OPEN-FILE REPORT OF-03-332

ASSESSMENT OF POTENTIAL DEBRIS-FLOW PEAK DISCHARGES FROM BASINS BURNED BY THE 2002 MISSIONARY RIDGE FIRE, COLORADO

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2003

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Abstract

These maps present the results of assessments of peak discharges that can potentially be generated by debris flows issuing from the basins burned by the Missionary Ridge fire of June 9 through July 14, 2002, near Durango, Colorado. The maps are based on a regression model for debris-flow peak discharge normalized by average storm intensity as a function of basin gradient and burned extent, and limited field checking. A range of potential peak discharges that could be produced from each of the burned basins between 1 ft3/s (0.03 m3/s) and 6,446 ft3/s (183 m3/s) is calculated for the 5-year, 1-hour storm of 0.80 inches (20 mm). Potential peak discharges between 1 ft3/s (0.03 m3/s) and >8,000 ft3/s (227 m3/s) are calculated for the 25-year, 1-hour storm of 1.3 inches (33 mm) and for the 100-year, 1-hour storm of 1.8 inches (46 mm). These maps are intended for use by emergency personnel to aid in the preliminary design of mitigation measures, and for the planning of evacuation timing and routes.

Introduction

The primary goal of this study is to estimate the potential magnitude of possible debris-flow events, for given storm conditions, from the basins burned by the Missionary Ridge fire of June 9 through July 15, 2002. In this evaluation we calculate a range of peak discharges that can be generated by debris flow from individual burned basins using a multiple-regression model for peak discharge defined specifically for post-wildfire debris-flow activity. Identification of debrisflow hazards from burned drainage basins is necessary to make effective and appropriate mitigation decisions and can aid emergency personnel and citizens in their decisions about evacuation timing and routes.

Fire-Related Debris-Flow Hazards

Wildfire can have profound effects on a watershed. Consumption of the rainfall-intercepting canopy and of the soil-mantling litter and duff, intensive drying of the soil, combustion of soil-binding organic matter, and the enhancement or formation of water-repellent soils can result in decreased rainfall infiltration into the soil and subsequent significantly increased overland flow runoff in channels. Removal of obstructions by wildfire can enhance the erosive power of overland flow, resulting in accelerated erosion of material from hillslopes. Increased runoff can also erode significant volumes of material from channels, the net result being the transport and deposition of large volumes of sediment both within and down-channel from the burned area.

Debris flows are frequently produced in response to summer convective thunderstorm activity over basins burned by wildfire. Debris flows pose a hazard distinct from other sediment-laden flows because of their unique destructive power; debris flows can occur with little warning, can exert great impulsive loads on objects in their paths, and even small debris flows can strip vegetation, block drainage ways, damage structures, and endanger human life. For example, a summer thunderstorm triggered debris flows from the steep basins burned by the 1994 South Canyon fire on Storm King Mountain, Colorado (Cannon et al.,2001; Kirkham et al., 2000). This event inundated nearly 5 km of Interstate 70 with tons of rocks, mud, and debris. Thirty vehicles and their occupants were engulfed in the flows, and in two cases, were pushed into the Colorado River. Although some travelers were seriously injured, no deaths resulted from this event.

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In studies of debris-flow processes throughout the western U.S., Cannon (2001) demonstrated that the great majority of fire-related debris flows initiate through a process of progressive bulking of storm runoff with sediment eroded from both hillslopes and channels. Although some infiltration-triggered landsliding does occur in burned basins, these failures generally contribute a small proportion to the total volume of material transported from the basin (Cannon et al., 2001). This finding points to the relative importance of runoffdominated, rather than infiltration-dominated, processes of debris-flow initiation in recently burned basins, and indicates that methodologies developed for unburned basins to map landslide potential may not be appropriate for recently burned areas. As an alternative, this finding suggests that the relations traditionally defined between peak discharges of floods and basin characteristics may be useful in predicting the magnitude of potential debris-flow response from burned basins.

Methods

A multiple regression model developed using data measured from postwildfire debris flows is used to define the range of peak discharges that can potentially be generated from the basins burned by the Missionary Ridge fire.

The data used in the development of the model consists of measurements from 53 recently burned basins located throughout the western U.S., and is a compilation of information both from the published literature and our own monitoring efforts. The data consists of indirect estimates of peak discharge (computed using either critical-flow, super-elevation, or slope-area1 methods from field surveys (O'Connor et al., 2001)), measurements of basin area, total area of basin burned, area burned at high severity, average basin gradient, percent of slopes greater than or equal to 30% within a basin, percent of slopes greater than 50% within a basin (determined from either 10 or 30 m DEMs), and the average intensity of the debris-flow triggering storm. Debris flows in basins considered in the analysis were all reported to have been triggered by summer convective thunderstorms. Burn severity for each basin included in the database was characterized using either maps of burn severity generated by the Burned Area Emergency Rehabilitation (BAER) Team, or the Normalized Burn Ratio (NBR), which was determined from Landsat Thematic Mapper data (Key and Benson, 2000). The maps of burn severity are considered to reflect the effects of the fire on soil conditions and the potential hydrologic response, and are an amalgam representation of the condition of the residual ground cover, soil erodibility, and degree of fire-induced water repellency (USDA Forest Service, 2002).

The regression model consists of a physical representation of peak discharge relative to average rainfall intensity as a function of both basin gradient and burned extent:

$$\mathbf{Qp/I = f(gradient,\ burned\ extent),}$$

where Qp is the peak discharge (in m3/s) and I is the average storm rainfall intensity (in m/s). We considered the effects on Qp/I of three possible measures of gradient—the average basin gradient (in percent), and the percent of slopes greater than or equal to 30% within the basin, and the percent of slopes greater than or equal to 50% within the basin. We also evaluated the effects of two measures of burned extent—the total area burned (in m2), and the area burned at high severity (in m2). A series of statistical analyses were used to obtain the most robust regression model possible. We used a combination of statistical measures including Mallow's Cp, adjusted R2, the variance inflation factor, and the prediction error of the sum of squares to assess the quality of each model (Helsel and Hirsch, 2002). For a model to be accepted, we also tested for adherence to the assumptions of linearity, constant variance, and normally distributed residuals.

Statistical analyses of the post-wildfire debris flow database yielded the following relation as the best predictive equation of wildfire-related peak discharge:

$$Qp/I = -4.5 \times 10^{7} - 4.2 \times 10^{4}\%GE50\% + 1.1 \times 10^{7} \log A_b,$$

[1]Note that the slope-area method for determination of peak discharge is generally not assumed to be applicable for non-Newtonian debris flow. However, its use does allow for at least a relative measure of the debris-flow response of burned basin. For the steep watersheds from which these measurements were made, it is generally assumed that the discharge estimates obtained using this approach are conservative in the context of engineering design. where %GE50% is the percent of slopes greater than or equal to 50% within a basin, and A_b is the area burned within a basin (in m^2). Although the R^2_{adj} of 33% for this relation indicates significant scatter in the data used in the regression, and thus some uncertainly in the predicted values, the combination of additional measures of statistical quality indicated that this model was the best possible result, given the data presently available for post-wildfire debris flows. Note that the additional measures of gradient and burned extent considered here produced less satisfactory models.

To apply the model to the basins burned by the Missionary Ridge fire, we first delineated each burned basin on a 10-m DEM. The basin area and measures of gradient of each basin were extracted from the DEM data. Areas burned at varying severities within each basin were determined using the Normalized Burn Ratio (NBR), which was determined from Landsat Thematic Mapper data (Key and Benson, 2000). Values of peak discharge for the 5-year, 1-hour storm of 0.80 inches (20 mm), for the 25-year, 1-hour storm of 1.3 inches (33 mm) and for the 100-year, 1-hour storm of 1.8 inches (46 mm) (Miller et al., 1973) were then calculated by entering the measured variables into the multiple regression model. Because of the uncertainty associated with the statistical model and the measurements of peak discharge, we then grouped the estimated discharges into the classes shown on the maps. Note also that although significantly higher peak discharges can be calculated using the regression model, the highest field estimate of peak discharge in the database is 7,867 ft3/s (223 m3/s). For this reason, the highest peak discharge class defined for these maps consists of those values greater than 8,000 ft3/s (227 m3/s).

Field observations were used to identify the extent and abundance of potential sediment supply within the burned basins, as well as other factors that may affect the potential debris-flow discharge. After a preliminary version of the map was generated, field evaluations and measurements of the debris-flow response to storms throughout the summer of 2002 were used to determine if debris-flow potential was adequately represented, and a final version was produced.

Note that a fundamental assumption in the approach taken here is that, given sufficient rainfall, all basins burned by the Missionary Ridge fires are susceptible to debris-flow activity. This assumption is reasonable given the similarities between the geologic materials, basin morphologies, and burn characteristics of basins burned by the South Canyon fire in 1994 near Glenwood Springs that produced debris flows and the basins burned by the Missionary Ridge fire (Cannon, et al., 2001, Kirkham, et al., 2000). In addition, the geologic materials, basin morphologies and burn characteristics in the basins burned by the

Missionary Ridge fire are similar to those identified by Cannon (2001) as indicating a susceptibility to post-fire debris-flow activity based on analysis of the response of 95 recently burned basins throughout the western U.S.

Results

No shortages of material for debris-flow generation were observed in the basins evaluated in this study during aerial and ground field reconnaissance; abundant loose, unconsolidated material mantles the steep hillslopes and lines the highgradient channels throughout the burned area. Cannon (2001) identified these conditions as those likely to produce post-wildfire debris flows. In addition, the Cutler formation, a geologic formation lithologically and mineralogically similar to that which produced the fire-related debris flows from Storm King Mountain, underlies a large part of the area (Carroll et al., 1997; Carroll et al., 1998; Carroll et al., 1999; Gonzales, et al., 2002). Further, the Cutler, Hermosa, and Morrison formations and the Eolus Granite have a history of debris-flow activity in the area (USDA Forest Service, 2002).

Peak discharges calculated for basins burned by the Missionary Ridge fire for the 5-year, 1-hour storm of 0.80 inches (20 mm) ranged between 1 ft3/s (0.03m3/s) and 6,446 ft3/s (183 m3/s). Peak discharges for the 25-year, 1-hour storm of 1.3 inches (34 mm) and the 100-year, 1-hour storm of 1.8 inches (46 mm) ranged between 1 ft3/s (0.03m3/s) and >8,000 ft3/s (227 m3/s).

Our modeling indicates that in response to the 5-year storm, Coon Creek (on the east side of the Animas Valley), Red and Shearer Creeks (tributaries to the Florida River), and Red Creek (tributary to the Los Pinos River) have the potential to produce debris flows with peak discharges between 6,000 and 8,000 ft3/s (170 to 227m3/s).

In response to a 25-year storm on the east side of the Animas Valley, Coon Creek, Elkhorn Canyon, Stevens Creek, and Freed Canyon have the potential to produce debris flows in excess of 8,000 ft3/s (>227 m3/s). Red, Shearer, True Creeks, Youngs Canyon, and Long Hollow (all tributaries to the Florida River) have the potential for a similar response, as do Freeman, Jack, Red and Wilson Creeks, two unnamed creeks, and North Canyon in the Los Pinos River basin.

The modeling effort indicates that in response to a 100-year recurrence storm, all basins but those with the gentlest gradients and sparse burn can be expected to produce a debris-flow response in excess of 8,000 ft3/s (>227 m3/s).

Estimates of peak discharges from debris-flow events that occurred during the summer of 2002 in response to storms with 2 year, or less, recurrence intervals indicate that the values presented here for the 5-year storm are reasonable (Cannon et al., 2003)

Use and Limitations of the Map

These maps provide estimates of possible ranges of peak discharges of debris flows that can potentially generate from the basins burned by the Missionary Ridge fire in response to the 5-year, 25-year, and 100-year, 1-hour storm. The maps are intended to be used by emergency personnel and citizens to identify the possible magnitude, in terms of peak discharge, of the debris-flow response. This information can be used to focus additional mitigation efforts, to aid in the design of mitigation structures and in decisions for evacuation, shelter, and escape routes in the event of the prediction of summer thunderstorms of similar magnitude to those evaluated here. Note that the potential for debris-flow activity decreases with time and concurrent revegetation and stabilization of hillslopes. Although we are not aware of studies that address burned area recovery rates for terrains similar to those evaluated here, work by Moody and Martin (2001) in decomposed granite terrains in Colorado indicates that recovery to pre-fire conditions can occur within about 4 years of the fire. We thus conservatively expect that the maps presented here may be valid for approximately 5 years after the fire.

In addition to the potential dangers identified within these basins, areas downstream are also at risk. The fire destroyed homes at the mouths of some of these basins. In these areas, workers and residents may be busy cleaning and rebuilding sites. These people are at risk for impact by debris flows during rainfall events. In addition, there is a great possibility of culverts plugging, or being overwhelmed, and roads being washed out. Such events could strand motorists for long periods of time. In addition, some of the drainage crossings in the study area occur on blind curves where motorists could abruptly encounter debris-flow deposits on the road.

Further, two slump blocks that have moved into the channel of Coon Creek were observed during the field reconnaissance. These blocks are only about 2 meters thick, and we estimated their volume to be approximately 650 yd3 (500 m3). Additional shallow landslides have been observed in other basins throughout the burned area (M. Burke, USDA Forest Service, personal communication, May 2003). Although the majority of these landslides do not appear to be presently active, increased flow in the channel could potentially destabilize them by undercutting of their toes. Mobilization of these blocks into debris flows, or damming and subsequent failure could contribute material to potential debris flows. The method used here does not account for the potential contribution of material to any potential debris flows by either of these processes.

Note that the method used for the generation of these maps has not been thoroughly tested and reviewed; this is the first time the regression model has been applied to recently burned basins. However, the fact that the method is based on analysis of data from post-wildfire debris flows, rather than estimates of flood runoff with assumed sediment-bulking factors, is a significant advantage to this approach. In addition, in this analysis we present the potential debris-flow response of the burned basins as a function of basin gradient and burned extent. It is likely that other variables also affect the magnitude of the response; continuing effort is focused on collecting data to document such effects.

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This assessment supersedes that shown in USGS Open-File Report 02-323.