Emergency Assessment of Potential Debris-Flow Peak Discharges, Coal Seam Fire, Colorado

By Susan H. Cannon, John A. Michael, Joseph E. Gartner, Alan H. Rea, and Steven P. Garcia

Open-File Report
OF 02-379

U.S. Department of the Interior
U.S. Geological Survey

Abstract: This map presents the results of an emergency assessment of potential peak discharges that can be generated by debris flows issuing from the basins burned by the Coal Seam fire of June 2002, near Glenwood Springs, Colorado. The assessment is based on a regression model for debris-flow peak discharge as a function of average storm intensity, basin gradient, and burned extent, and limited field checking. A range of potential peak discharges for each of the burned basins is calculated for the 25-year, 1-hour storm of 1.3 inches. Peak discharges between 1 and greater than 250 cubic meters per second (greater than8830 cubic feet per second) were calculated for the given storm conditions. This map is intended for use by emergency personnel to aid in the preliminary design of mitigation measures, and 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 Coal Seam fire of June 2002. In this study we calculate a range of peak discharges that can potentially 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 debris-flow 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 the soil-mantling litter and duff, and the formation of water-repellent soils, can result in decreased rainfall infiltration into the soil and subsequent significantly increased overland flow and runoff in channels. Removal of obstructions by wildfire can enhance the erosive power of overland flow, resulting in accelerated erosion of material from hill slopes. 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.

Basins adjacent to those burned by the Coal Seam fire have a history of debris-flow activity following wildfires. In 1994, a summer thunderstorm triggered debris flows from the steep basins burned by the South Canyon fire on Storm King Mountain, Colorado (Cannon et al., 1998, Kirkham et al., 2000, Cannon et al., 2001). 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.

In studies of debris-flow processes throughout the Western United States, 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 hill slopes 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 runoff-dominated, 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 post-wildfire debris flows is used to define the range of peak discharges that can potentially be generated from the basins burned by the Coal Seam fire. The data used in the development of the model consists of measurements from 45 basins located throughout the Western United States, and is a compilation of information both from the published literature and our own monitoring efforts. The data consists of indirect peak discharge measurements (computed using either slope-area, critical-flow, or super-elevation techniques from field surveys), measurements of basin area, total area of basin burned, area burned at high severity, average basin gradient, percent of slopes greater than 30%, percent of slopes greater than 50% (all determined from 30-m DEMs), the relief ratio (measured as the change in elevation of the basin divided by the length of the longest stream channel extended to the drainage divide from 1:24,000-scale topographic maps), and the average intensity of the debris-flow triggering storm. Debris flows in basins considered in the analysis were all reported to be triggered by summer convective thunderstorms.

Note that although the slope-area and critical-flow methods for determination of peak discharge are generally not assumed to be applicable for non-Newtonian debris flow, they do allow for at least a relative measure of the debris-flow response of burned basins. For the steep slopes from which these measurements are made, it is generally assumed that the discharges estimated using these approaches are conservatively small (C. Parrett, U.S. Geological Survey, personal communication, 2002).

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

Qp/I = f (gradient, burned extent),

where Qp is the peak discharge (in cubic meters per second), and I is the average storm rainfall intensity (in m/s). We considered the effects of four possible measures of gradient on Qp/I – the average basin gradient (in percent), the relief ratio, the percent of slopes greater than 30%, and the percent of slopes greater than 50%. 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 = -2.17x108 + 4.04x107logAb+2.31x105percent of slopes greater than30%,

where Ab is the area burned (in m2). Although the adjusted R2 of 41% for this relation indicates significant scatter in the data used in the regression, and thus some uncertainly in the predicated values, the combination of measures of statistical quality indicated that this model was the best possible result, given the data presently at hand for post-wildfire debris flows. The alternative measures of gradient and burned extent considered here produced less satisfactory models.

To apply the model to the basins burned by the Coal Seam fire we first delineated the basins within the burned area using a 30-m DEM. The basin area and measures of gradient of each basin were extracted from the DEM data. Areas within each basin burned at varying severities were characterized using the Normalized Burn Ratio (NBR), which was determined from Landsat Thematic Mapper data (Key and Benson, 2000). The map of burn severity is considered to reflect the effects of the fire on soil conditions and the potential hydrologic response, and is an amalgam representation of the condition of the residual ground cover, soil erodibility, and degree of fire-induced water repellency (USDA Forest Service, 2002). Values of peak discharge for the 25-year, 1-hour storm of 1.3 inches (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, and to aid in the interpretation of the map, we then grouped the estimated discharges into the classes shown on the map.

To augment the modeling effort, 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 a storm on August 5, 2002, were used to determine if debris-flow potential was adequately represented, modifications were made, and the present version was produced.

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 high-gradient channels throughout the burned area. Cannon (2001) identified these conditions as those likely to produce post-wildfire debris flows. In addition, the Maroon formation, which produced the majority of the fire-related debris flows from Storm King Mountain, underlies a large part of the area (Kirkham et al., 2000 and Cannon et al., 2001).

Peak discharges calculated for each basin burned by the Coal Seam fire for the 25-year, 1-hour storm of 1.3 inches (Miller, et al., 1973) ranged between 1 and greater than 250 cubic meters per second (1 and greater than8830 cubic feet per second). The large, extensively burned basins on the south side of the Colorado River, two smaller, but steeper, tributaries to Mitchell Creek, and two basins located behind the Glenwood Springs golf course show the potential to produce debris flows with peak discharges greater than 250 cubic meters per second (greater than8830 cubic feet per second) in response to the storm evaluated here.

Note that for some basins the combination of burned area and gradient were outside the predictive capability of the model. These were generally relatively small, sparsely burned basins, and are indicated on the map with peak discharge category 1. Because the burned extents, gradients, and morphologies are not known to have produced debris flows from other burned areas, we assume that these basins are not likely to produce debris flows in response to the rainfall conditions considered here.

We found that it was necessary to make some changes to the peak discharge classifications for some basins on the basis of field observations and measurements following a rainstorm on August 5, 2002, that impacted the tributaries to Mitchell Creek, the basins that drain Red Mountain, South Canyon, and the two basins immediately to the east of South Canyon. In response to between 0.35 and 0.47 inches of rainfall in about 20 minutes (recurrence interval of approximately 2 years), debris flows with peak discharges of between 3 and 25 cubic meters per second were produced from some of the small tributaries whose characteristics were outside the predictive capability of the model. Due to this response, it was necessary to reclassify the basins with gradients and burned extent similar to those that produced events in response to the August storm as having the potential for debris-flow activity of magnitudes greater than about 30 cubic meters per second (peak discharge category 2).

Further, the large basins in the northeast section of the map experienced a very discontinuous, or spotty, burn mosaic. This distribution of burn, although it amounts to extensive total burn coverage, is unlikely to produce sufficient runoff to generate debris flows (Cannon, 2001). For this reason, it was necessary to reclassify these basins as peak discharge category 1.

Use and Limitations of the Map

This map provides estimates of possible ranges of peak discharges of debris flows that can potentially generate from the basins burned by the Coal Seam fire in response to the 25-year, 1-hour storm. The map is intended to be used by emergency personnel and citizens to identify the possible magnitude, in terms of peak discharge, of the debris-flow response given rainfall over the entire basin. This information can be used to aid in the preliminary 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 the one evaluated here. Although we identify some basins as not likely to produce debris flows, these basins are still prone to significant sediment-laden flash flooding and may pose a significant threat to people and structures.

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 that may be busy cleaning and rebuilding sites 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.

Note that the method used for the generation of these maps has not been thoroughly tested and reviewed; this is one of the first times 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.

And last, in this analysis we present the potential debris-flow response of the burned basins as a function of slope 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.

Explanation

RANGE OF POTENTIAL
DEBRIS-FLOW MAGNITUDES
(PEAK DISCHARGES)

Basin characteristics outside predictive capabilities of model. Unlikely to produce significant debris flows.

Basin characteristics outside predictive capabilities of model. Field observations and measurements indicate potential for debris flows with peak discharges greater than 30 cubic meters per second (1,060 cubic feet per second).

1-50 cubic meters per second (1-1,770 cubic feet per second)

51-100 cubic meters per second (1,771-3,530 cubic feet per second)

101-150 cubic meters per second (3,531-5,300 cubic feet per second)

151-200 cubic meters per second (5,301-7,060 cubic feet per second)

201-250 cubic meters per second (7,061-8,830 cubic feet per second)

greater than 250 cubic meters per second (greater than8,830 cubic feet per second)

Boundaries of drainage basins

Fire perimeter

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