Emergency Assessment of Potential Debris-Flow Peak Discharges, _ Missionary Ridge Fire, Colorado

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Abstract
This map presents the results of an emergency assessment 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 15, 2002, near Durango, Colorado. The map is based on a regression model for debris-flow peak discharge as a function of average storm intensity, basin area, average 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 250m^3/s (>8750ft^3/s) 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 Missionary Ridge fire of June 9 through July 15, 2002. In this study 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 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 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. 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 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 45 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 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 estimated discharges from this equation are conservatively small (C. Parrett, U.S. Geological Survey, personal commun, 2002). Burn severity for each basin was 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).

The model consists of a fundamental physical representation of peak discharge relative to basin area and average rainfall intensity as a function of basin gradient and burned extent: $Q_p/A_T I$ = f(gradient, burned extent), where Q_p is the peak discharge (in m^3/s), A_T is the total basin area (in m^2), and is the average storm rainfall intensity (in m/s). We considered the effects on $Q_p/A_T I$ of three possible measures of gradient—the average basin gradient (in percent), 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 m^2), and the area burned at high severity (in m^2). 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 C_p, adjusted R^2, 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: $Q_p/A_T I = -61.8 + 1.3\theta_{avg} + 0.6A_b/A_T$,_
where θ_{avg} is the average basin gradient, and A_b is the area burned. Although the R^2_{adj} of 30% for this relation indicates significant scatter in the data used in the regression, and thus some uncertainly in the predicated values, the combination of additional measures of statistical quality indicated that this model was the best possible result, given the data presently at hand for postwildfire debris flows. Note that the additional measures of gradient and burned extent considered here did not produce satisfactory models.
To apply the model to the basins burned by the Missionary Ridge fire, we first delineated each burned catchment on a 30-m DEM. The downstream cumulative catchment area, areas burned at varying severities within the catchments, and measures of gradient of each catchment were extracted from the DEM data. Burn severity for each basin was characterized issuing the Normalized Burn Ratio (NBR), which was determined from Landsat Thematic Mapper data (Key and Benson, 2000). Values of peak discharge for the 25 year, one hour storm of 1.3 inches 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 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 storms on July 22 and August 3, 2002 were used to determine if debris-flow potential was adequately represented, and a final 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 Cutler formation, a geologic formation similar to that which produced the fire-related debris flows from Storm King Mountain, underlies a large part of the area. Further, the Culter, Hermosa and Morrison formations and the Eolus Granite have a history of debris-flow activity in the area (USDA Forest Service, 2002). Peak discharges were calculated for each basin burned by the Missionary Ridge fire for the 25 year, 1 hour storm of 1.3 inches (USDA Forest Service, 2002). Estimates of peak discharges between 1 and greater than 250 m^3/s _ (1 and >8750 ft^3/s) were obtained for this storm. On the east side of the Animas valley, Coon Creek, Steven’s Creek, Freed Canyon, and Haflin Canyon show the potential to produce debris flows with peak discharges greater than 250 m^3/s (>8750 ft^3/s). Shearer and Red Creeks (which drain into the Florida River), and Red Creek (which drains into the Los Pinos River), are also expected to produce significant post-wildfire debris flows.

Note that for some basins, the combination of burned area and gradient were outside the predictive capability of the model. These were generally sparsely burned basins with fairly gentle gradients, or drainage fronts without channels clearly defined from the 30-m DEM, and are indicated on the map with peak discharge category 1A. 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.

However, during field reconnaissance following a rainstorm on July 22, 2002 that impacted basins in the vicinity of Lemon Reservoir, and a storm on August 3, 2002 in the vicinity of Vallecito Reservoir, it was noted that in response to approximately 0.6 inches of rainfall in about 45 minutes (recurrence interval of approximately 2 years), debris flows with estimated peak discharges of less than 25 m^3/s were produced from some of the small tributaries within the basins identified as not prone to debris-flow activity. The debris flows we observed in these basins were generated from within channels that were too small to have been identified on the 30-m DEM. For this reason, we surveyed all the basins classified as 1A on the map to determine if channels on the scale of those that produced debris flows in the Vallecito area were present. If present, we then re-classified the basins as 1B, indicating that limited debris-flow activity is possible.

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 Missionary Ridge fire in response to the 25 year, one 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. This information can be used 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 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 should not be ignored.

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. We estimated the volume of each of these blocks to be approximately 500 m^3 (650 yd^3). It is also likely that additional slump blocks are present in other basins. Although these blocks are not 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 significant volumes of 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 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 response; continuing effort is focused on collecting data to document such effects. In addition, our field reconnaissance indicated that a more detailed basin delineation method would improve the presentation of the results.

References

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