Predicting the probability and volume of postwildfire debris flows in the intermountain western United States

Susan H. Cannon[1,†], Joseph E. Gartner[1], Michael G. Rupert[2], John A. Michael[1], Alan H. Rea[3], and Charles Parrett[4]
[1]*U.S. Geological Survey, Box 25046, Denver Federal Center, MS 966, Denver, Colorado 80225, USA*
[2]*U.S. Geological Survey, 201 East 9th Street, Pueblo, Colorado 81003, USA*
[3]*U.S. Geological Survey, 230 Collins Road, Boise, Idaho 83702, USA*
[4]*U.S. Geological Survey, Placer Hall, 600 J Street, Sacramento, California 95819, USA*

ABSTRACT

Empirical models to estimate the probability of occurrence and volume of postwildfire debris flows can be quickly implemented in a geographic information system (GIS) to generate debris-flow hazard maps either before or immediately following wildfires. Models that can be used to calculate the probability of debris-flow production from individual drainage basins in response to a given storm were developed using logistic regression analyses of a database from 388 basins located in 15 burned areas located throughout the U.S. Intermountain West. The models describe debris-flow probability as a function of readily obtained measures of areal burned extent, soil properties, basin morphology, and rainfall from short-duration and low-recurrence-interval convective rainstorms. A model for estimating the volume of material that may issue from a basin mouth in response to a given storm was developed using multiple linear regression analysis of a database from 56 basins burned by eight fires. This model describes debris-flow volume as a function of the basin gradient, aerial burned extent, and storm rainfall. Applications of a probability model and the volume model for hazard assessments are illustrated using information from the 2003 Hot Creek fire in central Idaho. The predictive strength of the approach in this setting is evaluated using information on the response of this fire to a localized thunderstorm in August 2003. The mapping approach presented here identifies those basins that are most prone to the largest debris-flow events and thus provides information necessary to prioritize areas for postfire erosion mitigation, warnings, and prefire management efforts throughout the Intermountain West.

INTRODUCTION

Methods for assessing the potential for debris flows from basins burned by wildfires over extensive areas are needed to rapidly assess hazards and to prioritize locations for prefire restoration efforts. Here, we describe a set of models that rely on data readily available immediately after a fire and that can be implemented in a geographical information system (GIS) to assess postfire debris-flow hazards. The assessments identify the probability that given basins will produce debris flows, and they estimate the potential volume of the debris flows at the basin outlet. This approach addresses two of the fundamental questions in debris-flow hazard assessment: where might debris flows occur and how big might they be?

The increased occurrence of catastrophic wildfires in the western United States (Westerling et al., 2006) and the encroachment of development into fire-prone ecosystems have highlighted the need for methods to quantify the potential hazards posed by debris flows produced from burned watersheds. Science-based information on postwildfire debris-flow hazards is necessary for federal, state, and local agencies to mitigate the impacts of fire on people and their property, and on natural resources. Identification of potential debris-flow hazards from burned drainage basins is necessary to make appropriate decisions for the design and location of mitigation measures and to develop effective emergency warnings and evacuation timings and routes. Application of predictive models for debris-flow hazards before the occurrence of wildfires with a projected burn severity distribution can help to identify potentially hazardous drainage basins and thus direct planning strategies that minimize the potential for catastrophic fires in those areas.

Fire-related debris-flow hazard assessments conducted in the past have relied on local knowledge of the response of unburned basins (e.g., A.J. Gallegos, USDA Forest Service, 1995, written commun.), on site-specific case studies of the known response of nearby burned basins (e.g., R. Gould, USDA Forest Service, 1997, written commun.; J.V. DeGraff, USDA Forest Service, 1997, written commun.), and on assessments of flooding potential with assumed sediment bulking factors (e.g., Biddinger et al., 2003; R. Gould, USDA Forest Service, 1997, written commun.). For example, Elliott et al. (2004) linked modeled flood hydrographs to a two-dimensional flood and debris-flow routing model (FLO-2D; O'Brien, 1993) and, using assumed postfire sediment concentrations, delineated potential areas of unconfined debris-flow inundation on alluvial fans and valley floors. Given the present lack of physical understanding of the factors that control debris-flow generation from burned basins, it is not uncommon for workers to rely on assumed effects. Mitsopoulos and Mironidis (2006) totaled assumed relative rankings of the effects of burn severity, hillslope gradients, and geologic materials to categorize relative hazards posed by debris flows in a Mediterranean setting. Spittler (1995) and Wohl and Pearthree (1991) made observations of the conditions that existed at the time of debris-flow occurrence and suggested that these factors determine a debris-flow response. For example, Spittler (1995) identified friable bedrock units; fractured bedrock; cohesionless soils, colluvium and alluvium; long regular slopes having gradients greater than 65% that are denuded of vegetation; concentrations of dry ravel; development of a continuous water-repellent soil; and removal of woody structural support from stream channels as those factors that control the debris-flow response of burned areas. Cannon and Gartner (2005), Weight and Johansen (2004), Rupert et al. (2003), and Cannon (2001) used uni- and bivariate statistical evaluations of measurements of these potential explanatory variables to identify specific conditions that are related to debris-flow occurrence.

[†] E-mail: cannon@usgs.gov

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The approach described here advances the previous qualitative and statistical evaluations by first providing a statistical identification of the storm-specific conditions that most strongly influence the generation of postfire debris flows and the magnitude of the flows, and then by presenting integrated, multivariate statistical models that characterize the combined effects of these conditions on postfire debris-flow probability and magnitude.

Fire-Related Debris-Flow Hazards

Wildfire can have immediate and profound effects on the hydrologic response of a watershed. Consumption of the rainfall-intercepting canopy and of the soil-mantling litter and duff, intensive drying of the soil, generation of vegetative ash, and the enhancement or formation of water-repellent soils and/or surface sealing of soil pores by wood ash can result in decreased rainfall infiltration and significantly increased runoff and movement of soil (e.g., Kinner and Moody, 2007; Shakesby and Doerr, 2006; Neary et al., 2005; Wondzell and King, 2003; Martin and Moody, 2001; Moody and Martin, 2001a; Doerr et al., 2000; Spittler, 1995; Troxell and Peterson, 1937). Smooth and continuous runoff paths resulting from the removal of vegetation can allow for rapid and pervasive overland flow (Meyer, 2002). Combustion of soil-binding organic material promotes dry ravel of noncohesive soils and channel loading (Swanston, 1991; Wells, 1987). Increased runoff can also erode significant volumes of material from hillslopes as rills and gullies, and from channels, either by bank failure or channel bed erosion (Santi et al., 2008; Wondzell and King, 2003; Moody and Martin, 2001b). The result of rainfall on burned basins is often the transport and deposition of large volumes of sediment, both within and down-channel from the burned area.

Debris flows are among the most hazardous consequences of rainfall on burned hillslopes. Debris flows pose a hazard distinct from other sediment-laden flows because of their unique destructive power. They can occur with little warning, exert great impulsive loads on objects in their paths, and strip vegetation, block drainage ways, damage structures, and endanger human life (Iverson, 1997). The deaths of 16 people during the 24–25 December 2003 storm and subsequent runoff from burned hillslopes in Southern California highlight the most drastic consequences of postwildfire debris flows (Chong et al., 2004). In addition to the lives lost, $23.5 million was spent to repair flood and debris-flow damage and to empty debris basins (Pat Mead, FEMA, 2004, personal commun.).

From field observations of debris flow–producing basins following fires in Yellowstone National Park in 1988, Meyer et al. (1995) described a process of debris-flow generation by progressive bulking of runoff by sediment eroded from hillslopes and channels, rather than discrete slope failures. Cannon and Gartner (2005) conducted a field and aerial photographic study of 210 recently burned debris flow–producing basins throughout the intermountain western United States that demonstrated the majority of postfire debris flows initiated through such a process. The flows occurred within 2 years after wildfires in response to short-duration (<1 h) storms with low-recurrence intervals (<2–10 years) (Cannon et al., 2008). Detailed surveys of 46 postfire debris flow–producing basins in Colorado, Utah, and southern California led Santi et al. (2008) to conclude that channel erosion and scour were the dominant sources of material for these flows.

Although infiltration-triggered landsliding can occur in burned basins, most landslide failures occur in response to prolonged and long-recurrence-interval rainfall events, and they typically contribute just a small proportion of the total volume of material transported from the basin (Cannon and Gartner, 2005; Cannon et al., 2001; Scott, 1971). These findings point to the relative importance of runoff-dominated, rather than infiltration-dominated, processes of debris-flow initiation in recently burned basins, and they indicate that methods to map landslide potential for unburned basins based on traditional slope stability analyses are inappropriate for assessments of recently burned areas. Such analyses may be appropriate when considering the response to storms with long recurrence intervals or to time periods of years to decades that allow for root-strength decay.

APPROACH AND METHODS

Studies of the erosional response of recently burned basins throughout the Intermountain West of the United States reveal that not all basins produce debris flows; most burned watersheds respond to even heavy rainfall by producing sediment-laden floods (Cannon, 2001). Debris flows, however, represent the more destructive end of the potential response spectrum and thus warrant particular attention. We thus need a way to identify basins that will specifically produce debris flows rather than simply sediment-laden floods. Here, we take the approach of defining a set of conditions that identify those basins that are specifically susceptible to debris-flow activity. When debris flows are generated through the process of progressive sediment bulking, the volume, velocity, and sedimentologic characteristics of a debris flow at any given point along a drainage network will depend on the formation processes and characteristics in the contributing basin area above the point (Cannon et al., 2001, 2003a). For this reason, we use the basin form as the unit of choice for evaluation, rather than the pixel (as is commonly used in GIS-based hillslope stability analyses).

We used data collected from recently burned basins throughout the U.S. Intermountain West (Gartner et al., 2005) (Fig. 1) to develop multivariate statistical models that can predict both the probability that a selected basin will produce debris flows and the potential volume that may issue from the basin mouth. The probability of debris-flow occurrence and estimates of volumes are considered to be functions of combinations of different measures of soil properties, basin characteristics, burn severity, and rainfall conditions. Application of the statistical models in a GIS to produce maps that show potential debris-flow hazards for a given storm event is illustrated using data from the 2003 Hot Creek fire in central Idaho. We used a procedure described by Chung and Fabbri (2003) to characterize the success and predictive effectiveness of the probability models and to identify the models that best predicted the response of burned basins in this setting. The models presented here can be used to identify those recently burned basins in the Intermountain West that, in response to given rainfall events, are most likely to produce debris flows (have estimated high probabilities of occurrence) and to estimate the likely volumes of material in the debris flows.

Debris-Flow Probability Models

Logistic regression multivariate statistical analyses (e.g., Hosmer and Lemeshow, 2000; Helsel and Hirsch, 2002) using data measured from 388 basins in 15 recently burned areas throughout the intermountain western United States were used to identify the variables that best indicate a susceptibility to debris flows. The analyses were further used to develop models that characterize the probability of debris-flow occurrence for recently burned basins (Fig. 1). The database to develop the models consists of a set of independent variables that potentially characterize runoff processes in burned basins (e.g., Moody et al., 2008; Beven, 2000). These variables include measures of basin gradient, basin aspect, burn severity distribution within the basin, soil properties, and storm rainfall conditions in basins that were characterized either as having produced debris flows, sediment-laden floods, or no response (Gartner et al., 2005).

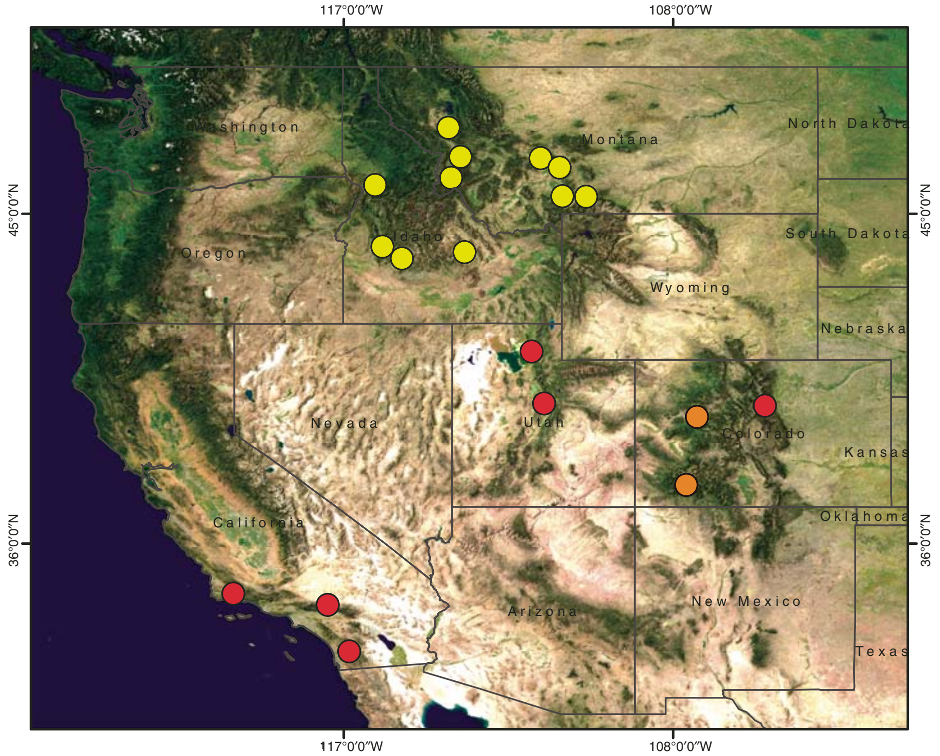

Figure 1. Map showing locations of basins used to develop models for the probability of debris-flow generation (yellow dots), for estimates of debris-flow volume (red dots), or both models (orange dots).

Basins were defined by the contributing area above an outlet located at a break in slope between a mountain front and a valley (or at the location of a general transition between erosion and deposition) or within the basin at a road crossing or above an identified value at risk. Defined basins ranged in area between 0.01 and 103 km^2, and the majority of basins were less than 1.0 km^2 in area (Fig. 2). Sixty-four of the 388 basins, or 16%, showed a debris-flow response. Low-order tributaries produced most debris flows, as indicated by the small mean (1.7 km^2) and median (0.2 km^2) areas for debris flow–producing basins. For this sample of basins in the Intermountain West, debris flows were not observed at the outlets of basins greater than ~30 km^2 in area (Fig. 2).

Field observations at basin outlets made within 1 wk of storms were used to determine if a basin produced debris flows. Debris-flow deposits were identified as indurated, poorly sorted, unstratified materials with some fine-grained matrix; levees and boulder berms lining the flow path with indurated, unsorted matrix material within the deposits; and an indurated muddy veneer lining the flow path and coating boulders and vegetation (Pierson, 2005). Deposits other than levees and boulder berms (which can lack matrix material along margins) that showed stratification or sorting, or that lacked matrix materials in any part of the deposit, were considered to be the result of sediment-laden streamflow, rather than debris flow. In some cases, observations of the surface of deposits indicated that the source might be a sediment-laden flood (e.g., sorted, clean sands or boulder berms), but matrix material that was found well within the deposits indicated a debris-flow origin (Pierson, 2005; Cannon, 2001; Meyer and Wells, 1997).

Five measures of basin gradient were compiled for use as potential explanatory variables using either 30 m or 10 m digital elevation models (DEMs), depending on availability. These measures include: (1) the average basin gradient, (2) percentage of basin area with slopes greater than or equal to 30%, (3) percentage of basin area with slopes greater than or equal to 50%, (4) basin ruggedness (change in basin elevation divided by the square root of the basin area; Melton, 1965), and (5) relief ratio (change in basin elevation divided by the channel thalweg length).

Basin aspect was quantified from either 10 or 30 m DEMs as the average direction, in azimuth degrees from the north, that a basin faces using the ArcGIS spatial analyst tool.

Five measures of burn severity for each basin were characterized using maps of burn severity generated from the normalized burn ratio (NBR), as determined from Landsat Thematic Mapper data (Key and Benson, 2006). These maps reflect the relative changes in pre- and immediately postfire vegetation cover. Measures of burn severity compiled for use as potential explanatory variables include: percentage of the basin area burned at low severity, percentage of the basin area burned at moderate severity, percentage of the basin area burned at high severity, percentage of the basin area burned at high and moderate severities, and percentage of basin area burned.

In addition to the relative changes in vegetation coverage in response to the fire, the burn severity classifications are considered to reflect relative measures of the distribution of water-repellent soils (Parsons et al., 2002). The extent of burn severity and basin area at different gradients were characterized as percentages (0%–100%) because they were used to calculate a relative probability that also varied between 0% and 100%.

Soil properties for each basin were compiled from two sources. First, soil-particle sizes were measured from samples of burned surficial soils collected within the basins. The soil-size properties characterized from the grain-size distribution include: mean particle size, median particle size, sorting of the grain-size distribution, and skewness of grain-size distribution, as described by Inman (1952). Second, various properties of unburned soils were compiled for each basin from the 1:250,000 STATSGO soils database (Schwartz and Alexander, 1995). Although the scale of this database indicates that it provides only a broad characterization of soil properties, it is the only source of consistent soil information available for the entire Intermountain West. This database was used to compile the following soil properties for each basin: percent clay content, available water capacity, permeability, erodibility (k-factor), percent organic matter, soil thickness, liquid limit, hydrologic group, and hydric capacity. Definitions of these properties are shown in Table 1.

Properties of the geologic material underlying the soils were not considered for use as explanatory variables in this study because the runoff and erosion leading to the generation of debris flow involve primarily surficial material, and because rock type did not appear as a significant variable in previous studies of fire-related debris-flow processes (Gartner, 2005; Cannon et al., 2003b; Rupert et al., 2003).

Data from tipping-bucket rain gauges located within 2 km of each basin were compiled and used to develop the following potential

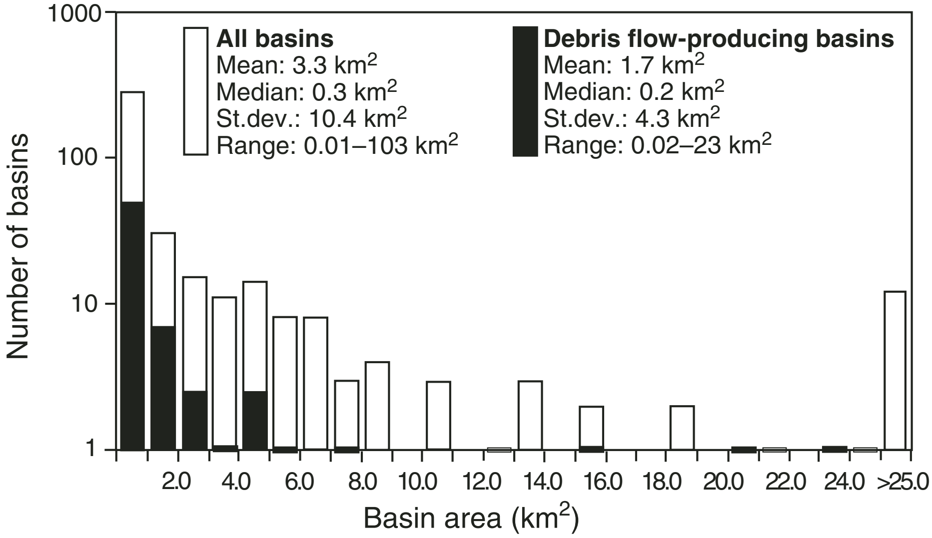

Figure 2. Histogram showing areas of recently burned basins used in development of the debris-flow probability model (open bars), and areas of basins that produced debris flows (filled bars).

TABLE 1. DEFINITIONS OF SOIL PROPERTIES INCLUDED IN THE STATSGO SOIL DATABASE (SCHWARTZ AND ALEXANDER, 1995)

Soil property	Definition
Percent clay content	Clay content of the soil or horizon, expressed as a percentage of material less than 2 µm in size.
Available water capacity	The volume of water that should be available to plants if the soil, exclusive of rock fragments, was at field capacity.
Permeability	The amount of water that will move downward through a unit area of saturated soil in unit time under a unit hydraulic gradient.
Erodibility (k-factor)	A relative index of the susceptibility of bare, cultivated soil to particle detachment and transport by rainfall.
Percent organic matter	The amount of organic material in the soil, in percent by weight.
Soil thickness	The weighted average thickness of all soil layers.
Liquid limit	The water content at the change between the liquid and plastic state of the soil.
Hydrologic group	The minimum steady-ponded infiltration rate for bare ground. Ratings are composed of four categories, A through D, with A having the highest saturated hydraulic conductivity.
Hydric capacity	The tendency for the soil to hold water. Soils are rated as hydric or nonhydric.

explanatory variables: total storm rainfall, storm duration, average storm rainfall intensity, peak 10 min rainfall intensity, peak 15 min rainfall intensity, peak 30 min rainfall intensity, and peak 60 min rainfall intensity.

Rainfall conditions were included in the evaluation of debris-flow probability because they are the driver of the system; the response of a given basin with a particular set of characteristics is directly dependent upon the storm rainfall that impacts it. Data recorded only from short-duration convective thunderstorms were used to develop the probability models. The storms had recurrence intervals ranging from less than 2 year up to 10 year.

Because the dependent variable in this analysis, debris-flow occurrence, is binomial (i.e., debris flows were produced or not produced), we used a logistic regression approach for analysis. Such analyses have been used in other settings for debris-flow hazard assessments (e.g., Pinter and Vestal, 2005; Griffiths et al., 2004). Logistic regression is conceptually similar to multiple regression because relations between one dependent variable and several independent variables are evaluated. Whereas multiple linear regression returns a continuous value for the dependent variable, logistic regression returns the probability of a positive binomial outcome (in this case, debris-flow occurrence) in the form:

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

where P is the probability of debris-flow occurrence, in percent; $x = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i$; β_i are logistic regression coefficients; x_i are values for the independent variables; and i is the number of variables (Hosmer and Lemeshow, 2000; Griffiths et al., 2004). In this model, as $(\beta_0 + \ldots + \beta_i x_i)$ increases, P approaches 1. As $(\beta_0 + \ldots + \beta_i x_i)$ decreases, P approaches 0. The coefficients (β_i) are estimated by the method of maximum likelihood, where coefficients with the highest probability of returning the observed values are selected (Griffiths et al., 2004). Logistic regression does not require normally distributed data because it is based on the log of the odds ratio (the ratio of the odds of an event occurring in one group to the odds of it occurring in another group), in contrast to linear regression, which is based upon ordinary least squares and which requires data transformation to make data distributions symmetrical (Hosmer and Lemeshow, 2000).

A series of univariate, multivariate regression, and multiple logistic regression analyses were used to identify those parameters that best determine debris-flow probability, and to identify statistically significant models (Hosmer and Lemeshow, 2000). Spearman's ρ (a measure of correlation in nonparametric statistics used when data are in ordinal form) was used to examine univariate correlations between each of the variables (Helsel and Hirsch, 2002). The univariate correlations were then used as an initial indicator of the variables that may be significant in the multivariate logistic regression models. Logistic regression analyses were used to develop multivariate models; all possible combinations of the independent variables were evaluated to determine the combinations that produced statistically robust models. Models were built by sequentially adding variables to the analysis and evaluating the resulting test statistics by comparing partial-likelihood ratios calculated before and after addition of that variable (Helsel and Hirsch, 2002; Nolan and Clark, 1997; Hosmer and Lemeshow, 2000). The difference in partial-likelihood ratios between two sequential models was calculated, and a χ^2 approximation was calculated with degrees of freedom equal to the number of variables in the new model. The p values from the χ^2 distribution were used to determine if the model had been significantly improved by the addition of the new variable. With the addition of each variable, model validity and accuracy were also determined by evaluating the log-likelihood ratio, McFadden's ρ^2, p values calculated for each independent variable, and the percentage of correct responses, or model sensitivity. The log-likelihood ratio measures the success of the model as a whole by comparing observed with predicted values (Hosmer and Lemeshow, 2000; Klienbaum, 1994); specifically, it tests whether the coefficients of the entire model are significantly different from zero. The most significant model is the one with the highest log-likelihood ratio, taking into account the number of independent variables (degrees of freedom) used in the model. The log-likelihood ratio follows a χ^2 distribution, and the computed p values indicate whether model coefficients are significantly different from zero. McFadden's ρ^2 is a transformation of the log-likelihood statistic and is intended to mimic the R^2 (R-square) of linear regression (SPSS, Inc., 2000). The value of ρ^2 is always between zero and one, and a ρ^2 value approaching 1 corresponds to a more significant result. The value of ρ^2 tends to be smaller than R^2, so a small number does not necessarily imply a poor fit. Values of ρ^2 between 0.20 and 0.40 indicate good results (SPSS, Inc., 2000). As a standard statistical measure, model sensitivity is calculated as the proportion of basins known to have produced debris flows to those predicted by the model to have a probability of occurrence greater than 50% (Hosmer and Lemeshow, 2000). Since it is harder to predict occurrences than nonoccurrences (because there are fewer of them in the database), we looked for models that returned the largest sensitivity.

Model Verification

Once all possible statistically significant models were identified, the effectiveness of each model in predicting postfire debris flows was evaluated using an approach described by Chung and Fabbri (2003). The approach is based on the calculation and evaluation of separate success rate and prediction rate curves. Chung and Fabbri (2003) calculated these curves using an analysis of mapped pixels, while here we consider basins as the unit of choice.

Success rate curves were calculated from the data used to derive the models, and they give a relative measure of each model's strength. Success rate curves compare the distributions of the proportion of basins known to have produced debris flows relative to the distributions of calculated probabilities of occurrence, and are simply an expanded measure of model sensitivity (as described above). A 1:1 slope indicates a random distribution, whereas steeper curves located closer to the *y*-axis indicate the highest success and represent higher probabilities of occurrence calculated for those basins that actually produced debris flows.

Prediction rate curves were used to evaluate the predictive strength of the debris-flow probability models for the Hot Creek fire, which burned in July 2003 in south-central Idaho. In contrast with success rate curves, data used for generation of prediction rate curves are a separate data set from that used to define the models. The burned area was impacted by a storm on 3 August 2003, and it produced debris flows from four of the 16 basins we evaluated. Prediction rate curves show the distributions of proportions of actual debris flow–producing basins relative to the distribution of predicted probabilities. Like the success rate curves, a 1:1 slope indicates a random distribution, and steeper curves located closer to the *y*-axis indicate the strongest predictions, which represent higher probabilities of occurrence calculated for basins that actually produced debris flows.

Debris-Flow Volume Model

A multiple-regression model (e.g., Draper and Smith, 1981) for estimating volumes of material that can potentially be generated from recently burned basins was developed on the basis of data from debris flows generated from 55 recently burned basins in eight different fires in Utah, Colorado, and California (Gartner et al., 2008) (Fig. 1). Volumes of material eroded from basins were estimated from surveys of a series of closely spaced cross sections, or they were obtained from reports of material volumes collected in debris basins. Volumes ranged from 174 to 864,300 m^3 and were generated from basins between 0.01 and 27.9 km^2 in area.

Different measures of basin gradient and channel network thought to be potential explanatory variables were calculated from either 10 or 30 m DEMs, depending on availability, and they include: average basin gradient, area of basin with slopes greater or equal to 30%, area of basin with slopes greater or equal to 50%, relief ratio, basin ruggedness, drainage density (the total length of streams in a basin divided by the square root of the basin area; Horton, 1932), and bifurcation ratio (the ratio of streams of any order to the number of streams of the next highest order; Horton, 1932).

The same measures of grain-size distribution and soils properties as described for the debris-flow probability models were also evaluated as potential explanatory variables. However, in contrast with the variables evaluated in the probability models, the measures of basin gradient and burn severity were quantified directly as areas, rather than as percentages of areas.

Rainfall data used in the development of the volume model were recorded from both long-duration frontal storms and short-duration convective thunderstorms. As with the storms used to develop the probability model, these storms had recurrence intervals ranging from less than 2 years up to 10 years.

Multiple linear regression analysis (e.g., Draper and Smith, 1981) was used to determine the factors that most strongly affect the volume of debris-flow material deposited at a basin outlet, and to build a model to predict debris-flow volume in response to a given storm. As a first step, histograms of all variables were examined to determine whether data were normally distributed. Square-root and natural-log transforms were applied to skewed data, and a correlation analysis was used to determine which of the independent variables were most strongly related to debris-flow volume. The independent variable with the strongest correlation to debris-flow volume was then used to create an initial regression model. ANOVA and Student *t*-tests were used to indicate whether 95% confidence in the coefficient of the variable existed. Independent variables were added sequentially to the regression model and retained if the R^2 value improved by more than 0.05 and the regression coefficient was significant at the 95% level, as determined by *F*- and *t*-statistics. A variable was discarded if its addition caused the model significance to fall below the 95% confidence level. A multiple regression model with all significant explanatory variables included was tested to ensure that assumptions of linearity, constant variance, and normally distributed residuals (Helsel and Hirsch, 2002) were met. Finally, a bias correction that accounted for the transformation from log units of the predicted variable (volume) was calculated using the procedure described in Helsel and Hirsch (2002). Without this, when log *V* is transformed to *V*, the value obtained represents a median value. On a log scale, the median can be much less than the mean, particularly for larger values. The bias correction changes the estimate of the median value to an estimate of the mean value.

Model Verification

The model was verified by comparing predicted volumes with actual volumes from a data set of 21 postfire debris-flow events reported in the literature and not used in the development of the model (Gartner et al., 2008). The 95% prediction interval (or two standard errors of the predicted value) of a one-to-one correspondence line of predicted values against actual values was used to evaluate how well the model predicted independent data (data not used to generate the model). The one-to-one correspondence line, rather than a regression line, was evaluated because of the multidimensionality of a multiple regression model with more than one independent variable. If the majority of the actual volumes are within the 95% prediction interval of the volume determined by the model, then the model is considered to be verified.

RESULTS

Debris-Flow Probability Models

Examinations of univariate correlations between each of the independent variables and the presence or absence of debris flows, as characterized by the absolute value of Spearman's ρ, indicate that the following variables are most strongly correlated with the presence of debris flows (Table 2): relief ratio, basin ruggedness, the percentage of the basin burned, and the percentage of the basin burned at a combination of high and moderate severities, the sorting of the burned soil grain-size distribution, and the available water capacity, percent clay, soil thickness, and soil permeability.

The logistic regression analyses identified five statistically significant multivariate models that incorporate the variables strongly correlated with debris-flow occurrence (Table 2). Measures of model sensitivity for each of these models (Table 2) show that more than 40% of basins known to have produced debris flows have a calculated probability of occurrence of at least 50%. Values for McFadden's ρ^2 are between 0.26 and 0.35 for each of these models (values of ρ^2 between 0.20 and 0.40 are considered to indicate good results; SPSS, Inc., 2000). These values, coupled with the additional tests of model quality during the model-building process, indicate that each one of the five models is statistically valid.

Of the five statistically significant models, each showed a different combination of variables most strongly correlated with debris-flow occurrence (Table 2). The percentage of the basin burned at a combination of high and moderate severities and the average storm intensity were significant in every model. Of the different measures of basin gradient, the percentage of the area with slopes greater than or equal to 30% and ruggedness were significant variables, appearing either in combination or separately. Soil properties, including the percent clay, the percent organic matter, the hydrologic group, the liquid limit, and the sorting of the burned soil grain-size distribution, either in combination or separately, were identified as significant by the five models. These variables, acting in combination, best separated basins that produced debris flows from those that did not produce debris flows. The other potential explanatory variables (measures of gradient, aspect, burned extent, soil properties, and rainfall) were not significant variables in the logistic regression models. Note that each of these models produces somewhat different results.

Model Verification

Success rate curves were used to evaluate the relative strength of each of the five models (Fig. 3) (Chung and Fabbri, 2003). These curves

TABLE 2. SUMMARY OF UNIVARIATE SPEARMAN'S ρ CORRELATIONS AND MULTIVARIATE LOGISTIC REGRESSION ANALYSES

	Spearman's ρ from univariate correlations	Model A	Model B	Model C	Model D	Model E
Sensitivity		44%	40%	41%	41%	40%
McFadden's ρ^2		0.35	0.31	0.30	0.27	0.26
Logistic regression constant		–0.7 (0.797)	–7.6 (0.000)	4.8 (0.132)	–0.3 (0.865)	–0.6 (0.707)
Topographic variables						
Average gradient	0.22	—	—	—	—	—
Percentage of basin area with gradients ≥30%	0.37	0.03 (0.035)	—	—	—	—
Percentage of basin area with gradients ≥50%	0.11	—	—	—	—	—
Ruggedness	0.49	–1.6 (0.000)	–1.10 (0.002)	—	—	—
Relief ratio	0.49	—	—	—	—	—
Aspect	0.19	—	—	—	—	—
Burn severity variables						
Percentage of basin area burned at low severity	–0.32	—	—	—	—	—
Percentage of basin area burned at moderate severity	0.32	—	—	—	—	—
Percentage of basin area burned at high severity	0.09	—	—	—	—	—
Percentage of basin area burned at moderate and high severity (percent)	0.54	0.06 (0.000)	0.06 (0.000)	0.05 (0.000)	0.04 (0.000)	0.04 (0.000)
Percentage of basin area burned at high, moderate and low severities	0.50	—	—	—	—	—
Soil property variables						
Grain-size distribution median	0.32	—	—	—	—	—
Grain-size distribution mean	–0.06	—	—	—	—	—
Grain-size distribution sorting	0.50	—	—	—	1.9 (0.000)	1.9 (0.000)
Grain-size distribution skewness	0.35	—	—	—	—	—
Clay content (percent)	0.53	0.2 (0.001)	0.09 (0.017)	0.2 (0.001)	—	—
Available water capacity	0.53	—	—	—	—	—
Permeability	–0.44	—	—	—	—	—
Erodibility	0.34	—	—	—	—	—
Organic matter (percent)	–0.27	—	–1.4 (0.025)	—	–1.0 (0.087)	—
Soil thickness	0.51	—	—	—	—	—
Liquid limit (percent)	0.38	–0.4 (0.001)	—	–0.4 (0.001)	—	—
Hydrologic group	–0.15	—	—	–1.5 (0.000)	—	—
Hydric capacity	0.14	—	—	—	—	—
Storm rainfall variables						
Total storm rainfall	0.25	—	—	—	—	—
Storm duration	0.06	—	—	—	—	—
Average storm intensity (mm/h)	–0.01	0.07 (0.004)	0.06 (0.002)	0.07 (0.004)	0.06 (0.000)	0.05 (0.000)
Maximum 10 min rainfall intensity	–0.12	—	—	—	—	—
Maximum 15 min rainfall intensity	–0.43	—	—	—	—	—
Maximum 30 min rainfall intensity	–0.13	—	—	—	—	—
Maximum 60 min rainfall intensity	0.28	—	—	—	—	—

Note: Sensitivity is the percentage of basins that produced debris flows with a calculated probability greater than 50%; McFadden's ρ^2 is a relative measure of the strength of each logistic regression model; values not enclosed in parentheses are logistic regression coefficients; values enclosed in parentheses are individual p values; — indicates no observed relation. Units are given for those independent variables found to affect debris-flow occurrence and are not dimensionless.

indicate that models A, B, and C (defined in Table 2) result in the highest proportion of actual debris flow–producing basins being characterized by the highest calculated probabilities; hence, they are the strongest models. The other models also deviate sufficiently from the 1:1 line to assume that they also adequately characterize the probability of postfire debris-flow occurrence. The fact that all five models are adequate and yet each produces somewhat different results suggests that different models might be more effective in predicting the probability of postfire debris flows in different settings.

Debris-Flow Volume Model

A plausible mean volume of material (V, in m^3) deposited by a debris flow at the outlet of a recently burned basin in the Intermountain West can be estimated from the multivariate regression model:

$$\ln V = 7.2 + 0.6(\ln A) + 0.7(B)^{1/2} + 0.2(T)^{1/2} + 0.3, \quad (2)$$

where A (in km^2) is the area of the basin having slopes greater than or equal to 30%, B (in km^2) is the area of the basin burned at high and moderate severity, T (in mm) is the total storm rainfall, and 0.3 is a bias correction that changes the predicted estimate from a median to a mean value (Helsel and Hirsch, 2002). The R^2 value and standard error of the residuals for this model are 0.83 and 0.90, respectively. Additional explanatory variables of gradient, burned extent, and rainfall produced less satisfactory models.

Model Verification

The model for debris-flow volume was verified using data from 21 basins not used in the generation of the model by comparing predicted values with reported values (Gartner et al., 2008). Eighty-seven percent of the actual volumes were within the 95% prediction interval, or within two standard errors of the predicted values on a one-to-one correspondence line. All of the reported volumes were within one order of magnitude of the volumes predicted by the model (Fig. 4).

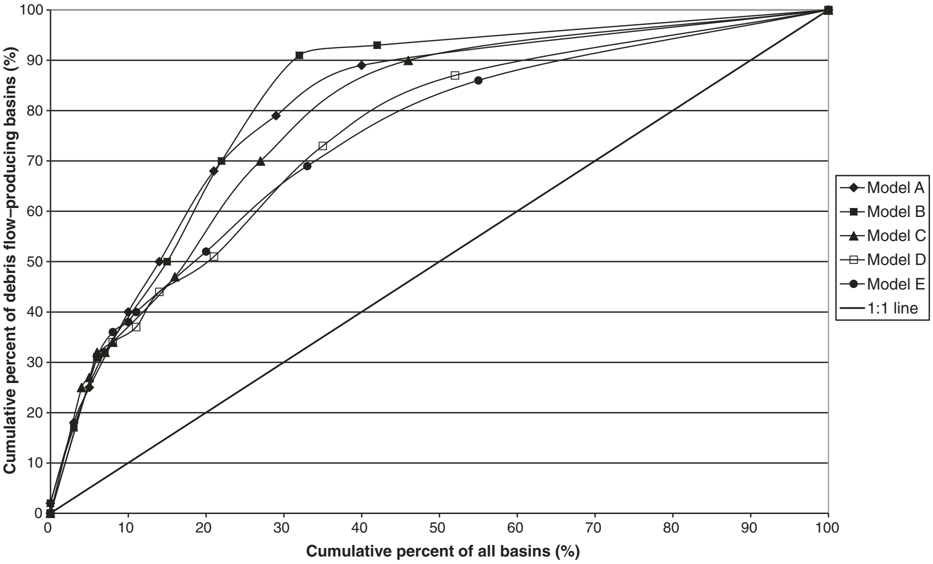

Figure 3. Success rate curves calculated using the method of Chung and Fabbri (2003) for each of the five logistic multiple regression models. The 1:1 line indicates a random distribution. The steepest curves located closest to the *y*-axis indicate the highest success and represent higher probabilities of occurrence calculated for those basins that actually produced debris flows.

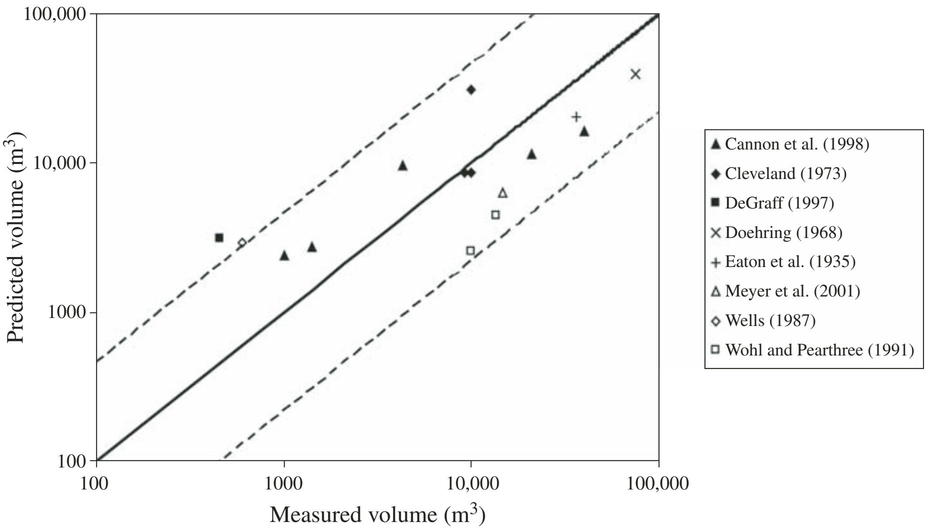

Figure 4. Comparison of debris-flow volume estimates reported in the literature to model predictions. The solid line indicates an exact fit, and the dashed lines represent the 95% prediction interval or two standard errors of the predicted values.

HAZARD ASSESSMENT OF BASINS BURNED BY HOT CREEK FIRE, IDAHO

Using data from the 2003 Hot Creek fire in central Idaho as an example, we illustrate how the debris-flow probability and volume models can be applied in a GIS framework to assess postfire debris-flow hazards for given storm conditions. The Hot Creek fire burned 120 km^2 of a subalpine fir ecosystem in steep (40%–75% gradients) mountainous terrain in the upper Middle Fork Boise River drainage, approximately 3 km west of the historical backcountry mining community of Atlanta, Idaho. The burned basins are strongly dissected by first- and second-order channels (Figs. 5A and 5B), and the elevation ranges from 1500 m along the Middle Fork Boise River corridor to nearly 2800 m in the vicinity of Steel Mountain. Sixty-two percent, or 80 km^2, of the area was burned at moderate and high severities (Fig. 5A). The area is underlain by the Late Cretaceous granitic Idaho Batholith. Granodiorite, quartz monzonite, and quartz diorite have weathered to form well-drained, noncohesive soils with little horizon development and moderate to low fertility (Boise National Forest, 2003, written commun.). Cool, moist, moderately deep sandy loam soils occupy north and east aspects and support forest vegetation.

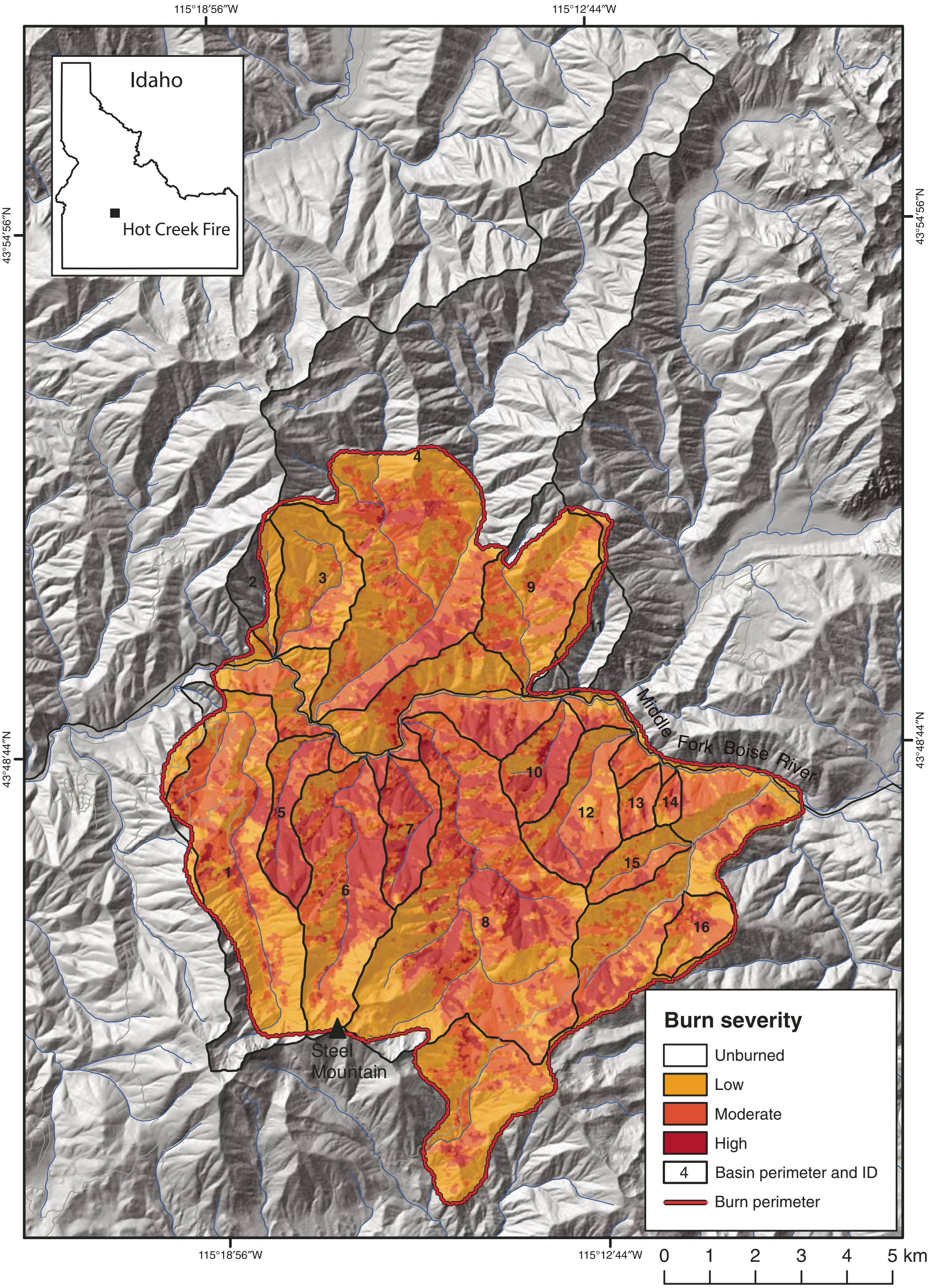

Figure 5 (*on this and following page*). **(A) Shaded relief image of area burned by the Hot Creek fire showing burn severity and basins evaluated. Burn severity map is from Boise National Forest (Boise National Forest, 2003, written commun.).**

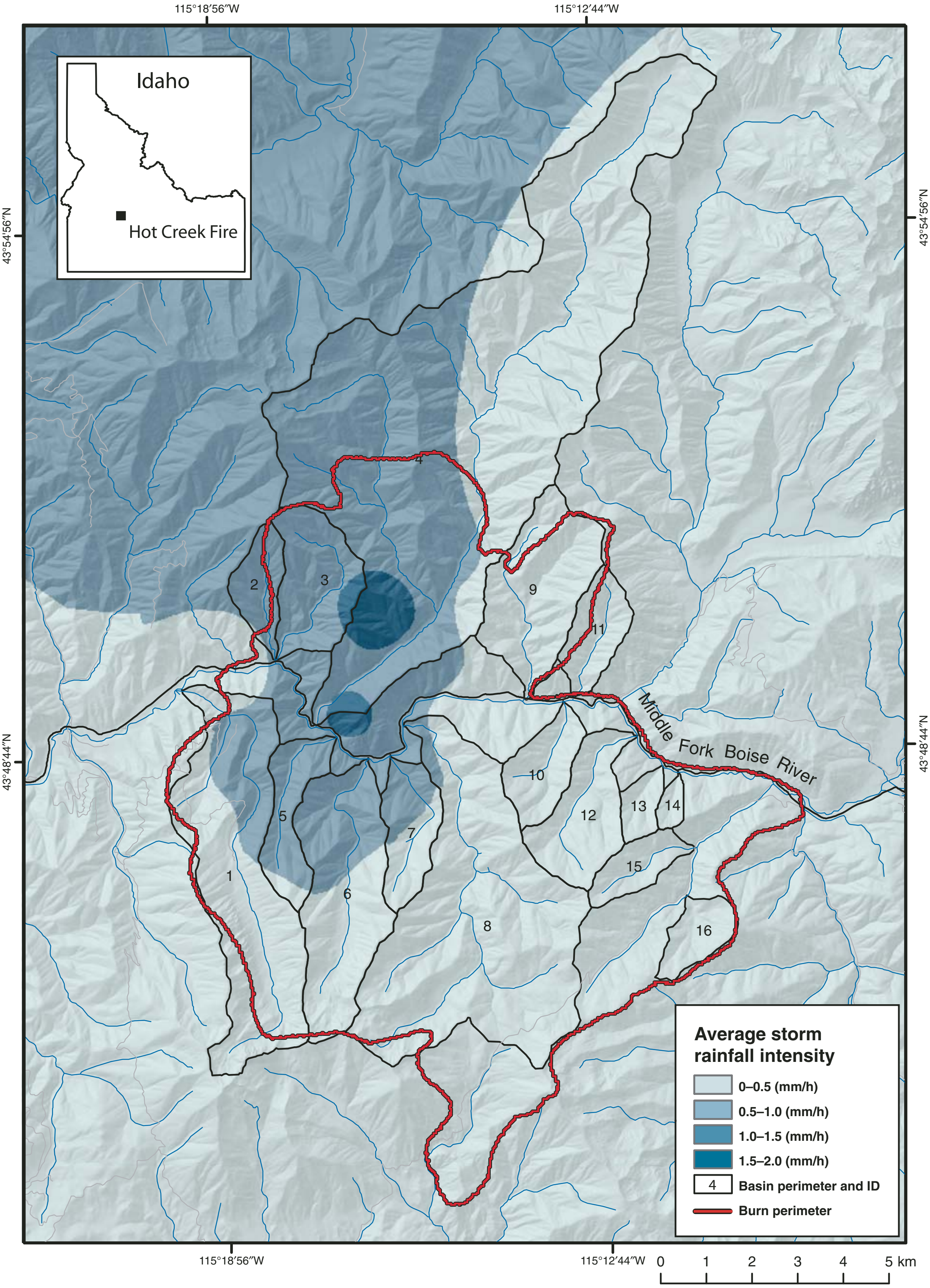

Figure 5 (*continued*). (B) Average rainfall intensity of 3 August 2003 storm over Hot Creek fire. Storm data from radar imagery were provided by Jay Briedenbach, National Weather Service (2003).

Granular, coarse sandy soils are found on south-facing slopes, which are mostly dry and sparsely vegetated. Deposits of glacially derived materials mantle some hillslopes.

For the Hot Creek assessment, 16 burned basins were delineated using a 10 m DEM and GIS hydrological tools. The outlets of basins to be evaluated were located at breaks in slope between mountain fronts and valleys, or at the location of an expected general transition between erosion and deposition (Figs. 5A and 5B). Basin outlets were positioned such that the sizes of basins evaluated ranged between 0.01 km^2 and 30 km^2, comparable to the basin sizes used in the development of the volume-estimation regression model. If necessary, basins larger than 30 km^2 can be subdivided into tributaries to the main channel. Basin outlets can also be located at road crossings if culvert capacities are in question, above reservoirs where sediment input is a concern, or above identified cultural features at risk. For example, in this assessment, concern about debris-flow impact to culverts in the dirt road that travels up the unnamed, easternmost burned basin prompted location of basin outlets at road crossings, rather than at the junction with the Middle Fork Boise River. It is also not necessary to evaluate every basin within the burned area. For example, the basin that drains off Steel Mountain to the south, although burned, showed no potential downstream impact, and so is not included in this analysis. Areas that are not well-defined basins, like those between basins 4 and 9, and between basins 8 and 10 along the Middle Fork Boise River, are also not included.

Once basins of interest were identified, basin outlets were positioned on a detailed stream network with the visual aid of a shaded-relief image. The watershed boundaries were automatically generated from the basin outlets using GIS hydrological tools.

Debris-Flow Probability Calculation and Map

The probability of debris-flow occurrence was calculated for each of the 16 basins using probability model A as an example, where

$$P \text{ (the probability of debris-flow occurrence)} = e^x/(1 + e^x),$$

and

$$x = -0.7 + 0.03(\%A) - 1.6(R) + 0.06(\%B) + 0.07(I) + 0.2(C) - 0.4(LL),$$

where $\%A$ is the percentage of the basin area with gradients greater than or equal to 30%, R is basin ruggedness, $\%B$ is the percentage of the basin area burned at high and moderate severity, I is average storm rainfall intensity (in mm/h), C is clay content (in %), and LL is the liquid limit. Table 2 provides the constants and coefficients for this model, as well as for an additional four models.

For each basin, values for each of the input variables for the model were determined. Table 3 shows measured parameters used in the assessment of debris-flow probability for the Hot Creek fire area. Basin area and measures of gradients were obtained using spatial analyst tools with 10 m DEMs, the basin areas burned at different severities were characterized from the watershed response map developed by the Burned Area Emergency Response (BAER) Team (Boise National Forest, 2003) (Fig. 5A), and soil parameters were obtained from the STATSGO database (Schwartz and Alexander, 1995). If more than one value for any independent variable was present in a basin, a single, spatially weighted mean value for that parameter was calculated by multiplying each value by the percentage of the basin area in which that value occurred and summing each of these products.

For this illustration, rainfall input into the model was a radar-derived rainfall distribution of an actual storm that impacted the area on 3 August 2003 (Fig. 5B). However, rainfall input into the model can be either as a single average intensity of a storm of interest, of a set of storms, or as a distributed storm across the burned area. Cannon and Gartner (2005) found that in the Intermountain West, the great majority of debris-flow events occur in response to low-recurrence (<2–10 years), low-duration (<1 h) convective thunderstorms. We recommend evaluating storms, or sets of storms, of similar recurrence and durations when using this approach (e.g., Cannon et al., 2003b).

A design rainfall must be included in the analysis. Because the models presented here do not have zero intercepts, it would be possible to calculate probability of debris flow and some volume even without rain. However, rainfall is the driver of the response, and so must be included.

After values of debris-flow probability are calculated for each basin, they are proportioned into classes and assigned a relative ranking to be presented in map form (Table 3; Fig. 6A). In this case, we divided the probabilities into four classes: 0%–25%; 26%–50%; 51%–75%; and 76%–100%. For the Hot Creek setting, the probability model identifies nine basins as having a greater than 75% probability of debris-flow occurrence, five as having between 51% and 75% probability, none with a probability between 26% and 50%, and two with less than a 25% chance of producing debris flows. For illustration purposes, the probability ranking is shown as a function of the entire basin, even if only a portion of the basin is burned. Note that every burned basin has some probability of generating debris flows. It may be low, but there is still a chance. This fact points to the necessity of addressing the additional question of the potential volume of debris flows.

Debris-Flow Volume Calculation and Map

We used Equation 2 to calculate potential debris-flow volumes. Input variables consist of the area of the basin with gradients greater than or equal to 30%, area burned at high and moderate severity, and the total storm rainfall (Table 4). Measures of basin gradients were again obtained using spatial analyst tools with 10 m DEMs, and the basin areas burned at different severities were characterized from the watershed response map developed by the BAER Team (Fig. 5A). As in the probability assessment, we used a radar-derived rainfall distribution of an actual storm that impacted the area on 3 August 2003 (Fig. 5B).

As in the case of the probability calculation, values of debris-flow volume calculated for each basin were proportioned into classes and assigned a relative ranking to be presented in map form (Table 4; Fig. 6B). In this example, and because in our verification we found that all of the reported volumes were within one order of magnitude of the volumes predicted by the model, we divided the volumes into four order of magnitude classes: 0–1000 m^3; 1001–10,000 m^3; 10,001–100,000 m^3; and greater than 100,000 m^3.

For the Hot Creek fire, the volume model identified one basin as capable of producing close to 1000 m^3 of material, five basins that could produce between 1001 and 10,000 m^3 of material, eight basins that could generate between 10,001 and 100,000 m^3 of material, and two basins that could potentially generate more than 100,000 m^3 of material in response to the 3 August 2003 storm. For illustration purposes, the calculated volume ranking is shown as a function of an entire basin, even if only a portion of a basin is burned.

Combined Relative Hazard Map

Debris-flow hazards from a given basin can be considered as the combination of both probability and volume. For example, in a given setting, the most hazardous basins will show both a high probability of occurrence and a large estimated volume of material. Slightly less hazardous would be basins that show a combination of either relatively low probabilities and

TABLE 3. DATA FROM BASINS BURNED BY THE HOT CREEK FIRE USED TO CALCULATE THE PROBABILITY OF POSTFIRE DEBRIS FLOWS, THE CALCULATED PROBABILITY, AND THE PROBABILITY CLASS RANKING USED TO GENERATE MAP OF DEBRIS-FLOW PROBABILITIES (FIG. 6A)

Basin name	Basin ID	Percentage of basin area with gradients greater than or equal to 30% (%*A*)	Basin ruggedness (*R*)	Percentage of basin area burned at high and moderate severity (%*B*)	Average storm rainfall intensity (*I*, mm/h)	Soil clay content (*C*, %)	Soil liquid limit (*LL*, %)	Calculated probability (*P*, %)[†]	Probability class ranking[§]
Hot Creek	1	89.4	0.41	41.0	10.7	9.2	13.25	67	3
Unnamed	2	98.4	0.76	2.7	19.6	9.2	13.25	24	1
Steppe Creek	3	98.1	0.52	31.2	25.1	9.2	13.25	75	3
Black Warrior Creek	4	91.8	0.18	15.1	17.2	9.2	13.25	52	3
Steel Creek*	5	94. 6	0.64	86.4	21.3	9.2	13.25	98	4
Lake Creek*	6	92.0	0.42	67.2	13.0	9.2	13.25	92	4
Bear Creek*	7	97.1	0.61	92.9	14.6	9.2	13.25	98	4
Bald Mtn Creek*	8	89.3	0.27	63.3	4.9	9.2	13.25	86	4
Eagle Creek	9	94.7	0.35	38.1	6.9	9.2	13.25	64	3
Burnt Log Creek	10	94.7	0.48	79.4	5.7	9.2	13.25	93	4
Snyder Creek	11	97.1	0.53	1.9	7.9	9.2	13.25	16	1
Fall Creek	12	92.9	0.47	72.2	2.5	9.2	13.25	88	4
Unnamed	13	96.7	0.77	86.1	3.7	9.2	13.25	92	4
Unnamed	14	98.8	0.95	78.7	4.8	9.2	13.25	87	4
West James Creek	15	90.8	0.55	49.7	3.7	9.2	13.25	65	3
East James Creek	16	84.7	0.36	56.6	5.2	9.2	13.25	77	4

*Debris-flow–producing basin in response to 3 August 2003 storm.

[†] Probability calculated using model A.

[§] Based on four class divisions: 1—0% to 25%; 2—26% to 50%; 3—51% to 75%; and 4—76% to 100%.

larger volume estimates or high probabilities and smaller volume estimates. The lowest relative hazard would be for basins that show both low probabilities and the smallest volumes. We thus suggest the possibility of combining the two maps to produce a single map of relative hazard ranking. By assigning rankings between 1 and 4 (with 4 being the highest) to both the probability and volume classes, adding the class ranks together, and then proportioning this value into classes, a single combined relative hazard ranking can be obtained for each basin (Table 5). A final map showing the combined relative hazard can then be generated (Fig. 6C). This map shows the spectrum of predicted basin response, from those basins with the lowest probability of producing the smallest events (basins 2 and 11) to those basins with the highest probability of producing the largest events (basins 4, 5, 6, 7, 8, 10, and 12). For illustration purposes, the combined relative ranking is shown as a function of an entire basin, even if only a portion of a basin is burned.

Application of the probability and volume models and calculation of the combined relative hazard ranking do not provide information on potential areas that can be impacted by debris flows as they travel downstream from the evaluated basins. However, we have found that it is often necessary to indicate, in a general sense, downstream reaches that can potentially be impacted by debris flows, as shown in Figures 6A, 6B, and 6C, to adequately convey the potential hazards on maps generated using this approach.

PREDICTIVE STRENGTH OF PROBABILITY, VOLUME, AND COMBINED MODELS IN CENTRAL IDAHO

On 3 August 2003, a thunderstorm impacted basins that had been burned by the Hot Creek fire in July 2003. The resultant basin response provided the opportunity to qualitatively evaluate the predictive strength of the five debris-flow probability models, the debris-flow volume model, and the combined mapping approach in this setting. The hour-long storm focused over the burned area, and radar estimates of precipitation intensity ranged between 2 and 45 mm/h (Fig. 5B; Table 4). Of the 16 basins burned by the Hot Creek fire and evaluated in this study, four produced debris flows in response to this storm: Steel Creek, Lake Creek, Bear Creek, and Bald Mountain Creek; the remaining basins showed evidence of sediment-laden floods (Tables 3, 4, and 5). The lack of discrete landslide scars at the heads of the debris-flow paths suggests that the flows were generated through progressive bulking of runoff with material eroded from hillslopes and from channel incision (Fig. 7).

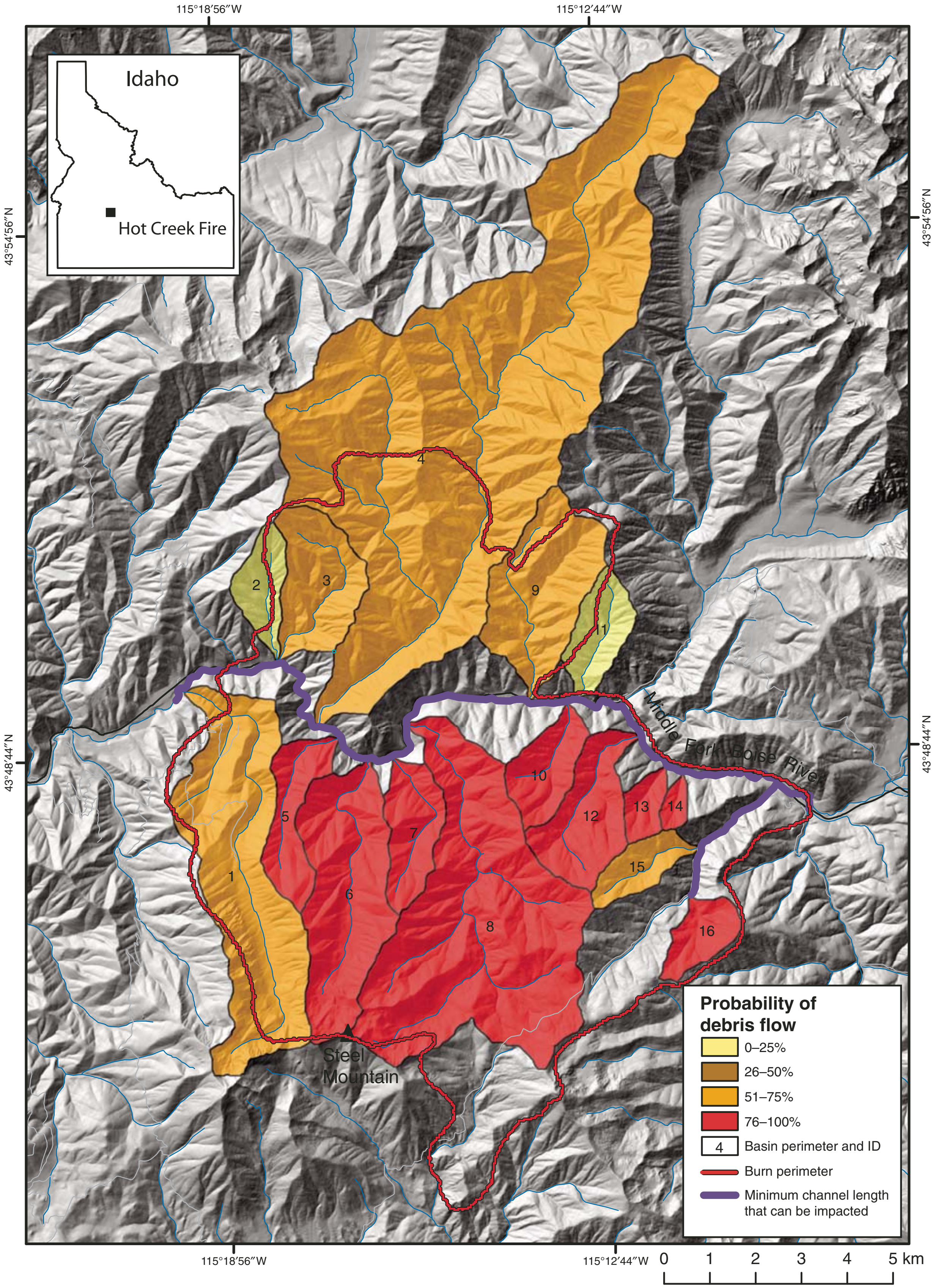

Figure 6 (*on this and following two pages*). **(A) Map of probability of debris-flow occurrence for basins burned by the Hot Creek fire in response to the 3 August 2003 storm (cf. Table 3).**

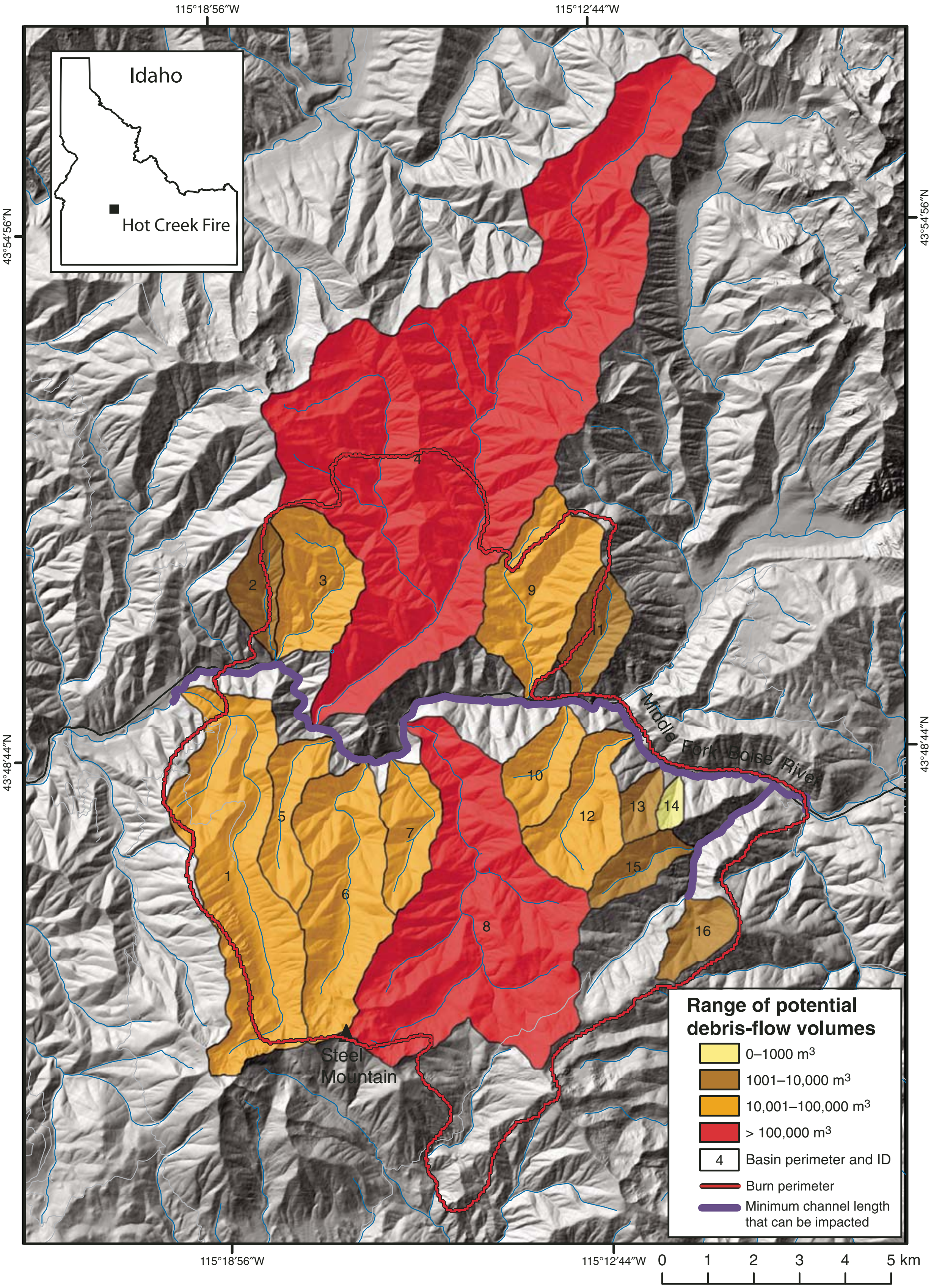

Figure 6 (*continued*). (B) Map of estimated debris-flow volumes from basins burned by the Hot Creek fire in response to the 3 August 2003 storm (cf. Table 4).

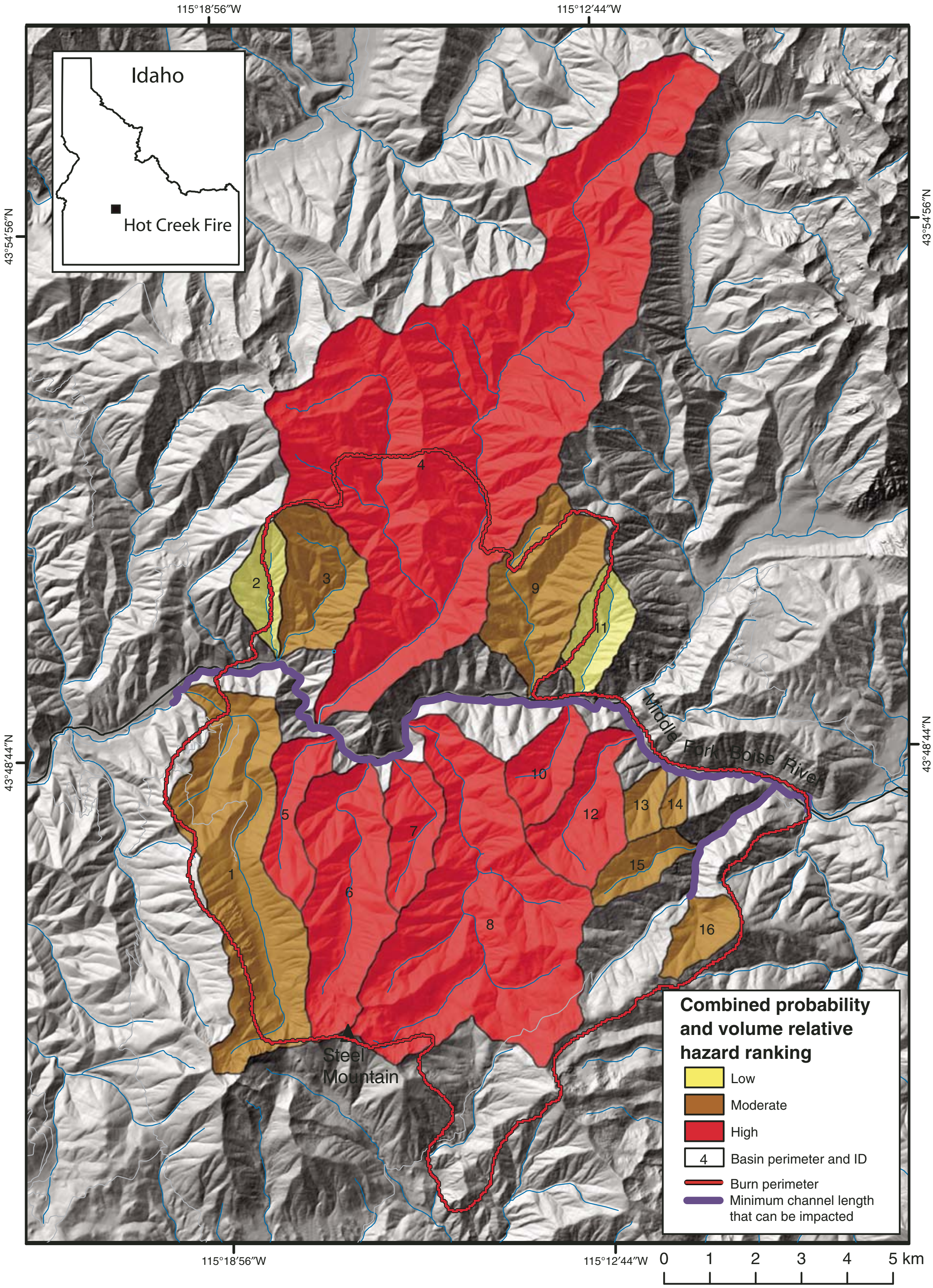

Figure 6 (*continued*). (C) Relative postfire debris-flow hazard map for Hot Creek fire in response to the 3 August 2003 storm. Map was generated by combining probability and volume class rankings (cf. Table 5).

TABLE 4. DATA FROM BASINS BURNED BY THE HOT CREEK FIRE USED TO CALCULATE THE VOLUME OF POSTFIRE DEBRIS FLOWS, THE CALCULATED VOLUME, AND THE VOLUME CLASS RANKING USED TO GENERATE MAP OF POTENTIAL DEBRIS FLOW VOLUMES (FIG. 6B)

Basin name	Basin ID	Area of basin with gradients greater than or equal to 30% (A, km^2)	Area of basin burned at high and moderate severity (B, km^2)	Total storm rainfall (T, mm)	Calculated volume (V, m^3)	Volume class ranking[†]
Hot Creek	1	12.9	5.9	10.7	88,000	3
Unnamed	2	2.1	0.1	19.6	8500	2
Steppe Creek	3	4.7	1.5	25.1	29,000	3
Black Warrior Creek	4	48.3	7.9	17.2	304,000	4
Steel Creek*	5	2.9	2.7	21.3	27,000	3
Lake Creek*	6	8.5	6.2	13.0	77,000	3
Bear Creek*	7	3.1	3.0	14.6	26,000	3
Bald Mtn Creek*	8	19.6	13.9	4.9	228,000	4
Eagle Creek	9	6.7	2.7	6.9	30,000	3
Burnt Log Creek	10	2.6	2.2	5.7	15,000	3
Snyder Creek	11	2.5	0.0	7.9	5500	2
Fall Creek	12	4.2	3.3	2.5	21,000	3
Unnamed	13	1.1	1.0	3.7	5700	2
Unnamed	14	0.5	0.4	4.8	2900	1
West James Creek	15	1.7	0.9	3.7	7100	2
East James Creek	16	1.6	1.1	5.2	7900	2

*Debris-flow–producing basin in response to 3 August 2003 storm.

[†] Based on four class divisions: 1—1 to 1000 m^3; 2—1001 to 10,000 m^3; 3—10,001 to 100,000 m^3; 4—>100,000 m^3.

Debris fans were deposited in the Middle Fork Boise River and, in some cases, either dammed the river completely or pushed it against its north bank (Fig. 8). The road to Atlanta along the Middle Fork Boise River was destroyed by these events.

Prediction rate curves (Fig. 9) indicate that models A, B, and C produced the highest proportion of basins that actually produced debris flows. These models best assessed postfire debris-flow susceptibility in this part of the Intermountain West. Models D and E were less satisfactory in this setting, in that debris flows were produced from basins for which low potential probabilities were calculated.

Unfortunately, comparable information for evaluating the predictive strength of the volume model in this setting is not available. However, field estimates of debris flows depositing 10,000–20,000 m^3 of material in the Middle Fork Boise River at the Lake Creek tributary (Boise National Forest, 2004) compare roughly with a model estimate of 48,000 m^3, and a field estimate of 80,000–100,000 m^3 of cumulative material deposited by debris flows from Lake, Steele, and Bear Creeks (Boise National Forest, 2004, written commun.) compares well with a model prediction of 77,000 m^3. Both estimates are within the 95% confidence interval estimate of the model shown in Figure 4.

The map of combined relative hazard (Fig. 6C) shows six basins for which the highest probabilities of producing the largest events were predicted. Four of these basins did indeed produce debris flows of significant size, indicating that the approach may produce a conservative result that would err on the side of caution. The two basins identified as presenting high relative hazards but that did not produce debris flows are the smallest and the largest of the sample, perhaps illustrating the pitfalls of linear statistical analyses.

USES AND LIMITATIONS OF APPROACH

The approach described here for assessing debris-flow hazards provides estimates of the probability of debris-flow occurrence and potential debris-flow volumes that can issue from outlets of burned basins over extensive areas in the Intermountain West in response to short-duration (<1 h), low-recurrence-interval (<2–10 years) convective thunderstorms. Application of the predictive models before the occurrence of wildfires using a projected burn severity distribution and a specified, or design, storm can help identify sensitive drainage basins that could benefit from management efforts to prevent catastrophic burning. Application of these models using conditions of a specified storm, or set of storms, immediately following a fire will provide information necessary to make effective and appropriate mitigation and planning decisions, and will guide decisions for evacuation, shelter, and escape routes in the event of forecasts of storms of similar magnitude to those evaluated. The models described here can also potentially be linked with real-time precipitation forecasts and measurements to generate dynamic maps of potential postfire debris-flow hazards as storm conditions develop. We suggest the use of these empirical tools until a better understanding of the physical processes that generate debris flows can be developed.

TABLE 5. COMBINED PROBABILITY AND VOLUME CLASS RANKINGS FOR BASINS BURNED BY THE HOT CREEK FIRE USED TO GENERATE RELATIVE HAZARD MAP (FIG. 6C)

Basin name	Basin ID	Probability class ranking	Volume class ranking	Combined hazard ranking (probability class + volume class)	Combined relative hazard ranking[†]
Hot Creek	1	3	3	6	Moderate
Unnamed	2	1	2	3	Low
Steppe Creek	3	3	3	6	Moderate
Black Warrior Creek	4	3	4	7	High
Steel Creek*	5	4	3	7	High
Lake Creek*	6	4	3	7	High
Bear Creek*	7	4	3	7	High
Bald Mtn Creek*	8	4	4	8	High
Eagle Creek	9	3	3	6	Moderate
Burnt Log Creek	10	4	3	7	High
Snyder Creek	11	1	2	3	Low
Fall Creek	12	4	3	7	High
Unnamed	13	4	2	6	Moderate
Unnamed	14	4	1	5	Moderate
West James Creek	15	3	2	5	Moderate
East James Creek	16	4	2	6	Moderate

*Debris-flow–producing basin in response to 3 August 2003 storm.

[†] Based on three class divisions: 1 to 3—low; 4 to 6—moderate; 7 to 9—high.

Figure 7. Channel incision from passage of debris flow in Lake Creek tributary to the Middle Fork Boise River. Photograph by Dave Hilgendorf, U.S. Department of Transportation Federal Highway Administration.

The potential for debris-flow activity decreases with time and the concurrent revegetation and stabilization of hillslopes. A compilation of information on postfire runoff events reported in the literature from throughout the intermountain western United States indicates that most debris-flow activity occurs within about 2 years following a fire (Gartner et al., 2004). We thus conservatively expect that maps generated using this approach may be applicable for approximately 3 years after fires for the storm conditions considered.

Over longer time frames (years to decades after a fire), decay of tree-root systems may reduce the shear strength of hillslope materials and, along with reduced evapotranspiration, can result in the generation of shallow landslides that mobilize into debris flows (Meyer, 2002; Swanson, 1981; Ziemer, 1981). This assessment method does not address these processes.

The assessments presented here are specific to postfire debris flows; significant hazards from flash flooding can remain for many years after a fire and will require separate assessments. Furthermore, this approach does not provide science-based information on potential areas that can be inundated by fire-related debris flows. It may be necessary to indicate the areas that can potentially be impacted by debris flows on maps generated using this approach to adequately convey the potential hazards. Because the data used to generate the probability model come exclusively from the Intermountain West, application of the probability model (and thus the combined relative hazard assessment technique) is not appropriate in other climatologic and geographic settings. However, similar region-specific models (for example, Southern California) can be developed, given appropriate data.

SUMMARY AND CONCLUSIONS

In this paper, we identified those factors that most strongly control the debris-flow response of burned basins in the Intermountain West to short-duration, low-recurrence-interval convective thunderstorms, and we developed integrated, multivariate statistical models that can be used to estimate the probability and volume of potential debris flows. The models are functions of combinations of different measures of burn severity, basin morphology, material properties, and storm rainfall. A combination of the probability and volume assessments can be used to identify a relative hazard ranking of recently burned basins.

Logistic multivariate regression analyses indicated that the percentage of basin burned at a combination of high and moderate severities and the average storm rainfall intensity were strongly correlated with the debris-flow response. Of the different measures of basin gradient evaluated, the percentage of basin area with slopes greater than or equal to 30% and basin ruggedness were significant variables, either in combination or separately. Soil properties, including the percent clay, the percent organic matter, the hydrologic group, the liquid limit, and the sorting of the burned soil grain-size distribution, either in combination or separately, were identified as significant in the modeling effort. These variables, acting in combination, are those that best separated basins that produced debris flows from those that did not produce debris flows. Additional measures of gradient, aspect, burned extent, soil properties, and rainfall intensities were not significant variables in the logistic regression models. The physical significance of these findings requires further evaluation.

Although five models for fire-related probability were found to be statistically valid, comparisons of model predictions with actual debris-flow events indicate that two of the five models do a better job than the other three of predicting debris-flow probability in central Idaho. These findings point to the necessity of model verification for specific settings, and they indicate that some of the models may be better suited to different settings in the Intermountain West.

A multiple regression analysis indicated that the mean volume of debris-flow material that can exit a basin outlet can be represented as a combined effect of the area of the basin burned at a combination of high and moderate severities, the area of the basin having slopes greater than or equal to 30%, and the total storm rainfall. Additional measures of gradient, burned extent, and rainfall considered here produced less satisfactory models. As with the probability model, the physical significance of these findings requires further evaluation.

The parameters included in both the probability and volume models are considered to be possible first-order effects that can be rapidly evaluated immediately after a fire. Other conditions than those used in the models may certainly affect debris-flow occurrence and volumes from recently burned basins. For example, an abundance of material stored in a channel, either dry ravel or alluvium, will affect debris-flow frequency and magnitude (Bovis and Jakob, 1999). A frequently occurring fire-flood sequence, like that which characterizes Southern California basins, may similarly limit material availability (e.g., Spittler, 1995). The erodibility of hillslope and channel materials will also impact debris-flow occurrence and magnitude.

Continuing work is focusing on assessing effectiveness of the probability models in different settings throughout the Intermountain

West and developing probability and volume models that are specific to the Southern California climatologic and geologic setting. This effort will evaluate the time since the last fire and the last erosive event on debris-flow generation and magnitude, and will focus particularly on the development of methods to better characterize the effects of physical properties on the erodibility of surficial materials and debris-flow generation, and on the effect of different degrees of basin confinement on debris-flow occurrence.

Figure 8. Aerial view of debris-flow deposits in the Middle Fork Boise River. The river was completely dammed at this location, and the road to Atlanta, Idaho, was destroyed. Photograph by Dave Hilgendorf, U.S. Department of Transportation Federal Highway Administration.

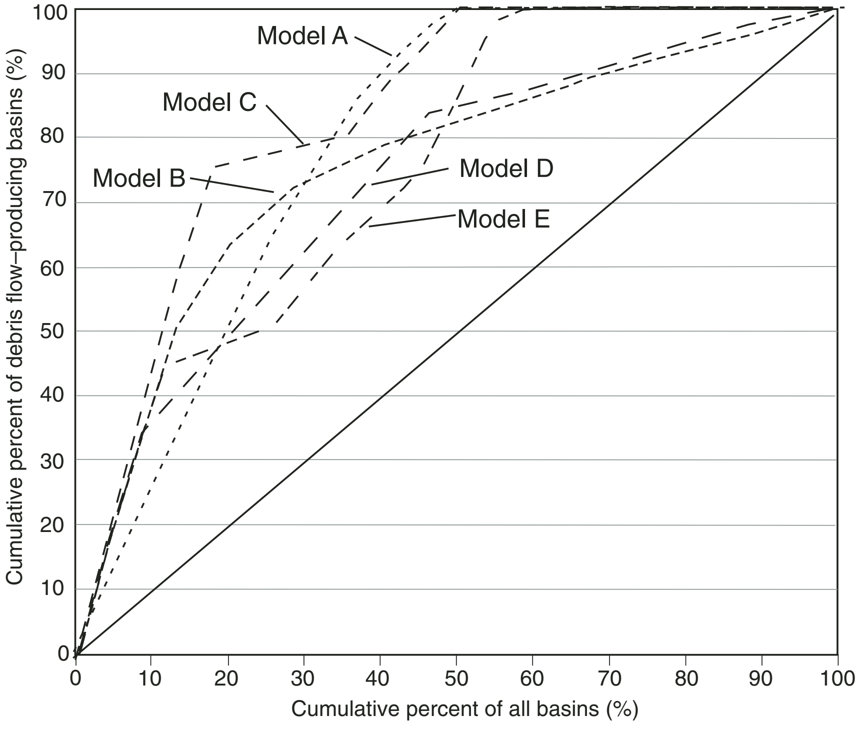

Figure 9. Prediction rate curves for probability models from Hot Creek fire showing the proportions of actual debris flow–producing basins to the predicted probabilities. Models A and C produced the best predictions of the 3 August 2003 event in this setting. The 1:1 line indicates a random distribution, and the steepest curves located closest to the *y*-axis indicate the strongest predictions.

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