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Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S.

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Abstract

Recently burned basins frequently produce debris flows in response to moderate-to-severe rainfall. Post-fire hazard assessments of debris flows are most useful when they predict the volume of material that may flow out of a burned basin. This study develops a set of empirically-based models that predict potential volumes of wildfire-related debris flows in different regions and geologic settings.

The models were developed using data from 53 recently burned basins in Colorado, Utah and California. The volumes of debris flows in these basins were determined by either measuring the volume of material eroded from the channels, or by estimating the amount of material removed from debris retention basins. For each basin, independent variables thought to affect the volume of the debris flow were determined. These variables include measures of basin morphology, basin areas burned at different severities, soil material properties, rock type, and rainfall amounts and intensities for storms triggering debris flows. Using these data, multiple regression analyses were used to create separate predictive models for volumes of debris flows generated by burned basins in six separate regions or settings, including the western U.S., southern California, the Rocky Mountain region, and basins underlain by sedimentary, metamorphic and granitic rocks.

An evaluation of these models indicated that the best model (the Western U.S. model) explains 83% of the variability in the volumes of the debris flows, and includes variables that describe the basin area with slopes greater than or equal to 30%, the basin area burned at moderate and high severity, and total storm rainfall. This model was independently validated by comparing volumes of debris flows reported in the literature, to volumes estimated using the model. Eighty-seven percent of the reported volumes were within two residual standard errors of the volumes predicted using the model. This model is an improvement over previous models in that it includes a measure of burn severity and an estimate of modeling errors. The application of this model, in conjunction with models for the probability of debris flows, will enable more complete and rapid assessments of debris flow hazards following wildfire.
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Keywords: Debris flow; Wildfire; Multiple regression; Hazard assessment

1. Introduction and previous work

Hazards related to wildfire can continue well after the flames are extinguished. Wildfires consume rainfall-intercepting canopy, litter and duff, leaving bare, unprotected soil that is more susceptible to erosion through rain

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splash and overland flow (Moody and Martin, 2001a,b; Meyer, 2002; Cannon and Gartner, 2005). The intense heat of a wildfire may create or enhance existing water repellent soils (DeBano, 1981; Doerr et al., 2000; Letey, 2001; Woods et al., 2006) that reduce infiltration and increase overland flow and erosion through the production of rills and channels (Wells, 1987). Infiltration of water into burned soils may also decrease because of the presence of fine ash, which expands when wetted and blocks pore spaces at the soil surface (Rompkins et al., 1990). When rain falls on a burned basin, these changes may result in catastrophic floods and debris flows (e.g., Cannon et al., 1998; Moody and Martin, 2001a,b; Cannon et al., 2003a; Parrett et al., 2003).

Debris flows in burned areas have been described as initiating from the progressive bulking of runoff with sediment eroded from the hillslopes and channels (Meyer and Wells, 1997; Parrett et al., 2003), from landslides (Morton, 1989; DeGraff, 1997; Schaub, 2001), or from a combination of the two processes (Cannon and Gartner, 2005). Progressive bulking develops as runoff travels through a network of rills and channels. Material is increasingly incorporated into the flow until enough has been entrained to impart the characteristics of debris flows to the runoff (Parrett, 1987; Meyer, 2002; Cannon et al., 2003a). A database containing information from 216 burned, debris flow producing basins indicates 161 debris flows initiated by progressive bulking, 25 initiated by landsliding, and 17 initiated by a combination of the two processes (Gartner et al., 2005).

With the ability to rapidly erode and transport large amounts of material, debris flows have the potential for massive destruction and may be the most hazardous consequence of wildfire-related erosion. Following the South Canyon fire in 1994, debris flows engulfed several cars traveling on I-70, sweeping two into the Colorado River, and causing many injuries. These debris flows crossed a four-lane highway and partially blocked the Colorado River (Cannon et al., 1998). Debris flows produced from the adjacent Coal Seam fire (August 2003) derailed a train, trapped a person in a car, and inundated several houses (Cannon et al., 2003a). Debris flows triggered by a December 25, 2003 storm in the Grand Prix and Old fire areas of southern California, killed sixteen people, destroyed numerous homes (Fig. 1), and cost an estimated $26.5 million for repairs and clean up (U.S. Army Corps of Engineers, 2005). These recent catastrophic debris flows indicate a need to improve our understanding of erosion processes following wildfire, and a demand for predictive models that provide critical information on the location and magnitude of these potential disasters.

Empirically-based models have been developed to predict the probability of occurrence of a debris flow and the magnitude of the response. Cannon et al. (2003b) used logistic multiple regression to create a model that describes the probability of the occurrence of a debris flow in a burned basin as a function of basin gradient, material properties, burned extent, and storm rainfall intensity. In addition, Cannon et al. (2003b) used multiple regression analyses to generate a predictive model for post-wildfire peak discharge of a debris flow that reflects material eroded from the hillslopes and channels. Although peak discharge is the standard indicator of flood magnitude, it can seldom be determined reliably for debris flows using indirect methods (Pierson, 2004). Magnitudes of debris flows are, therefore, better characterized using measures of total volume rather than peak discharge.

In southern California, debris retention basins are designed based on a multiple regression model that predicts sediment yields of floods and debris flows (Gatwood et al., 2000). This model is based on measurements of the rates of erosion on unburned hillslopes, and does not take into account the potentially large volume of material eroded from the channel by a runoff response. In a similar study, Johnson et al. (1991) used principal components and multiple regression analyses to model the magnitude and frequency of debris flows in southern California as a function of relief ratio, hypsometric index, drainage basin area, and the time interval between fires. This model does not describe volume as a function of rainfall characteristics and is based on small basins with areas less than 8 km^2. Both models evaluate the effects of wildfire based on the time since a basin was last burned rather than the extent and severity of fire within a basin.

New tools, methods, and models are needed to better estimate the range of potential volumes of debris flows generated from recently burned basins. Many workers have found that recently burned basins are likely to generate debris flows in response to even moderate rainfall (e.g., Meyer et al., 2001; Cannon et al., 2003b; Cannon and Gartner, 2005). Little existing research attempts to identify how volumes of debris flows relate to burn severity and rainfall characteristics. This occurs partly because of the difficulties associated with measuring the volume of a debris flow, burn severity, and rainfall. Few studies contain data on wildfire-related volumes of debris flows, and the quality of the existing data ranges from mere guesses to more precise surveys of deposit volume. Spatial variability of rainfall makes it difficult to measure the characteristics of rainfall that triggers debris flows, and burn-severity maps are not always made following wildfires.

Fig. 1. Photograph of a home buried by debris flows in Devore, California on Dec. 25, 2003.

The purpose of this study is to develop empirical models that can be used to predict volumes of debris flows. To improve upon current models, we suggest that volumes of debris flows be predicted as a function of a combination of variables that characterize basin morphology, burn severity, material properties and rainfall characteristics. The objectives of this study were to; 1) measure volumes of debris flows generated by burned basins, 2) measure a set of variables that may potentially influence the volume of a debris flow, 3) generate empirical models using multiple regression that predict potential volumes of wildfire-related debris flows in different settings, and 4) evaluate which models best predict volumes of debris flows based on statistical validity and predictive accuracy. The ultimate goal of this study is to develop models that can be used for hazard assessments immediately following wildfires.

2. Study areas

Characteristics of debris flows vary from region to region. To develop models that describe the volume of a debris flow in a variety of terrains, study sites were located in southern California, Colorado, and Utah (Fig. 2). All of the basins evaluated burned between 2002 and 2005. For all the basins, debris flows occurred within the first two years following the fire.

In California, the Gaviota fire burned in the Santa Ynez Mountain Range, which forms the western extent of the Transverse Ranges of southern California, and mostly consists of Tertiary and Quaternary marine sedimentary rocks (Diblee, 1981). The Grand Prix fire burned in the San Gabriel Mountains and the Old fire burned in the San Bernardino Mountains. These mountains are also part of the Transverse Ranges in southern California and are composed of highly fractured, weathered and faulted coarsely crystalline igneous and metamorphic rocks with smaller extents of sedimentary rocks (Bortugno and Spittler, 1998). The Paradise and Cedar fires burned just east of San Diego in the Peninsular Ranges of southern California, which are dominantly underlain by crystalline plutonic rocks (Norris and Webb, 1990). Vegetation in the Transverse and Peninsular Ranges of California consists of chaparral, mixed hardwood, southern Oak and southern pine forests (Küchler, 1977). In southern California, rainfall usually comes from long duration, low intensity, frontal storms (Arkell and Richards, 1986).

The fires in Colorado and Utah were located in the foothills of the Rocky Mountains at elevations ranging from 1200 to 3000 m above sea level. The area burned by the Coal Seam fire, near Glenwood Springs, Colorado, is underlain by interbedded sandstones, siltstones and conglomerates, a gneissic quartz monzonite, quartzite and smaller extents of dolomite, dolomitic sandstone, shale and limestone (Kirkham et al., 1997). These rocks are part of the Grand Hogback monocline, which separates the vertically uplifted, southern Rocky Mountains to the east and the flat-lying, gently folded Colorado Plateau to the West (Kirkham et al., 1997). The Missionary Ridge fire burned near Durango, Colorado, and rock types within the burned area are interbedded sandstones, siltstones, shales, conglomerates, limestones

Fig. 2. Map showing the locations of burned areas examined in this study.

and small extents of granite (Carroll et al., 1997; Carroll et al., 1998; Carroll et al., 1999; Gonzales et al., 2002). The Overland fire burned in the foothills of the Front Range in Colorado and is underlain by Lyons formation sandstone and older granitic rocks uplifted by the Laramide Orogeny (Bilodeau et al., 1988).

Two wildfires during 2002 and 2003 burned approximately 40 km^2 of steep terrain along the Wasatch front near Salt Lake City, Utah (McDonald and Giraud, 2002). The Mollie fire burned near Santiaquin, Utah. This area is heavily faulted, resulting in a complex assemblage of Precambrian quartzites, sandstones, siltstones, schist, gneiss and amphibolite with local intrusions of pegmatite and granite dikes, and smaller extents of Cambrian dolomites, limestones and shales. These rocks are overlain by Mississippian limestones and sandstones with thin layers of shale and dolomite (Witkind and Weiss, 1991). The Farmington fire burned near Farmington, Utah and underlying rock types consist of Precambrian schist and gneiss with pegmatite dikes and sills (Bryant, 1990). Local deposits of alluvium, colluvium and mass movements are present in all of the field areas. Vegetation in Colorado and Utah includes pinyon pine and juniper woodlands, mountain shrublands and aspen, ponderosa pine, mixed pine, mixed conifer, Douglas fir and spruce-fir forests. Rainstorms in Colorado and Utah are typically short duration, high intensity convective thunderstorms (Arkell and Richards, 1986).

3. Methods

3.1. Volume estimation

Field-based estimates of the volumes of debris flows were determined by surveying a series of closely spaced channel cross-sections in each basin. Channel cross-sections were measured using a slope profiler, which is a 0.9 m length of wood with legs and an inclinometer

attached to measure the slope of the ground surface (Santi, 1989). The slope profiler was used to record angles across the surface of a channel in 0.9 m increments. From these data, a set of x and y coordinates were calculated to represent the geometry of a cross-section. While measuring each cross-section, notes were taken to identify which measurements corresponded to channel scour, bedrock and/or levees. Recently scoured surfaces in burned areas were easily identified because the marks left by the fire, such as burned soil, litter and duff, were removed by the passage of the debris flow. These notes were used to help reconstruct the original channel surface and to determine the amount of material removed from each cross-section.

Cross-sections were plotted in Grapher (Golden Software, Inc., 2004) and then imported into Canvas (ACD Systems of America, Inc., 2005) to determine the area of material removed. The slopes of the undisturbed hillslopes were projected into the scoured channels to draw polygons representing estimates of the amount of material removed from each cross-section by the passage of the debris flow (Fig. 3).

We interpolated the original channel surfaces of scoured channels as being v-shaped to consistently recreate the channel geometry. We observed several channels where debris flows had not occurred and found no consistent shape to these channels. Fig. 4 shows how this method adequately recreates a channel surface even if the channel was incised (i.e., not v-shaped) prior to the debris flow. The interpolated channel surface theoretically falls both above and below the original channel surface, and the areas above and below the interpolated channel surface are approximately equal and, thus, cancel each other out.

Channel cross-sections were measured at 15 to 100 m intervals along the length of scoured channels. The distance between cross-section measurements depended on the homogeneity of the channel reach. More cross-sections were measured in channels with high variability in channel morphology, and fewer cross-sections were measured where channel morphology was more consistent. The number of cross-sections measured in a basin ranged from 30 to over 200, depending on total channel length. On average, we measured about three cross-sections per 100 m of channel length. Scoured areas of two adjacent cross-sections were averaged and multiplied by the distance between cross-sections to define a volume

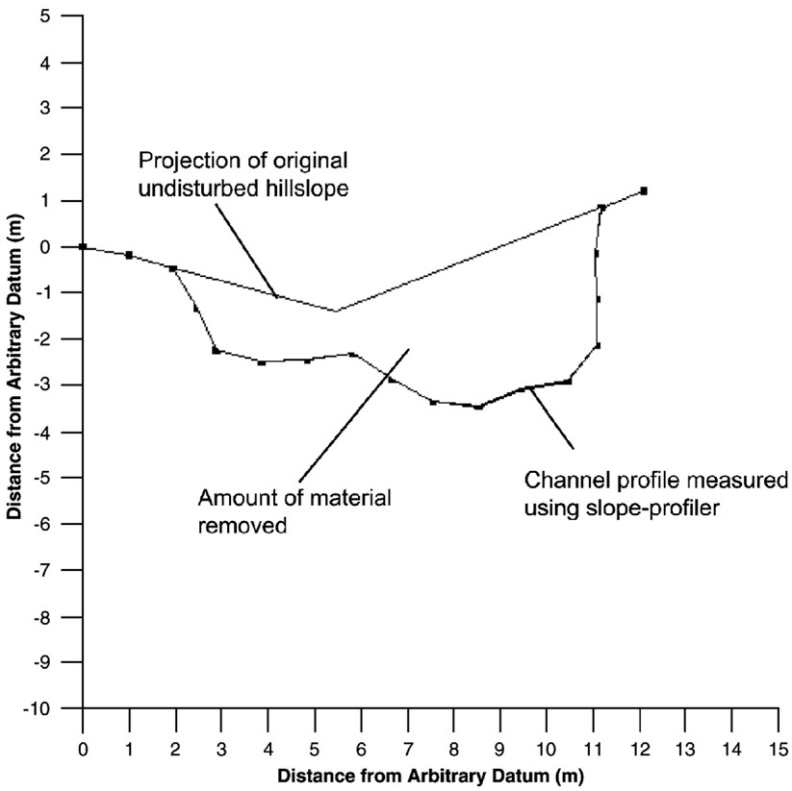

Fig. 3. Example of a channel cross-section showing how scoured area is estimated. Undisturbed hillslopes are projected into the scoured channel to represent the original channel surface, and the area of the polygon is determined.

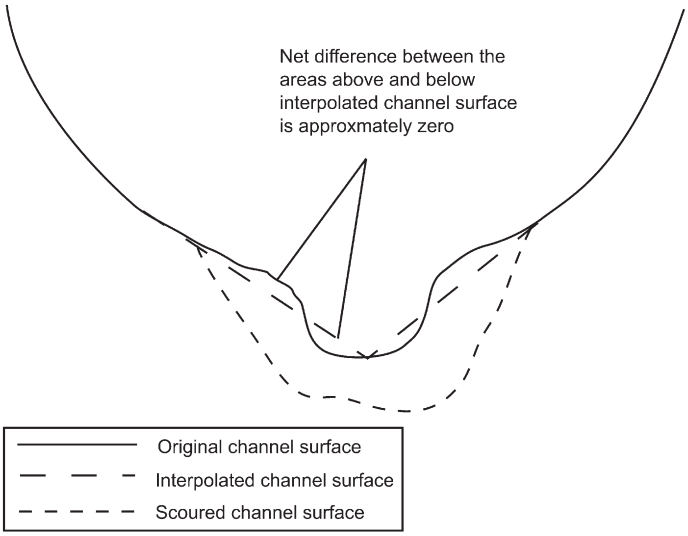

Fig. 4. Justification for the method used to interpolate the original channel surface. The interpolated channel surface falls above and below what an original channel surface may have looked like. The areas above and below the interpolated channel surface are approximately equal and cancel each other out.

of material removed by the debris flow. The sum of all segments of scoured channel represents the total volume of material eroded from the channel and theoretically corresponds to the amount of material deposited at the mouth of the basin.

Channel and levee deposits were measured, and in most cases accounted for less than 10% of the volume scoured from the channel. Because of the high spatial variability of these deposits, and to estimate a maximum volume of debris flow generated by each burned basin, the deposit volumes were not subtracted from the total volume of material scoured. In some cases, a basin may have generated a small flood or small debris flow following a large, initial debris flow, and the estimated volume may, therefore, represent multiple erosive events. For all basins examined, however, the initial debris flows were the most erosive and responsible for the majority of channel scour.

Santi and deWolfe (2005) compared the accuracy of the estimates of the volume of debris flows based on channel scour measurements to the volumes of the debris flow fans measured by a Computer Aided Drafting (CAD) analysis, Global Positioning System (GPS) mapping, and counting the number of dump trucks needed to clear debris flow deposits from a debris fan. The channel scour method was found to be more repeatable than the other methods by having lower error values associated with the volume measurements. Volume measurements made using GPS mapping of a debris flow fan and using the channel scour method were also compared and found to be within 30% of each other (Santi et al., 2008-this volume).

For larger basins (greater than 5 km^2) measuring channel scour was not feasible, and the volumes of debris flows were estimated from the volume of material collected in debris retention basins. The San Bernardino County Flood Control District in southern California provided volume estimates for debris flows for 8 basins following a storm on December 25, 2003 (U.S. Army Corps of Engineers, 2005).

3.2. Basin morphology

Basins producing debris flows were delineated in ArcGIS (ESRI, 2003) using 10- and 30-meter digital elevation models (DEMs), depending on availability. Slopes greater than 30% and 50%, were determined from slope grids and used with the spatial analyst tools in ArcGIS to determine the area of each slope class within individual basins (km^2).

Measures of basin morphology, including relief ratio, basin ruggedness, drainage density, and bifurcation ratio, were determined for each basin. Relief ratio reflects the gradient of the channel in a basin and is calculated by dividing the change in elevation between the basin mouth and the top of the longest channel extended to the drainage divide, by the length of that channel (Meyer and Wells, 1997). Ruggedness, also known as Melton's number, is the maximum change in elevation within the basin divided by the square root of the basin area (Melton, 1965). Drainage density (m^{-1}) is calculated as the total length of streams in a basin divided by the basin area, and bifurcation ratio is the ratio of the number of streams of

any order to the number of streams of the next highest order (Horton, 1945). Relief ratio and ruggedness were measured from DEMs using ArcGIS. Drainage densities and bifurcation ratios were determined by analyzing DEMs using River Tools (Rivix LLC, 2001).

3.3. Burn severity

Burn severity approximates the effect fire has on the hydrologic response of a basin caused by the heating of the soil, the generation of water repellant soils, introduction of ash into the soil, and removal of vegetation. Burn-severity maps were provided by the U.S. Geological Survey EROS Data Center and the U.S. Department of Agriculture (USDA) Forest Service Burned Area Emergency Rehabilitation (BAER) reports. These maps were generated from aerial and ground surveys or from remotely sensed data using the normalized burned ratio (Key and Benson, 2000). These maps were used to quantify the basin areas burned at low severity (km^2), moderate severity (km^2), high severity (km^2), moderate and high severity (km^2), and total area of the basin burned (km^2).

3.4. Material properties

A soil sample, collected in each basin and consisting of the top 20 cm of soil, was used to quantify the grain-size distribution of the burned soils of the basin. The median, mean, sorting, and skewness of the grain-size distribution were calculated according to the methods of Inman (1952), and are represented in phi (Φ) units (Krumbein, 1934). The dominant rock type of each basin producing a debris flow was determined from geologic maps and field observations. Rock types were represented as binary variables in the statistical analyses.

3.5. Rainfall triggering debris flows

We installed networks of tipping-bucket rain gages in the Grand Prix, Old, Coal Seam, and Missionary Ridge fires shortly after these fires were extinguished and before any major rainstorms impacted the burned areas. Rain gages, installed and maintained by the San Bernardino Flood Control District, provided additional rainfall data for the Grand Prix and Old fires. Remote Access Weather Stations (RAWS), installed and maintained by the USDA Forest Service, provided supplemental rain data for the Coal Seam fire. The Santa Barbara Flood Control District provided rainfall data for the Gaviota fire, and the San Diego Flood Control District provided rainfall data for the Paradise and Cedar fires. Rainfall data for the Farmington fire in Utah were provided by the Wasatch-Cache National Forest, and rainfall data for the Mollie fire were provided by the Utah State Geological Survey (McDonald and Giraud, 2002).

The tipping-bucket rain gages record rain using an event-recording data logger. Rainfall timing information was used to determine the rainfall characteristics of total storm rainfall (mm), storm duration (h), average rainfall intensity (mm/h), and peak rainfall intensities (mm/h) measured over 10-, 15-, 20-, 30- and 60-minute intervals for storms producing debris flows. Individual rainstorms were defined as periods of continuous rainfall, bounded by thirty minute periods of no recorded rainfall. For rain-gage networks installed in the Grand Prix and Old fires, maps representing the spatial distribution of each rainfall variable were created using inverse-distance weighting. Whereas orographic effects on rainfall were not incorporated into the generation of the rainfall maps, the rain-gage networks installed were sufficiently dense (average spacing between rain gages was between one and two kilometers) to account for these factors. Using these maps, values for each rainfall variable were spatially averaged across each basin. For the other burned areas, rainfall data were only available from a few, nearby rain gages. For these burned areas, the data from the nearest rain gage to the basin producing debris flows were used to provide the best approximation of rainfall triggering debris flows.

3.6. Statistical analysis and model generation

The data were split into six datasets to develop models that are specific to different geographic regions and geologic settings. The six regions and settings were the Western U.S. (all eight burned areas), Southern California, the Rocky Mountains, and burned basins underlain by granitic, metamorphic, and sedimentary rock types. Multiple regressions of these datasets generated region- and rock-type specific models that predict the volume of debris flow using a combination of independent variables.

Summary statistics and histograms were calculated for each independent variable to verify that the data were normally distributed, and to indicate which variables needed to be transformed to normal distributions. Depending on the skewness of the data, the square root (less skewed data) or natural log (more skewed data) of the data were calculated. A correlations matrix indicated relations between all of the variables, and outlying data points that should be eliminated. The variable with the highest correlation coefficient was used to create an initial model, which was accepted if it explained at least 50% of the variation in the volume data of the debris

flows, and if ANOVA and *T*-tests indicated 95% confidence in the coefficient of the variable. Variables were then added individually to the model and retained if the R^2 value improved by more than 5% and if the variable had a coefficient with a probability of at least 95%. A variable was removed from the model if the probability of the coefficient fell to less than 95% because of the addition of another variable. Residual plots were checked at each step of the regression to verify that the residuals have no visible trends or changes in variance. Individually adding and subtracting variables generated reasonable models that predict the volume of a debris flow based on a small number of explanatory variables. For some variables, data were not available for all of the basins. These basins were omitted from the multiple regression analyses if they lacked data for a variable used in the model being analyzed.

3.7. Model evaluation

The models were evaluated according to which had the highest R^2 value, lowest residual standard error, and residual plots that showed normality, constant variance, and an absence of trends in the residuals. The models were also evaluated according to whether the model reflects observations of wildfire-related debris flow processes. For example, a model was not considered if it indicated a negative correlation between rainfall and volumes of debris flows, because high rainfall totals and intensities have been observed to result in larger debris flows (Gartner et al., 2004). Further evaluation was based on how readily the model could be implemented, because hazard analyses of potential volumes of debris flows generated by burned basins must be done immediately after a fire when the hazard is greatest. Models were considered not applicable if they would be difficult to implement in a short time frame.

The models were independently validated using estimates of the volume of a debris flow and related basin morphology, burn severity, and rainfall characteristics provided in the literature that were not used in the generation of the models (Eaton, 1935; Doehring, 1968; Cleveland, 1973; Wells, 1987; Wohl and Pearthree, 1991; DeGraff, 1997; Cannon et al., 1998; Meyer et al., 2001). Volumes of debris flows were calculated using each appropriate model and compared to the volumes of debris flows reported in the literature. The proportion of the predicted volumes that were within two residual standard errors of the measured volume was used to evaluate the predictive ability of each model. Two residual standard errors were used to approximate a prediction interval with a 95% probability.

The models were further evaluated by performing regressions of the measured volumes of the debris flows and the volumes of debris flows predicted by each model. The ability of the models to predict the volume of a debris flow was determined by how close the slope and R^2 of the regression were to one. The tendency of the models to over- or under-predict volumes for debris flows was determined based on slope of the regression and patterns evident in the residuals. Because of insufficient data available in the literature, not all models could be validated by comparing predicted and measured volumes.

4. Results

Fifty-three recently burned basins that produced debris flows were examined for this study. The absence of landslide scars at the heads of the majority of debris flow paths indicates that they were generated by the progressive bulking of runoff with material eroded from the channel. In a few cases, landslides provided approximately 10% of the source material. Twenty-eight debris flows in southern California, seventeen debris flows in Colorado and eight debris flows in Utah were measured. Twenty-eight debris flows were generated by basins primarily underlain by metamorphic rock types, twelve by granitic rock types and thirteen by sedimentary rock types. Forty-five volumes for debris flows were estimated by measuring channel scour, and these volumes ranged between 170 m^3 and 59,000 m^3. The eight volumes estimated from debris retention basins ranged from 6800 m^3 to 610,000 m^3. Basin areas were between 0.01 km^2 and 27.90 km^2 with 10% to 100% of the basin area burned. Triggering storm rainfall totals ranged from 2 to 154 mm, and peak 10-minute intensities ranged from 8 to 72 mm/h.

A correlations analysis (Table 1) for all the data indicated that variables describing basin area were most strongly correlated to the natural log of the volume of a debris flow. The variable with the most correlation to the natural log of the volume of a debris flow was the natural log of the basin area with slopes greater than or equal to 30%. Among the basin morphology variables, bifurcation ratio had the highest correlation to the natural log of the volume of a debris flow. For burn-severity variables the square root of the basin area burned at moderate severity (km) and the square root of the basin area burned at a combination of moderate and high severities (km) were most strongly correlated to the natural log of the volume of a debris flow. The rainfall variable most strongly correlated to the natural log of the volume of a debris flow volume was the square root of the total storm rainfall (mm). Average storm rainfall

Table 1
Correlations between the natural log of the volume of a debris flow and all variables estimated in this study

Independent variable	Correlation to the ln of the Volume of a Debris Flow
ln basin area with slopes > = 30% (ln km^2)	0.8
Square root of the basin area burned at moderate and high severity (km)	0.78
Square root of the basin area burned at moderate severity (km)	0.78
ln of the total burned area of the basin (ln km^2)	0.78
ln of the basin area burned at moderate and high severity (ln km^2)	0.78
ln of the basin area (ln km^2)	0.75
ln of the basin area with slopes > = 50% (ln km^2)	0.64
Square root of the basin area burned at low severity (km)	0.48
Square root of the storm rainfall total ($mm^{1/2}$)	0.44
ln of the total storm rainfall (ln mm)	0.4
ln of the basin area burned at high severity (ln km^2)	0.23
Peak 60-minute intensity (mm/h)	0.18
Bifurcation ratio	0.15
Peak 15-minute intensity (mm/h)	0.05
Peak 30-minute intensity (mm/h)	0.04
Peak 10-minute intensity (mm/h)	0.02
Sorting of the burned soil grain-size distribution (Φ)	− 0.02
Mean of the burned soil grain-size distribution (Φ)	− 0.03
Median of the burned soil grain-size distribution (Φ)	− 0.05
ln of the drainage density (ln km^{-1})	− 0.06
Average gradient (%)	− 0.08
Skewness of the burned soil grain-size distribution (Φ)	− 0.09
Average Storm Rainfall Intensity (mm/h)	− 0.27
Ruggedness	− 0.61
Relief ratio	− 0.67

These correlations reflect data from all of the basins examined.

intensity was found to be negatively correlated to the log of the volume of a debris flow. Among the soil material-property variables, the mean (Φ) and median (Φ) of the burned soil grain-size distribution were the most correlated to the natural log of the volume of a debris flow.

Three basins from southern California, which are underlain by metamorphic rocks, were excluded from the stepwise multiple regression analyses; the correlations matrix and residual plots indicated that the data for these basins were outliers. These basins had very large volumes of debris flows associated with small basin areas, which suggests that these values are abnormal and potentially inaccurate. Removing these basins significantly improved the models by increasing R^2 and reducing the residual standard error. Because of the lack of data for some variables, eight basins from the Rocky Mountain dataset, and two basins from the sedimentary dataset were excluded from the regressions.

The multiple regressions provided models for each of the six previously described regions and settings. These models are referred to as the Western U.S., Southern California, Rocky Mountain, Granitic, Metamorphic and sedimentary models. Table 2 shows each model, and includes the relational coefficients, multiple R^2, residual standard error and sample size for each model. Unless otherwise indicated, the confidence in the values of each coefficient is at least 95% and residual plots show a normal distribution with constant variance and absence of trends in the residuals.

The Western U.S. model predicts volumes of debris flows generated by recently burned basins as a function of the natural log of the basin area with slopes greater than or equal to 30% (km^2), the square root of the basin area burned at moderate and high severity (km^2), and square root of the total storm rainfall (mm). This model has a high R^2 (0.83), low residual standard error (0.79 ln m^3) and includes variables that are easy to obtain and derive. The residuals show a normal distribution with constant variance and no visible trends. This model reflects the largest dataset examined by this study ($n = 50$) and is a combination of all the data used to generate the other models. The Western U.S. model predicts 87% of the reported volumes of debris flows (Eaton, 1935; Doehring, 1968; Cleveland, 1973; Wells, 1987; Wohl and Pearthree, 1991; DeGraff, 1997; Cannon et al., 1998; Meyer et al., 2001) to within two residual standard errors of the model prediction (Fig. 5). All of the predicted volumes are within an order of magnitude of the reported volumes. A regression of these predicted

Table 2
Models generated by the stepwise multiple regressions

Model	Equation	Multiple R^2	Residual standard error	Sample size
Western USA	$\ln V = 0.59(\ln S) + 0.65(B)^{1/2} + 0.18(R)^{1/2} + 7.21$	0.83	0.79	50
Southern California	$\ln V = 0.56(\ln S) + 0.59(B)^{1/2} + 0.25(R)^{1/2} + 6.59$	0.90	0.62	25
Rocky Mountain	$\ln V = 0.72(\ln S) - 0.02(P)^{a} + 8.54$	0.75	0.78	17
Metamorphic	$\ln V = 0.97(\ln Bt) + 0.32(\ln R) + 0.77(D) + 6.83$	0.91	0.64	25
Granitic	$\ln V = 0.66(\ln Bt) + 0.84(\ln R) + 5.24$	0.82	0.68	12
Sedimentary	$\ln V = 0.97(\ln S) + 2.79(M)^{b} + 0.15$	0.82	0.71	11

The variables are defined as; A=basin area, B=basin area burned at moderate and high severity (km^2), Bt=total area of the basin burned, D=drainage density (km^{-1}), M=median of the burned soil grain-size distribution (Φ), P=peak 10-minute rainfall intensity (mm/h), R=total storm rainfall (mm), S=basin area with slopes greater than or equal to 30% (km^2), V=volume of a debris flow (m^3).

[a] The coefficient for this variable is only accurate to 93%.

[b] The data for this variable is bimodally distributed.

and reported volumes of debris flows has an R^2 of 0.63, and a slope of 1.43.

The Southern California model is supported by a high R^2 (0.90) and a low residual standard error (0.62 ln m^3). The Southern California model predicts the volume of a debris flow as a function of the same variables used by the Western U.S. model, and the relations described are very similar. The R^2 value for the Southern California model is higher than the R^2 of the Western U.S. model (R^2=0.90 vs. 0.83), however, the residual have a positive trend. This trend indicates that the volume will under-predict smaller volumes and over-predict larger volumes. The Southern California model does not perform as well as the Western U.S. model in predicting reported volumes of debris flows from southern California (Eaton, 1935; Doehring, 1968; Cleveland, 1973; Wells, 1987; Wohl and Pearthree, 1991; DeGraff, 1997; Cannon et al., 1998; Meyer et al., 2001). Sixty-seven percent of the reported volumes are within two residual standard errors of the model predictions (Fig. 6). A regression of the predicted and reported volumes of debris flows had an R^2 of 0.7, and a slope of 2.06. The slope of this line is not as close to one as the regression of reported volumes of debris flows and volumes predicted using the Western U.S. model.

The Rocky Mountain model has a small sample size (n=17), and the lowest R^2 (0.75) of all the models. The peak 10-minute intensity variable used in this model is accurate to only 93% and was forced into this model to include a measure of rainfall. No variables of burn severity showed a correlation to the volume of a debris flow, which prevents the model from indicating how wildfire influences the volume of debris flow. Consequently, the model would predict the same volume for a debris flow for burned and unburned basins.

Binary rock-type variables were not significantly related to the volume of a debris flow and could not be

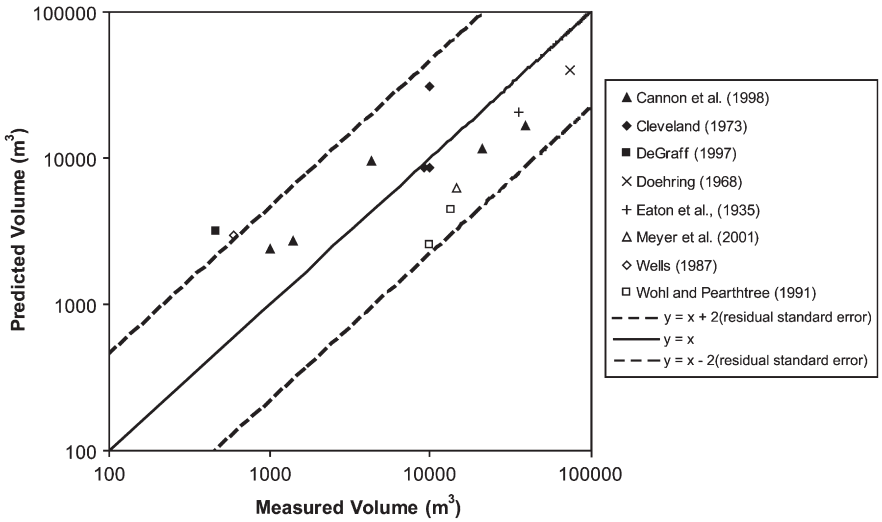

Fig. 5. Comparison of the estimates of the volumes of debris flows from the literature to predictions of the Western U.S. model. The solid black line indicates a perfect fit and the dotted lines represent the plus and minus one residual standard error.

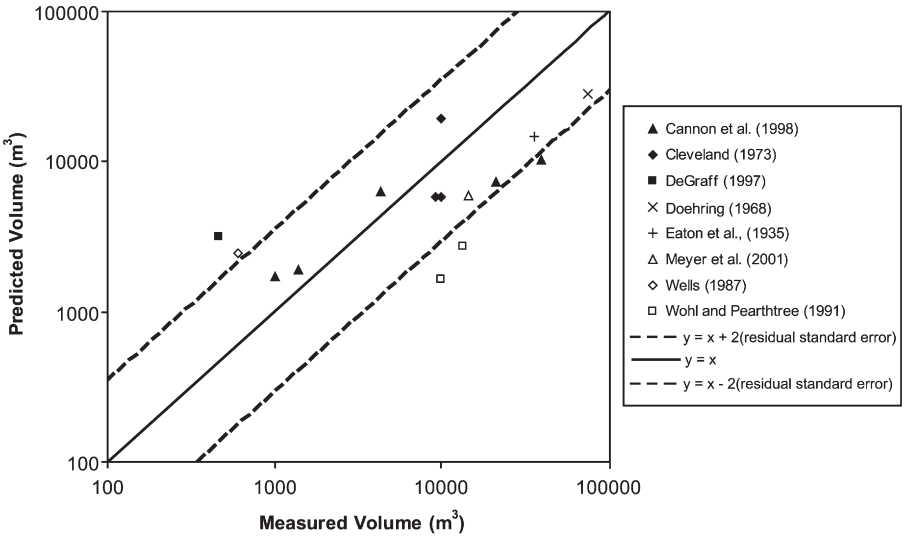

Fig. 6. Comparison of the estimates of the volumes of debris flows from the literature and predictions of the Southern California model. The solid black line indicates a perfect fit and the dotted lines represent the plus and minus one residual standard error.

included in any of the models. The rock-type models presented here are specific to rock type because the data used to generate each model were compiled based on common rock types. None of the variables used in each model directly reflect specific rock types, which makes it difficult to prove that the models are truly rock-type specific.

Among the three rock-type specific models, the Metamorphic model is the best. This model has the largest sample size ($n=25$), R^2 (0.91) is the highest of all the models, the residual standard error is low (0.64), and the residuals are normally distributed without any trends or changes in variance. It was not possible, however, to validate this model because drainage density data were not available for the test cases, and could not be determined from field maps.

The Granitic model has an R^2 of 0.82 and a residual standard error of 0.68. This model predicts the natural log of debris flow volume as a function of the natural log of the total area of the basin burned and the square root of the total storm rainfall. This model does not include any measure of slope or basin morphology, and does not do very well in predicting volumes of debris flows not used in the generation of the model (Eaton, 1935; Doehring, 1968; Cleveland, 1973; Wells, 1987; Wohl and Pearthree, 1991; DeGraff, 1997; Cannon et al., 1998; Meyer et al., 2001). Only 53% of the reported volumes were within two residual standard errors of the predicted volumes.

The sedimentary rock-type model was the weakest model generated by this study. This model was derived from a small dataset ($n=11$), and the residuals show a trend and have an unequal variance. This model does not describe relations thought to affect the volume of a debris flow generated by burned basins. For example, the model lacks variables for burn severity and rainfall. These variables had little correlation to the volume of a debris flow for this dataset, and could not be included. The sedimentary model also predicts the volume of a debris flow as a function of the median of the burned soil grain-size distribution, however, the data representing this variable has a bimodal distribution, making the model invalid. More detailed investigation and characterization of the material properties of basins producing debris flows could include information on soil erodability, degree of bedrock weathering, and depth of soils.

5. Discussion

Twenty-five variables were identified that could be related to debris flows generated from burned basins. Among these only a few were found to be related to the volume of a debris flow. When analyzing these correlations for underlying physical relationships with the volume of a debris flow, it is important to determine whether a variable is actually related because it directly influences the volume of a debris flow, or because it is correlated to another variable that influences the volume of a debris flow.

The variables of basin area with slopes greater than or equal to 30% and basin area burned at moderate and high severities were found to be most correlated to the volume

of a debris flow. This suggests that a critical angle for significant erosion of burned soils may be about 30%. Variables describing the basin area burned at moderate and high severities and basin area burned at moderate severity were equally correlated to the volume of the debris flow. For the basins examined, the basin area burned at moderate and high severity is not much different than the basin area burned at moderate severity, possibly resulting in the similar correlation coefficients. These results suggest that when the soil is burned at a moderate and high severity, the changes to soil caused by fire result in heightened erosion, and that the heat the soil experiences during a low severity burn is not sufficient to cause these changes.

The contribution of the burn severity and slope variables to the volume of a debris flow could not be assessed because these variables are correlated. Removing either of the correlated variables from the Western U. S. and Southern California models caused a decrease in the correlation coefficients of the model. Both of these variables were included to maximize the predictive ability of the model.

Rainfall plays a key role in the development of debris flows. Among the rainfall variables examined, the square root of the total storm rainfall was the most correlated to the volume of a debris flow (0.44). Although average intensity of storm rainfall has been reported to affect the probability of a debris flow (Cannon et al., 2003b), total storm rainfall appears to have a greater influence on the volume of a debris flow.

Basin morphology variables of relief ratio and ruggedness were negatively correlated to the volume of a debris flow. The negative correlations of these basin morphology variables may be linked to basin area, where small basins tend to be steeper, resulting in lower values for relief ratio, and ruggedness. Even though drainage density was not highly correlated to the volume of a debris flow in the correlations analysis of the Western U.S. dataset, it was a significant predictive variable in the Metamorphic model. This result suggests that a higher density of channels increases the volume of a debris flow. The majority of material in post-fire debris flows is eroded from the main channel of the basin and its tributaries (Santi et al., 2008-this volume), and it is, thus, reasonable to assume that the characteristics of the drainage network affect the volume of the debris flow.

Among the six models generated to predict volumes of debris flows in a variety of burned terrains, only a few are recommended for use as predictive tools. In addition to being statistically valid, an empirical model should 1) describe relations that are consistent with findings of research on wildfire-related debris flows, 2) be easily implemented, and 3) be validated with data not used to generate the model. Using these criteria, each model was evaluated to determine which model is most useful in a hazard assessment of recently burned basins.

The best models generated by this study are the Western U.S., Southern California, and Metamorphic models. All of these models satisfy the first two criteria listed above; however the Western U.S. model best satisfies the third criteria. The Southern California and Metamorphic models have merit, although more work is necessary to refine and validate these models. Insufficient data prevented a validation of the Metamorphic model. The Southern California model predicts 67% of the measured volumes of debris flows from the literature to within two residual standard errors of the model prediction. A regression of these predicted and measured values has a slope of 2.06, which indicates that the Southern California model consistently over-predicts the volume of a debris flow. The Western U.S. model predicts more of the measured volumes of debris flows (87%) to within one residual standard error of the model prediction, and a regression of these predicted and measured volumes of debris flows has a slope closer to one (1.43). Volumes of debris flows generated by burned basins in southern California are, therefore, probably better predicted using the Western U.S. model than the Southern California model.

The Western U.S. model is recommended as the most accurate of the models and is a suitable tool to use in the assessment of the hazards posed by wildfire-related debris flows. This model improves on pre-existing models (e.g., Johnson et al., 1991; Gatwood et al., 2000) because it incorporates the effect of burn severity on the volume of a debris flow and provides an error estimate (the residual standard error) that allows a range of potential estimates of the volume of a debris flow. Furthermore, this model appears to adequately predict volumes of debris flows for a variety of regions and rock types. The model is statistically valid, consistent with theories on wildfire-related debris flows, and is based on a large unique dataset that represents debris flows generated from a variety of terrains. The Western U.S. model is easily applied and uses information that can be quickly derived from DEMs, burn-severity maps, and estimates of potential storm rainfall totals based on a design storm of the user's preference (e.g., Miller et al., 1973).

Because of the range of volumes of debris flows used to create the Western U.S. model, estimates of smaller volumes of debris flows will be more accurate than estimates of larger volumes. The regression of measured volumes of debris flows and predicted volumes of debris flows using the Western U.S. model has a slope greater

than one, suggesting that the model may over-predict volumes of larger debris flows. Volume estimates greater than 610,000 m^3 should also be treated with caution, because these values exceed the range of data used to generate the model. For similar reasons, the model should not be used for basins greater than about 30 km^2. Although the model might perform adequately for larger areas and volumes of debris flows, additional factors may affect the relations between burned basins and volumes of debris flows larger than those used to generate the model. In addition, the model should only be used to predict the amount of material that may potentially flow out of a basin mouth. The model predicts the log of volume of a debris flow (ln m^3), which becomes the geometric median of the volume of a debris flow when transformed to m^3. If several potential volumes of debris flows are calculated using the Western U.S. model and then added together to get a total volume, the calculated total will underestimate the true mean volume of the area. The Western U.S. model can be implemented in conjunction with models that predict debris flow probability (e.g., Cannon et al., 2003b) to

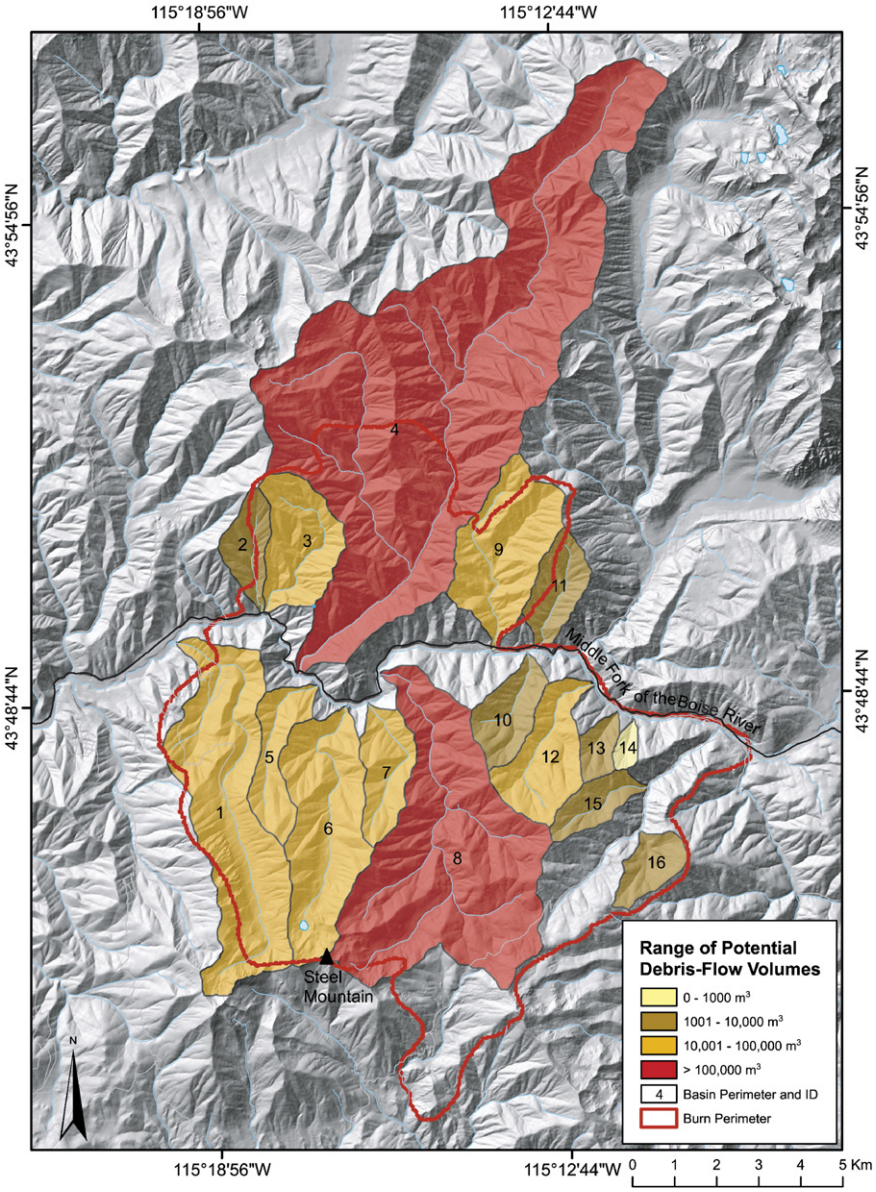

Fig. 7. Example of a debris flow hazard map for an area near Boise, Idaho, that indicates potential volumes for debris flows generated by burned basins in response to 10 mm of rainfall.

completely assess the potential debris flow hazards of a burned area. A debris flow probability model generates a probability map that shows the likelihood that a debris flow will occur in response to storms with various return intervals, whereas the Western U.S. model estimates how large these predicted events may be (Fig. 7). Using these two models, basins that are most likely to produce the largest debris flows can be identified and measures can then be taken to safeguard against potential wildfire-related debris flow hazards.

6. Summary and conclusions

For 53 basins in eight burned areas located in Colorado, Utah, and California, volumes of debris flows were measured by quantifying either the amount of material eroded from a channel by the passage of the flow or the amount of material deposited in a debris retention basin. Measures of basin area, gradient, and morphology were calculated from DEMs, and maps of burn severity were used to quantify basins area burned at various severities. Grain-size distributions were determined from field samples of burned soil, and rock types were determined from geologic maps and field observations. Networks of rain gages, installed throughout the burned areas, provided rainfall amounts and intensities for storms triggering debris flows.

A correlations analysis indicated that the variables most strongly related to the volume of a debris-flow were 1) storm rainfall total (mm), 2) basin area burned at moderate and high severity (km^2), and 3) basin area with slopes greater than or equal to 30% (km^2). This suggests that 1) total rainfall, rather than average rainfall intensity, influences the volume of a debris flow, 2) moderate and high burn severities cause more erodible soils, 3) burned slopes steeper than 30% are particularly susceptible to erosion. The presence of drainage density as a predictive variable for the metamorphic model suggests that a higher density of channels in a basin may increase the volume of a debris flow from burned basins.

Six predictive models for wildfire-related volumes of debris flows were generated. These models describe debris flows from burned basins located in the Western U.S., Southern California, and Rocky Mountain regions, and for burned basins underlain by metamorphic, granitic, and sedimentary rocks. The Western U.S. model was determined to be the best predictive model because it has a high R^2 of 0.83, a low residual standard error of 0.79, a normal distribution of residuals, and it was validated by data not used to generate the model.

The Western U.S. model is a useful addition to current research on debris flows because it can be used for rapid post-fire hazard assessments. Human casualties and damage to infrastructure occur because the hazards of debris flow processes are difficult to predict. Application of the Western U.S. model may help protect communities potentially affected by debris flows by enabling land managers and engineers to better address basins prone to post-fire debris flows. This model can be used to help determine which basins should receive erosion mitigation treatments after fires, and to guide the design and location of debris retention basins. Maps generated using the Western U.S. model can also be used to convey the debris flow hazards of burned basins to the public (Fig. 7).

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References

ACD Systems of America, Inc., 2005. Canvas 8.0, ACD Systems of America, Inc., 1150 NW 72 Avenue, Suite 180, Miami, FL, 33126. www.deneba.com.

Arkell, R.E., Richards, F., 1986. Short duration rainfall relations for the Western United States. Preprint Volume of the Conference on Climate and Water Management — A Critical Era and Conference on the Human Consequences of 1985's Climate, August 4–7, 1986, Asheville, N.C. American Meteorological Society, Boston, MA, pp. 136–141.

Bilodeau, S.W., Van Buskirk, D., Bilodeau, W.L., 1988. Geology of boulder CO, U.S.A. Bulletin of the Association of Engineering Geologists 24 (3), 293–332.

Bortugno, E.J., Spittler, T.E., 1998. Geologic map of the San Bernardino Quadrangle, 1:250,000: California Division of Mines and Geology, Regional Geologic Map Series, San Bernardino Quadrangle, Map 3A.

Bryant, B., 1990, Geologic map of the Salt Lake City 30′ x 60′ quadrangle, north-central Utah, and Uinta County, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1944, 2 plates, scale 1:100,000.

Cannon, S.H., Gartner, J.E., 2005. Wildfire-related debris flows from a hazards perspective, chapter 15. In: Hungr, O., Jakob, M. (Eds.), Debris-flow Hazards and Related Phenomenon. Praxis Publishing Ltd, Chichester, UK.

Cannon, S.H., Powers, P.S., Savage, W.Z., 1998. Fire-related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA. Environmental Geology 35 (2–3), 210–218.

Cannon, S.H., Gartner, J.E., Holland-Sears, A., Thurston, B.M., Gleason, J.A., 2003a. Debris-flow response of basins burned by the 2002 coal seam and Missionary Ridge Fires, Colorado. In: Boyer, D.D., Santi,

P.M., Rogers, W.P. (Eds.), Engineering Geology in Colorado — Contributions, Trends, and Case Histories. Association of Engineering Geologists Special Publication, vol. 14. on CD-ROM.

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Djokic, D., Sreedhar, S., 2003b. Emergency assessment of debris-flow hazards from basins burned by the Grand Prix and Old Fires of 2003, southern California. U.S. Geological Survey Open-File Report 03-475.

Carroll, C.J., Kirkham, R.M., Wracher, A., 1997. Geologic map of the Rules Hill Quadrangle, La Plata County, Colorado — description of map units, economic geology and references. Colorado Geological Survey Open-file Report 97-1.

Carroll, C.J., Kirkham, R.M., Wilson, S.C., 1998. Geologic map of the Ludwig Mountain quadrangle, La Plata County, Colorado — description of map units, economic geology, fracture data and references. Colorado Geological Survey Open-file Report 98-2.

Carroll, C.J., Gillam, M.L., Ruf, J.C., Loseke, T.D., Kirkham, R.M., 1999. Geologic map of the Durango East quadrangle, La Plata County, Colorado — description of map units, fracture data and analysis, economic geology and references. Colorado Geological Survey Open-file Report 99-6.

Cleveland, G.B., 1973. Fire and Rain=Mudflows, Big Sur, 1972. California Geology 26, 127–135.

DeBano, L.F., 1981. Water repellant soil: a state-of-the-art: U.S. Department of Agriculture, Forest Service, General Technical Report PSW-46, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 21 pp.

DeGraff, J.V., 1997. Geologic Investigation of the Pilot Ridge Debris Flow, Groveland Ranger District, Stanislaus National Forest. USDA Forest Service. 20 pp.

Diblee, T.W., 1981. Geologic map of the Gaviota quadrangle, California: U.S. Geological Survey Open-File Report OF-81-374, scale 1:24,000.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews 15, 33–65.

Doehring, D.O., 1968. The Effect of Fire on Geomorphic Processes in the San Gabriel Mountains, California. In: Parker, R.B. (Ed.), Contributions to Geology, 7(1). University of Wyoming, Laramie, pp. 43–65.

Eaton, E.C., 1935. Flood and Erosion Control Problems and Their Solution. American Society of Civil Engineers Transactions, 101, pp. 1302–1362.

ESRI, 2003. ArcGIS 8.0, ESRI, 380 New York Street, Redlands, CA, 92373. www.esri.com.

Gartner, J.E., Bigio, E.R., Cannon, S.H., 2004. Compilation of post wildfire runoff-event data from the western United States. U.S. Geological Survey Open-File Report 04-1085.

Gartner, J.E., Cannon, S.H., Bigio, E.R., Davis, N.K., Parrett, C., Pierce, K.L., Rupert, M.R., Thurston, B.L., Trebish, M.J., Garcia, S.P., Rea, A.H., 2005. Compilation of data relating to the erosive response of 606 recently burned basins in the Western U.S., U.S. Geological Survey Open-File Report 05-1218.

Gatwood, E., Pederson, J., Casey, K., 2000. Los Angeles district method for prediction of debris yields. U.S. Army Corps of Engineers, Los Angeles District.

Golden Software, Inc., 2004. Grapher 5.02, Golden Software, Inc., 809 14th Street, Golden, CO, 80401.

Gonzales, D.A., Stahr III, D.W., Kirkham, R.M., 2002. Geologic map of the Hermosa quadrangle, La Plata County, Colorado. Colorado Geological Survey Open-file Report 02-1.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56, 275–370.

Inman, D.L., 1952. Measures for describing the size distribution of sediments. Journal of Sedimentary Petrology 22, 125–145.

Johnson, P.A., McCuen, R.H., Hromadka, T.V., 1991. Magnitude and frequency of debris flows. Journal of Hydrology 123, 69–82.

Key, C.H., Benson, N.C., 2000. Landscape Assessment, in Fire Effects Monitoring System (FireMon): Integration of Standardized Field Data Collection Techniques and Sampling Design with Remote Sensing to Assess Fire Effects, D. Lutes, et al., USDA and USDI Joint Fire Sciences. http://www.fire.org/firemon/Lav1_methods.pdf.

Kirkham, R.M., Streufert, R.K., Cappa, J.A., 1997. Geologic Map of the Glenwood Springs Quadrangle, Garfield County, Colorado — Description of Map Units, Economic Geology, Geochemical Analyses, and References. Colorado Geological Survey Map Series, 31.

Krumbein, W.C., 1934. Size frequency distributions of sediments. Journal of Sedimentary Petrology 34, 195–196.

Küchler, A.W., 1977. The Map of the Natural Vegetation of California, Department of Geography, University of Kansas, Lawrence, Kansas, 31 pp, 1 map.

Letey, J., 2001. Causes and consequences of fire-induced soil water repellency. Hydrological Processes 15, 2867–2875.

McDonald, G.N., Giraud, R.E., 2002. Fire-related debris flows east of Santaquin and Spring Lake, Utah County, Utah. Utah Geological Survey Technical Report 02-09. 15 pp.

Melton, M.A., 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. Journal of Geology 73, 1–38.

Meyer, G.A., 2002. Fire in western conifer forests — geomorphic and ecologic processes and climatic drivers. Geological Society of America Abstracts with Programs 34, 46.

Meyer, G.A., Wells, S.G., 1997. Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA. Journal of Sedimentary Research 67 (5), 776–791.

Meyer, G.A., Pierce, J.L., Wood, S.H., Jull, A.J.T., 2001. Fire, storms, and erosional events in the Idaho Batholith. Hydrological Processes 15, 3025–3038.

Miller, J.F., Frederick, R.H., Tracey, R.J., 1973. Precipitation–Frequency Atlas of the Western United States. Colorado. NOAA Atlas 2, National Weather Service, National Oceanic and Atmospheric Administration, vol. III. U.S. Department of Commerce, Silver Spring, Md.

Moody, J.A., Martin, D.A., 2001a. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26, 1049–1070.

Moody, J.A., Martin, D.A., 2001b. Hydrologic and sedimentologic response of two burned watersheds in Colorado. U.S. Geological Survey Water Resources Investigative Report 01-4122.

Morton, D.M., 1989. Distribution and Frequency of Storm Generated Soil Slips on Burned and Unburned Slopes, San Timoteo Badlands, Southern California. In: Sadler, P.M., Morton, D.M. (Eds.), Landslides in a Semi-Arid Environment with emphasis on the Inland Valleys of Southern California. Publications of the Inland Geological Society, 2, pp. 279–284.

Norris, R.M., Webb, R.W., 1990. Geology of California, Second Edition. John Wiley and Sons, Inc., NY. 541 pp.

Parrett, C., 1987. Fire-Related Debris Flows in the Beaver Creek Drainage, Lewis and Clark County, Montana. U.S. Geological Survey Water — Supply Paper, 2330, pp. 57–67.

Parrett, C., Cannon, S.H., Pierce, K.L., 2003. Wildfire-related floods and debris flows in Montana in 2001. U.S. Geological Survey Water — Resources Investigations Report 03-4319. 28 pp.

Pierson, T.C., 2004. Distinguishing Between Debris Flows and Floods from Field Evidence in Small Watersheds. U.S. Geological Survey Fact Sheet 2004-3142.

Rivix LLC, 2001. RiverTools User's Guide release 2001, Boulder, Colorado, Research Systems, Inc. 202 pp.

Rompkins, M.J.M., Prasad, S.N., Whisler, F.D., 1990. Surface sealing and infiltration, Chapter 5. In: Anderson, M.G., Burt, T.P. (Eds.), Process Studies in Hillslope Hydrology. John Wiley and Sons, New York, pp. 127–172.

Santi, P.M., 1989. The kinematics of debris flow transport down a canyon. Bulletin of the Association of Engineering Geologists 26 (1), 5–9.

Santi, P.M., deWolfe, V.A., 2005. Comparisons of Debris-Flow Volume Measurements and Predictions. Association of Engineering Geologists, 48th Annual Meeting Program with Abstracts, Las Vegas, NV.

Santi, P.M., deWolfe, V.A., Higgins, J.D., Cannon, S.H., Gartner, J.E., Santi, P.M. 2008. Sources of debris flow material in burned area. Geomorphology 96, 310–321 (this volume). doi:10.1016/j.geomorph.2007.02.022.

Schaub, S., 2001. Landslides and Wildfire — An Example from the Boise National Forest. Boise State University, Boise, Idaho. 85 pp.

U.S. Army Corps of Engineers, 2005. Analyses of the debris and sedimentation impacts at selected debris basins associated with the wildfires of 2003 and the December 25, 2003 storm. Hydrology and Hydraulics Section. U.S. Army Corps of Engineers, Los Angeles District. after action report DRAFT, 45 pp.

Wells, H.G., 1987. The effects of fire on the generation of debris flows in southern California. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches — Process, Recognition, and Mitigation. Geological Society of America, Reviews in Engineering Geology, 7, pp. 105–114.

Witkind, I.J., Weiss, M.P., 1991. Geologic map of the Nephi 30X 60 minute quadrangle, Carbon, Emery, Juab, Sanpete, Utah, and Wasatch Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1937, 16 pp. pamphlet, scale 1:10,000.

Wohl, E.E., Pearthree, P.P., 1991. Debris flows as geomorphic agents in the Huachuca Mountains of southeastern Arizona. Geomorphology 4, 273–292.

Woods, S.W., Birkas, A., Ahl, R., 2006. Spatial variability of soil hydrophobicity after wildfires in Montana and Colorado. Geomorphology. doi:10.1016/j.geomorph.2006.09.015.