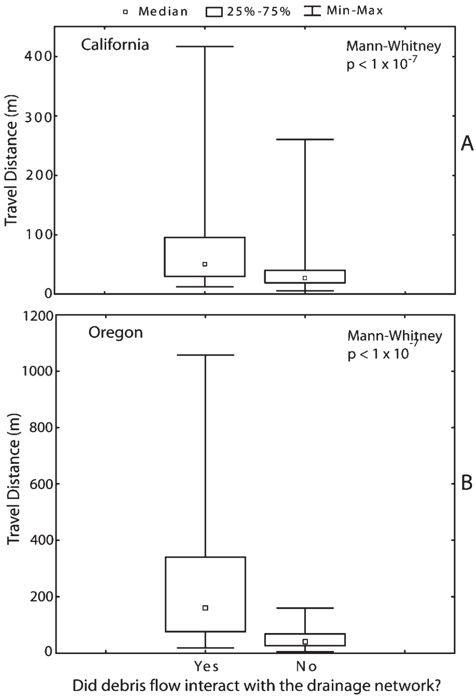

Fig. 8 - Box and whisker plots showing travel distance data, grouped with respect to whether the flows interacted with the drainage network, for debris flows from single initiation areas. A) California. 179 flows interacted with the drainage network, 1829 did not. B) Oregon. 89 flows interacted with the drainage network, 26 did not

(p=0.002) travel distances than planar or divergent topography (curvature ≥ 0). None of the topographic variables were useful for forecasting whether or not flows would interact with the drainage network.

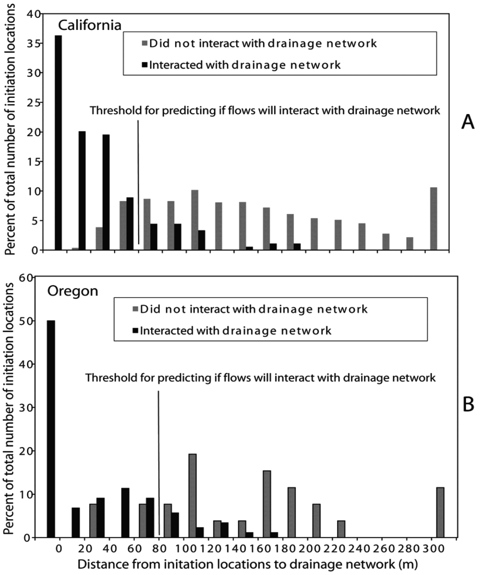

Fig. 9 - Histograms showing distance from initiation locations to drainage network, grouped by whether or not debris flows interacted with the drainage networks. Distance values of zero are from initiation locations within the drainage network. Only flows with a single initiation location are shown. A) California. 2008 flows. B) Oregon. 115 flows

PROXIMITY TO DRAINAGE NETWORK

The proximity of initiation locations to the drainage network was distinctly different for the two study areas (Fig. 7). In Oregon, 52% of debris flow initiation locations were within the drainage network, and the overall median distance to the network was 0. In California, only 3% of initiation locations were within the drainage network and the median distance to the network was 135 m (Fig. 7). In Oregon, the distribution of initiation location proximity is approximately log normal and decreases as distance to the drainage network becomes larger. In California, the distribution of initiation location proximity is approximately normal about a mean of 156 m.

We investigated our distance to drainage network data further by grouping travel distances according to whether or not debris flows interacted with our defined drainage networks. Using Mann-Whitney U tests we found that the travel distances of flows that interacted with the drainage networks were significantly ($p < 1x10^{-7}$) longer than flows that did not (Fig. 8). Using our proximity to drainage network data, we selected a generalized threshold for forecasting whether or not flows would reach the drainage network in each study area (Fig. 9). These thresholds correspond to distance

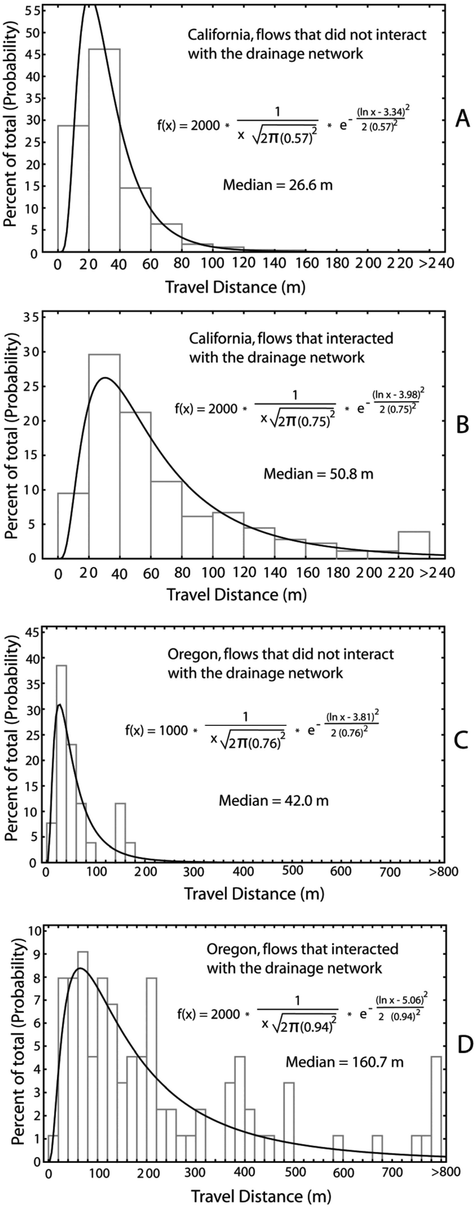

Fig. 10 - Probability density functions for debris-flow travel distance data, grouped by whether or not debris flows interacted with the drainage network. Log normal equations are shown. A) California flows, n= 1829. B) California flows, n= 179. C) Oregon flows, n= 26. D) Oregon flows, n= 89

values where about 85% of flows that entered the channel were less than the threshold, and 85% that did not enter the channel were greater than the threshold. The thresholds for entering the networks are 60 m in California and 80 m in Oregon.

Probability density functions (pdfs) of travel distances for flows that interacted with the drainage networks, and for those that did not, are shown in Fig. 10. For both study areas, log normal pdfs provide good fits to the observed data. In a predictive sense, these functions could be used in combination with Fig. 9 to estimate the distribution of travel distances in each study area.

DISCUSSION

Predictive maps and models of debris-flow initiation locations, probability of occurrence, entrainment potential, expected volumes, and travel distances are critical to the efficient management of debris-flow hazards (e.g., Baum *et alii*, this volume), yet high-quality data sets from natural debris flows that are needed to support these maps and models are relatively rare (e.g., McCoy, *et alii*, this volume; Staley *et alii*, this volume). Our results, using high quality debris-flow inventory maps and recently available LiDAR data, show that there are distinct differences in the topographic and drainage network characteristics of debris-flow initiation locations of our two study areas. However, only three variables, the number of contributing initiation locations (Fig. 4), contributing area, and distance from initiation locations to the drainage network (Figs. 8-10), were useful for estimating debris-flow travel distances. Slope and planform curvature of initiation locations could not consistently predict travel distance.

The positive correlation between number of initiation locations and travel distance reinforces the concept that flow volume is a primary factor controlling travel distance, but it also indicates that the number of contributing initiation locations may be used as crude proxy for volume. The regression equation for Oregon applies to flows where volume increased from entrainment, whereas the equation for California applies to flows with minimal entrainment. These relations suggest that similar equations could be developed for other geographic areas.

Results from our analysis of contributing area and distance from initiation locations to the drainage network indicate that distance from initiation locations is the better predictor of travel distance ($p \geq 0.001$ for contributing area vs. $p < 1x10^{-7}$ for distance from initiation locations). Distance from initiation locations to the drainage networks is also a good indicator of the likelihood of debris flows interacting with the drainage network (Fig. 9). Our statistical analyses show that flows which interact with the network generally travel farther than flows that do not (Figs. 8 and 10). This effect is likely related to the availability of surface water and readily erodible sediment in drainage networks. In contrast, these effects are subdued on hillslopes. Based on field work in Oregon, most small, steep drainage basins where slides initiate contain steep-walled channels with perennial surface water flow and channel sediments that are typically saturated, especially in the winter wet season when debris flows are likely. Springs are common at and near channel heads throughout the year. In our northern California study area, most debris flows do not initiate in the drainage network and the flow of surface water at initiation locations is rare, at least prior to failure. Here, shallow slides are triggered by positive pore-pressure pulses (Johnson & Sitar, 1990) that may or may not reflect the moisture level of downslope surficial sediments. Recent work at the USGS experimental debris-flow flume in Oregon shows that the potential for sediment entrainment by debris flows is positively correlated with the moisture content of the bed sediment (Reid *et alii*, this volume); in these experiments entrainment of wetter sediment enhanced travel distance whereas entrainment of drier sediment retarded flow, and it follows that flows that entrain sediment have larger volumes and may travel greater distances than flows that do not.

CONCLUSIONS

We analyzed two separate, large-scale, debris-flow data sets from the west coast of the U.S. using high resolution LiDAR data. Both data sets, one from northern California and the other from southern Oregon, record precipitation triggered debris flows. In both areas, debris flows mobilized from slides, but entrainment and travel distances of the flows differed markedly. In California, debris flows did not entrain material and had relatively short travel distances. In Oregon, nearly every flow entrained material and median travel distances were 5 to 8 times longer than those in California.

Our results show that there are distinct differences in the topographic and drainage network characteristics of debris-flow initiation locations in the two study areas, but that only three variables were useful for estimating debris-flow travel distances: the number of contributing initiation locations (Fig. 4), contributing area, and distance from initiation locations to the drainage network (Figs. 8-10). A positive, power-law relation exists between median debris flow travel distance and the number of contributing debris-flow initiation locations. For the events we studied, this relation is defined as $y=29.7x^{1.6}$ in California and $y=125.6x^{1.8}$ in Oregon, where y is median travel distance and x is number of contributing initiation locations.

In both study areas, our analyses showed that flows which interacted with the drainage network flowed farther than flows that did not. We used distance to drainage network data for specific triggering events to establish a distance threshold to classify which flows (that begin from single initiation locations) will enter the network. The threshold is 60 m in California and 80 m in Oregon. Sources closer than these values will likely enter the network, whereas flows from farther away will not. Log normal probability density functions of travel distances differ significantly for flows that interact with the drainage network, compared to flows that do not. These density functions could be used to estimate travel distances of flows from single initiation locations in the two study areas.

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