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IMPLEMENTATION OF POST-FIRE DEBRIS-FLOW HAZARD ASSESSMENTS ALONG DRAINAGE NETWORKS, SOUTHERN CALIFORNIA, U.S.A.

Joseph E. GARTNER(*), Susan H. CANNON (*) & Paul M. SANTI (**)

(*)U.S. Geological Survey
(**)Colorado School of Mines

ABSTRACT

Burned watersheds in Southern California steeplands can be particularly susceptible to debris flow. Rapid assessments of potential debris-flow hazards following a fire are necessary to provide timely information to the public, land managers, and emergency-response agencies about locations most prone to debris-flow impact. Here we present a method to implement a set of existing debris-flow susceptibility models along a drainage network using input variables that are quantified for the contributing drainage basin areas to each grid cell along a drainage network. This method accounts for the spatially variable properties within contributing drainage basin areas as debris flows travel through the drainage network. Applying the models along drainage networks, rather than to an entire drainage basin, provides hazard assessments that identify the potential impacts within the primary channels of a watershed, where destructive debris flows may both erode and deposit large volumes of material.

Key words: *debris-flow susceptibility, post-fire erosion, drainage networks, continuous variables*

INTRODUCTION

Empirical models that provide estimates of the probability and magnitude of post-fire debris flows are currently used to assess hazards from recently burned drainage basins in southern California (e.g. Cannon *et alii,* 2009; Cannon *et alii*, 2010), and the intermountain western USA (Stevens *et alii,* 2008; Cannon *et alii*, 2010). These multi-variate models estimate probabilities and volumes of debris flows using combinations of predictive variables that describe the extent and severity of fire within a drainage basin, the drainage basin morphology and soil characteristics, and storm rainfall characteristics. These models are specific to particular geographic regions and fire regimes. Some models can be used to estimate debris-flow susceptibility within the first few years following a fire (e.g. Gartner *et alii*, 2008; Cannon *et alii,* 2009; 2010), and some models define time-dependent factors to quantify the diminishing effect of fire on debris-flow susceptibility, allowing the model to be applied over a range of timescales following a fire (e.g., Gatwood *et alii*, 2000; Gartner *et alii*, 2009).

The multi-variate, debris-flow susceptibility models are presently implemented in a geographic information system (GIS) by identifying specific drainage basin outlets, and then extracting the measures of the model input variables for the drainage basin areas upstream from the drainage basin outlets. These measures, along with specified design storm rainfall conditions, are then used to estimate the probability and volume of debris flow for each identified drainage basin outlet (Fig. 1). Although this approach can be used to identify debris-flow susceptibility for specific locations, it provides only a single estimate for each drainage basin, and thus does not reflect the range of debris-flow hazards that may exist upstream of the

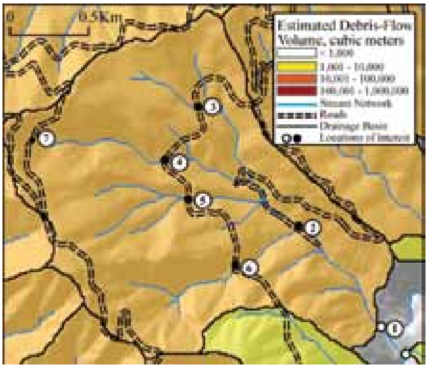

Fig. 1 - Map showing results from a drainage-basin wide approach for implementing a model for estimating post-fire debris-flow volumes. This map shows estimated debris-flow volumes expected at drainage basin outlets (open circles) as a function of model input variables obtained for each drainage basin. Debris-flow volumes at additional locations (solid circles), for example, at road crossings within the drainage basin, are not identified. The gray area represents the inter-basin area for which hazard information is also not obtained

drainage basin outlet. Debris-flow impacts within a drainage basin will be greatest in the channels through which a debris flow travels, eroding and depositing material, and on the fan below the drainage basin outlet where material is deposited. In addition, if assessments of debris-flow probability and volume are needed for multiple locations along a channel, then the process of identifying each drainage basin outlet, delineating drainage basins, and obtaining measures for the input variables used in the models is labor intensive and time-consuming. Last, this approach identifies debris-flow hazards only in flow-accumulating terrain, so that hazards in inter-basin areas are not assessed, as in Fig. 1.

OBJECTIVES AND APPROACH

We present a new method for implementing debris-flow susceptibility models that better characterizes potential hazards within recently burned areas than the present drainage-basin wide approach. With this new method, termed the continuous variable method, we generate sets of continuous variable grids to implement the debris-flow susceptibility models along the drainage network. The continuous variable grids provide measures of the model input variables for each grid cell along a drainage network based on the upstream conditions (Fig. 2). These continuous variable grids are then used as input to the susceptibility models to generate estimates of debris-flow probability and volume for each grid cell along the drainage network. Ranked output from the debris-flow volume and probability models are added together to generate a combined relative debris-flow hazard ranking.

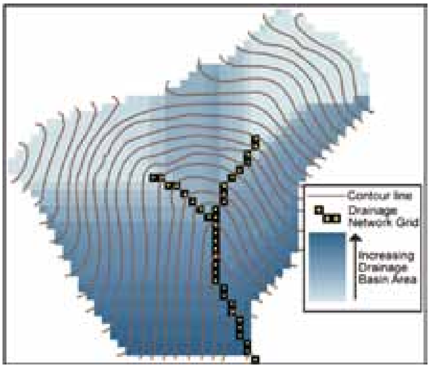

Fig. 2 - Schematic illustration of the continuous variable method, where grids of continuous variables are defined for each contributing area to each grid cell along the drainage network. The size of each contributing area increases with distance downstream

The application of debris-flow susceptibility models along drainage networks allows for a spatially specific assessment of potential debris-flow susceptibilities within a burned area. Maps that identify hazardous locations within the drainage network may be used to help guide post-fire debris flow mitigation plans and plan emergency evacuation routes. Further, such an application provides a means to estimate how debris-flow volumes change as they travel down drainage networks.

In this paper, we describe the basis and form of existing debris-flow susceptibility models, followed by a discussion of the process used to generate the continuous variable grids used as data input to the models. We then present results of an assessment for a hypothetical drainage basin. Within this basin, we identify several locations within the drainage network where estimates of debris-flow probability, debris-flow volume, and combined relative debris-flow hazard ranking could be beneficial. This example demonstrates how the continuous variable approach for applying debris-flow susceptibility models provides spatially specific information on debris-flow susceptibilities within a burned drainage basin.

As more data becomes available and the understanding of post-fire debris-flow processes increases, the empirical debris-flow susceptibility models are frequently updated. As a result, the predictive variables in the models, and their coefficients, may change. In this paper we provide a framework to implement a generic set of debris-flow susceptibility models along drainage networks using continuous variable grids so that the approach will be applicable to both existing and future models.

BACKGROUND

Existing models for characterizing post-fire, debris-flow susceptibility have been generated from databases consisting of measures of debris-flow volumes and observations of debris-flow occurrence as the dependent variables, and independent variables that characterize drainage basin morphology, soil conditions, the extent and severity of the fire, and storm rainfall conditions (e.g., Gartner *et alii*, 2008; Rupert *et alii*, 2008; Gartner *et alii,* 2009; Cannon *et alii*, 2010). Each measure of debris-flow volume or observation of debris flow is associated with both a single drainage basin for which the independent variables are defined and a single storm rainfall event.

The databases used to generate the debris-flow susceptibility models include information compiled from drainage basins with areas between 0.01 km^2 to 30 km^2 (Gartner *et alii*, 2005; Gartner *et alii*, 2008; Rupert *et alii,* 2008; Gartner *et alii*, 2009; Cannon *et alii*, 2010). Measurements of debris-flow volume and observations of debris-flow occurrence were made along drainage networks at channel confluences or road crossings, at the mouth of the drainage basin, or at locations along first order channels where single debris-flow paths were identified (Gartner *et alii*, 2008; Santi *et alii*, 2008). Because these measurements and observations were made at positions throughout drainage networks with drainage basin areas between 0.01 and 30 km^2, we consider the models to be applicable to any location along a drainage network within this range of basin areas. Increased erosion due to wildfire is most pronounced within the first two to three years following a fire and so these models are temporally applicable to this time period (Cannon *et alii,* 2010).

MODELS FOR ESTIMATING DEBRIS-FLOW VOLUMES

Debris-flow volumes were measured either as the amount of material removed from the main channels within a drainage basin, or as the amount of material deposited in debris-retention basins, and range between 300 and 1,000,000 m^3 (Gartner *et alii,* 2008; Cannon *et alii*, 2010). Independent variables associated with each volume measurement include the drainage basin relief, the length of the longest flow path within the drainage basin, the drainage basin area with gradients greater than or equal to 30 percent, several measures of soil physical properties, the basin area burned at high, moderate, and low severity, total triggering storm rainfall, storm duration, and measures of peak rainfall intensity at different durations. The data used to define the independent variables include 10-m resolution DEMs and burn severity grids, 1:250,000 scale soil maps, and tipping bucket rain gage data collected in the field

Multiple linear regression analyses of the databases were used to generate models that relate debris-flow volume to a set of predictor variables with the form;

$$V = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \ldots\ldots \alpha_i x_i \quad (1)$$

where *α* are coefficients and *x* are variables, and i is the number of variables used in the model (Helsen & Hirsch, 2002). The variables selected in the analyses provide the best model for a given dataset based on multiple linear regression statistics (adjusted r^2, residual standard error, etc.) and the ability to predict debris-flow volume from an independent test dataset (Gartner *et alii*, 2008). In general, each model includes at least one variable that characterizes the effects of drainage basin morphology, soil properties, burn severity, and storm rainfall on debris-flow volume. The volume model presented in Cannon *et alii* (2010) has an R^2 of 0.83 and a residual standard error of 0.90. In addition, the model predicted 87 percent of debris flow volumes from a test dataset to within an order of magnitude.

MODELS FOR ESTIMATING DEBRIS-FLOW PROBABILITY

Models that predict the spatial probability of debris-flow occurrence were developed using logistic multiple regression analyses of databases that link observations of debris-flow presence or absence with independent variables similar to those described above (Rupert *et alii*, 2008; Cannon *et alii,* 2010). The probability of debris flow (P) is characterized as:

$$P = e^x/(1 + e^x),$$

where

$$x = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots \beta_i x_i, \quad (2)$$

In this case, β are logistic regression coefficients, x are values for the predictor variables, and i is the[3] number of variables in the model (Hosmer & Lemeshow, 2000). The variables selected in the analyses provide the best model for a given dataset based on logistic regression statistics (Rupert *et alii,* 2008; Cannon *et alii*, 2010). As above, each model includes at least one variable that characterizes the effects of drainage basin morphology, soil properties, burn severity, and storm rainfall conditions on the probability of debris-flow generation.

The best probability model is identified using McFadden's ρ^2, which is a similar measure to R^2 used in linear regression but with acceptable values ranging from 0.2 to 0.4. Additionally, model sensitivity can be evaluated based on the percent of debris flow occurrences correctly identified with a probability greater than 50 percent. The probability model developed by Cannon *et alii* (2010) has a McFadden's ρ^2 of 0.35 and a model sensitivity of 44 percent.

COMBINED RELATIVE DEBRIS-FLOW HAZARD RANKING

Because of uncertainties associated with the debris-flow volume and probability estimates, Cannon *et alii* (2010) recommended that, rather than presenting estimates with several significant figures, each estimated debris-flow volume and probability be assigned to a class rank between 1 and 4. Estimated debris-flow volumes less than 1000 m^3 are assigned a class rank of 1, volumes between 1001 and 10,000 m^3 are assigned to class 2, volumes between 10,001 and 100,000 m^3 are assigned to class 3, and volumes greater than 100,000 m^3 are assigned to class 4. Further, estimates of debris-flow probabilities less than 25 percent are assigned to class 1, probabilities between 26 and 50 percent are assigned to class 2, probabilities between 51 and 75 percent are assigned to class three, and probabilities between 76 to 100 percent are assigned to class four.

Debris-flow hazards from a given basin can be considered as the combination of both probability and volume, with the most hazardous basins being characterized by both a high probability of occurrence and a large estimated volume of material. The least hazardous basins are characterized by both low probabilities and the smallest volumes. In between these extremes are basins that are characterized by a combination of either relatively low probabilities and larger volume estimates or high probabilities and smaller volume estimates. Due to the different combinations of low to high debris-flow volumes and probabilities, Cannon *et alii* (2010) suggested that, for a given basin, the debris-flow volume and probability rankings be added together to generate a "combined relative debris flow hazard ranking", with the lowest values representing the least hazardous basins, and the highest values representing the most hazardous basins. These two suggestions are followed in this paper to provide a single hazard assessment in addition to the individual debris-flow volume and probability estimates.

METHODS

To implement debris-flow susceptibility models along drainage networks, a set of continuous variable grids are generated that provide measures of each of the necessary independent variables for each grid cell in a DEM. Independent variables used in the debris-flow susceptibility models can be divided into four categories: 1) measures of the drainage basin area that meet a particular criteria (e.g., drainage basin area with gradients greater than or equal to 30 percent), 2) measures of the percentage of the drainage basin area that meet a particular criteria (e.g., the percentage of the drainage basin area burned at moderate and high severity), 3) measures of average values of the drainage basin area (e.g., average gradient of the drainage basin area), and 4) measures of the drainage basin morphology (e.g., drainage basin relief, ruggedness, and length of the longest flow path within the drainage basin). Each of these different types of variables can be determined for each grid cell located along the drainage network using DEMs, binary grids, integer grids (e.g., a gradient or burn severity grid) and hydrology algorithms available in a GIS.

A flow-direction grid is generated from a DEM using an eight direction flow model (Jenson & Domingue, 1988) wherein each cell is coded to indicate the direction water will travel from the cell based on the greatest elevation change between adjacent grid cells. This grid is used to generate a flow-accumulation grid, which provides measures of the number of grid cells that flow into each grid cell. The flow accumulation grid can be weighted with another grid to create a grid where the value of each grid cell equals the upstream sum of values from the weight grid.

The flow-accumulation grid is multiplied by the grid cell area (e.g., 100 m^2 for a 10-m DEM), to generate a drainage basin area grid where each grid cell contains a measure of the contributing drainage basin area. The drainage network for a given area (Fig. 2) is then defined by converting the drainage basin area grid to a binary grid; values of one are assigned to those grid cells with drainage basin areas between 0.01 km^2 and 30 km^2 and values of zero are assigned to grid cells with values outside of this range.

In this paper we use ArcGIS (ESRI, 2008) and Rivertools (Rivix, 2001) software to implement the debris flow susceptibility models. Other software and hydrology algorithms may be used to implement the susceptibility models, however, this may potentially introduce error into the results.

GRIDS FOR MEASURES OF THE DRAINAGE BASIN AREA THAT MEET A PARTICULAR CRITERIA

To generate grids with measures of basin area that meet a particular criteria (e.g., drainage basin area with gradients greater than or equal to 30 percent), the flow-accumulation command is weighted with a binary grid with cell values equal to one for locations that meet the specific criteria and then multiplied by the grid cell area.

GRIDS WITH MEASURES OF THE PERCENTAGE OF THE DRAINAGE BASIN AREA THAT MEET A PARTICULAR CRITERIA

Grids with measures of the percentage of the drainage basin area that meet particular criteria are generated using a flow-accumulation command weighted with a binary grid that represents the unique criteria with values of one, dividing the output grid by a drainage basin area grid, and then multiplying this output grid by 100 to calculate a percentage value.

GRIDS FOR MEASURES OF THE AVERAGE VALUES OF THE DRAINAGE BASIN AREA

A grid of average values for the drainage basin area (e.g., the average drainage basin gradient) is created by weighting a flow-accumulation command with an integer grid (e.g., a gradient grid) and then dividing the output by a drainage basin area grid. This action divides the sum of the upstream values of the integer grid by the contributing drainage basin area.

GRIDS WITH MEASURES OF THE DRAINAGE BASIN MORPHOLOGY

Generating continuous variable grids that characterize drainage basin morphology (e.g. drainage basin ruggedness, drainage basin relief, and the length of the longest flow path within a drainage basin) require specific hydrology algorithms. The flow-length hydrology tool in the spatial analyst of ArcGIS (ESRI, 2008), with the upstream option, can be used to create a grid that represents the distance of the longest flow path within a drainage basin. A grid that represents the upstream relief can be determined using the Rivertools program (Rivix, 2001). The relief grid is used to calculate drainage basin ruggedness by dividing the relief grid by the square root of a drainage basin area grid (Melton, 1965). Other software may be used to generate these continuous variable grids, however the outputs should mimic the grids generated here to avoid introducing error into the model results.

CALCULATING DEBRIS-FLOW PROBABILITIES AND VOLUMES USING MAP ALGEBRA

Once the necessary continuous variable grids for the variables used in the debris-flow susceptibility models have been generated, map algebra (ESRI, 2008) is used to calculate debris-flow volumes and probabilities along the drainage network. Each continuous variable grid is used as the input variables in the map algebra expression, and the outputs are grids with cell values equal to the predicted debris-flow volume and probability, and combined relative debris-flow hazard ranking. These outputs are multiplied by a binary grid representing the applicable drainage network (between 0.01 and 30 $km^{2)}$ so that volume, probability, and combined relative hazard ranking are estimated only along the drainage network.

EXAMPLE OF A CONTINUOUS VARIABLE BASED HAZARD ASSESSMENT

Here we apply the debris-flow susceptibility models to a hypothetical watershed to illustrate their implementation in a continuous variable framework.

The watershed contains several locations where information on expected debris-flow hazards could be beneficial, including roads that cross the main channels. Debris-flow probabilities, volumes, and combined relative debris-flow hazard rankings are calculated along the drainage network, including the locations where the roads intersect the drainages. This example demonstrates how a land manager might use the debris-flow susceptibility models to identify locations where debris-flows impacts will be greatest. This information could be used for many applications; to identify the type of equipment needed to remove the material, to size culverts and debris-retention structures, and to determine if portions of the road are safe for travel during evacuations.

DEBRIS-FLOW VOLUME MODEL

For this example, we use a model for estimating the volume of debris-flow material expected along the drainage network as a function of the drainage basin area burned at all severities, the length of the longest flow path within a drainage basin, the drainage basin relief, and the peak 60-minute storm rainfall intensity The drainage basin area burned at all severities is generated as described previously by weighting a flow-accumulation command with a grid that represents burned grid cells with values of one, and zero for unburned. This grid is multiplied by the area of each grid cell (1×10^{-4} km$^{2)}$ to determine the upstream area burned at all severities in square kilometers. The length of the longest flow path within a drainage basin is determined using the flow-length command in ArcGIS spatial analysis, hydrology toolbox with the upstream option chosen (ESRI, 2008). The input for this command is a flow-direction grid, and the output is divided by 1000 to convert to units of kilometers. The drainage basin relief is determined using the relief command in Rivertools (Rivix, 2001).

These grids are used as the inputs for the debris-flow volume model using single output map algebra. A value of 10 mm/hr was chosen for a peak 60-minute rainfall intensity based on values used in a recent hazard assessment in southern California (Cannon *et alii*, 2009). The resulting grid from the map algebra represents the estimated debris-flow volume for each grid cell within the burned drainage network (Fig. 3).

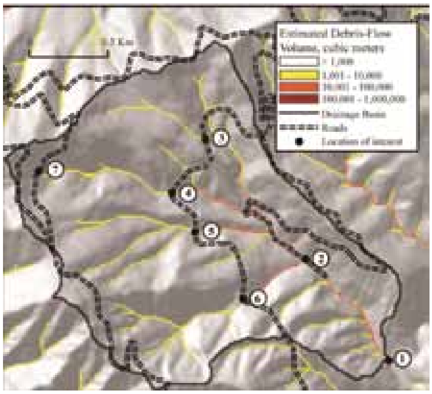

Fig. 3 - Potential debris-flow volumes calculated along a hypothetical burned drainage network in response to a 10 mm of rain in 1 hour. Debris-flow volumes increase with distance downstream and increasing drainage basin area

DEBRIS-FLOW PROBABILITY MODEL

In this example, debris-flow probability is calculated as a function of the percentage of drainage basin area with gradients greater than or equal to 30 percent, drainage basin ruggedness, the percentage of drainage basin area burned at moderate and high severity, the average clay content and liquid limit of soils within the drainage basin, and average storm rainfall intensity

As described above, the continuous variable grid for the percentage of the drainage basin area with gradients greater than or equal to 30 percent is generated using the flow-accumulation command, weighted with a binary grid consisting of values of one for gradients greater than 30 percent and values of zero for gradients less than 30 percent. The output of this command is then divided by a non-weighted, flow-accumulation grid and multiplied by 100 to determine the percentage of the drainage basin area with gradients greater than or equal to 30 percent. The grid with measures for drainage basin ruggedness is determined by dividing the relief grid, generated using Rivertools (Rivix, 2001), by the square root of a drainage basin area grid. The grids representing the average clay content and liquid limit of soils within the drainage basin are generated using flow-accumulation commands weighted with grids representing clay content and liquid limit derived from the USSOILS database (Schwarz & Alexander, 1995). The outputs of these operations are divided by a drainage basin area grid and multiplied by 100 to calculate percent values. A value of 10 mm/hr is chosen for an average storm rainfall intensity based

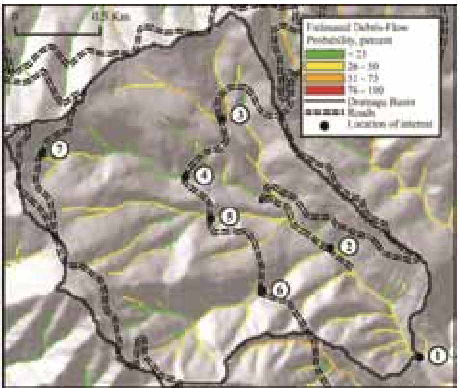

Fig. 4 - Debris-flow probabilities estimated along a burned drainage network in response to 10 mm of rain in one hour. Probabilities can both increase and decrease along the drainage network, reflecting changing conditions within contributing areas

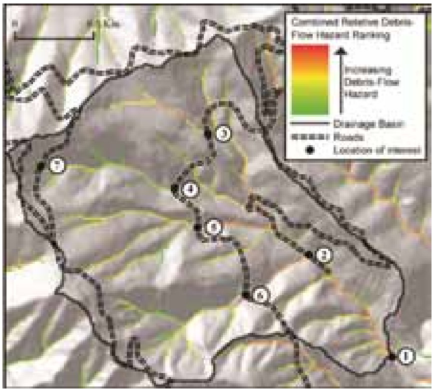

Fig. 5 - Combined relative debris-flow hazard rankings calculated along a burned drainage basin network. Rankings can both increase and decrease along a drainage network, reflecting changes in probability estimates associated with changing conditions within drainage basin areas

on a recent hazard assessment for southern California (Cannon *et alii*, 2009). These grids and average storm rainfall estimate are used as the inputs to the model which is processed using map algebra (ESRI, 2008). The resulting grid from the map algebra represents the debris-flow probability at each grid cell along the burned drainage network (Fig. 4)..

COMBINED RELATIVE DEBRIS-FLOW HAZARD RANKING

Combined relative debris-flow hazard rankings for the drainage network were calculated as the sum of ranked values of the estimated debris-flow volume and probability. These values ranged between 2 and 5 (Tab. 1). In addition, combined relative debris-flow hazard rankings were calculated for each of the locations of interest indicated on Figure 5 (Tab. 1).

Site	1	2	3	4	5	6	7
Volume (m^3)	60215	33264	4188	9189	9431	10388	899
Volume rank	3	3	2	2	2	3	1
Probability (%)	34	36	37	10	37	32	17
Probability rank	2	2	2	1	2	2	1
Combined rank	5	5	4	3	4	5	2

Tab. 1 - Debris-flow susceptibilities for locations of interest within a burned drainage basin

DISCUSSION AND CONCLUSIONS

Applying existing empirical debris-flow hazard assessment models along drainage networks provides additional information to basin-wide hazard assessments. This new method estimates debris-flow volumes and probabilities at all locations along the drainage network, where debris-flow impacts are most likely to be most significant. Implementation of this approach also eliminates the need to manually identify specific drainage basin outlets of interest, thus decreasing the time needed to generate emergency post-fire debris-flow hazard assessments. In addition, the combined relative debris-flow hazard ranking identified along the drainage network provides a single map output that identifies the locations most susceptible to debris-flow impacts.

The example application provided here demonstrates how debris-flow susceptibilities may vary at different locations along a drainage network in a burned area. The application of an existing model for post-fire debris-flow volume indicates that volumes will generally increase with distance down the drainage network, reflecting the addition of material from sequentially larger drainage basin areas, and more importantly, longer channel lengths (Santi *et alii,* 2008). This application characterizes the process whereby debris flows originating in lower-order portions of the drainage network will progressively increase in volume as they travel downstream. The rate of volume increase is a function of basin morphology, the extent and severity of the burned area, soil physical properties, and storm rainfall.

Estimates of the probability of post-fire debris flows indicate that debris-flow probabilities can both increase and decrease along the drainage network, reflecting changing conditions within drainage basin areas. Specifically, an area that is unburned or burned at low severity between locations 4 and 7 on Figure 3 results in a channel reach where debris-flow probability estimates decrease with distance downstream. The lower probability estimates result from the mitigating effects of unburned areas, and areas burned at low severity within the drainage basin. Similarly, the channel above location 3 on Figure 4 shows probabilities that increase and then decrease with distance downstream due to the effects of the drainage network passing through an area of lower gradients. These changes in debris-flow probabilities are also reflected in the map showing the combined relative debris-flow hazard ranking.

Maps generated using this approach can be used to identify hazardous locations within the drainage network, guide post-fire debris-flow hazard mitigation plans, and plan emergency evacuation routes. For example, these maps indicate that debris-flow impacts will be greatest at locations 1, 2, and 6, and the least at locations 7 and 4, thus providing information on where to focus post-fire channel erosion mitigation treatments. In addition, the maps show that roads crossing the upper reaches of the drainage are more suitable for an evacuation route, as opposed to the road that passes through locations 3 through 6.

The continuous variable approach presented here optimizes the predictive capability of debris-flow susceptibility models and provides more spatially specific information on potential debris-flow hazards following wildfire. Future research on how topography affects debris-flow processes of channel incision, transport and deposition will better identify where debris-flow incision and transport give way to debris-flow deposition.

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