ESTIMATED PROBABILITY OF POST-WILDFIRE DEBRIS-FLOW OCCURRENCE AND ESTIMATED VOLUME OF DEBRIS FLOWS FROM A PRE-FIRE ANALYSIS IN THE THREE LAKES WATERSHED, GRAND COUNTY, COLORADO

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INTRODUCTION

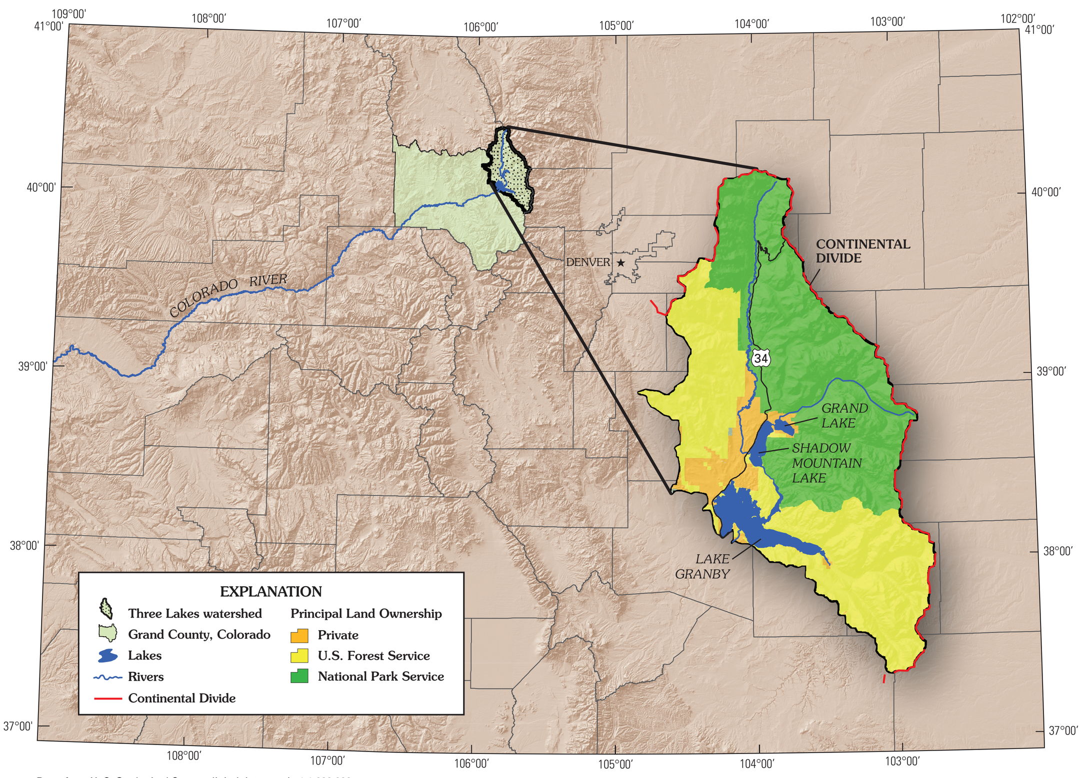
Few post-wildfire hazards are as potentially devastating as a debris flow. Debris flows are fast-moving, high-density slurries of water, sediment, and debris with enormous destructive power and are caused by periods of intense rain or rapid snowmelt on steep hillsides covered with erodible material. Although debris flows are a common geomorphic process in some areas, even without the influence of fire, a wildfire can transform a watershed with no recent history of debris flows into a substantial hazard for residents, communities, infrastructure, aquatic habitat, and water supply. Researchers are developing new techniques to assess the hazards posed by debris flows after wildfires. These techniques can be used in a pre-fire analysis to estimate hazards to life, property, infrastructure, and water resources before wildfires occur.

The Three Lakes watershed (fig. 1) is an 805-square-kilometer (km^2; 311-square-mile) area in northeastern Grand County, Colorado, that serves as the collection system for the Northern Colorado Water Conservancy District's (NCWCD) water-supply system and is important to residents east and west of the Continental Divide. This system provides about 213,000 acre-feet of water annually to 30 cities and towns on Colorado's northern Front Range and Piedmont for domestic and industrial uses and to about 693,000 acres of irrigated farmland (Northern Colorado Water Conservancy District, 2007). Grand Lake, Shadow Mountain Lake, and Lake Granby constitute the collection, storage, and part of the water-transport system associated with the Colorado Big Thompson Project, which is administrated by the NCWCD. The Three Lakes watershed also contains a wildland/urban interface, an area where homes are interspersed with wildlands, with growing populations in the towns of Grand Lake and Granby, and in unincorporated areas around parts of the lakes. Although much of the water infrastructure is owned by the Bureau of Reclamation and the infrastructure and lakes are managed by the NCWCD, most of the land composing the watershed is owned and managed by the National Park Service; the U.S. Department of Agriculture, Forest Service; and private owners.

Colorado has recently (2002 and 1977) experienced severe drought conditions (Kuhn, 2005). Drought, combined with the accelerated spread of the mountain pine beetle and the accumulation of fuel in the forest due to many years of active fire suppression, has made the forests in large portions of the Three Lakes watershed increasingly susceptible to wildfire.

During 2006, the U.S. Geological Survey (USGS), in cooperation with the NCWCD, initiated a pre-wildfire study to determine the potential for post-wildfire debris flows in the Three Lakes watershed. The objective of this study is to estimate the probability of post-wildfire debris flows and to estimate the approximate volumes of debris flows from each subbasin in the Three Lakes watershed in order to provide the NCWCD with a relative measure of which subbasins might constitute the most serious debris-flow hazards. Although the location, percentage of burned area, severity of wildfire, and storm intensity and duration after a fire cannot be known in advance, hypothetical or designed scenarios, such as those used in this report, are useful planning tools for conceptualizing potential wildfire effects.

This report describes the results of the study and provides estimated probabilities of debris-flow occurrence and the estimated volumes of debris flow that could be produced in 109 subbasins of the watershed under an assumed moderate- to high-burn severity of all forested areas. A summary table shows expected debris-flow volumes when varying percentages of forested areas burn. Using information provided in this report, land and water-supply managers can consider where to concentrate pre-wildfire planning, pre-wildfire preparedness, and pre-wildfire mitigation in advance of wildfires. Also, in the event of a large wildfire, this information will help managers identify the watersheds with the greatest post-wildfire debris-flow hazards.



Base from U.S. Geological Survey digital data, scale 1:1,000,000
Land Ownership: CoMap version 5, public edition,
Natural Resources Ecology Lab, Colorado State University
Universal Transverse Mercator projection
Zone 13, North American Datum 1983

Figure 1. Location of Three Lakes watershed, Grand County, Colorado.

DEBRIS-FLOW REGRESSION MODELS

Equations developed by Susan Cannon and others (U.S. Geological Survey, written commun., 2006) and Gartner (2005) were used to estimate the probability of debris-flow occurrence and estimated volumes of debris flows, respectively, in 109 unburned subbasins that range in size from about 0.10 to 25 km^2 (approximately 0.04 to 10 mi^2) in the Three Lakes study area (figs. 2 and 3). The probability and volume equations are based on results from extensive studies of post-wildfire debris flows in the intermountain western United States.

DEBRIS-FLOW PROBABILITY

The regression equation of debris-flow probability is based on empirical data described by Susan Cannon and others (U.S. Geological Survey, written commun., 2006). The equation is:

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

$$x = -0.68 + 0.025(\%SG30) - 1.55(R) + 0.06(\%AB) + 0.06(I) + 0.23(\%C) - 0.40(LL),$$

where P is the probability of debris-flow occurrence in fractional form; $\%SG30$ is the percentage of the basin area with slopes equal to or greater than 30 percent; R is basin ruggedness, the change in basin elevation (meters) divided by the square root of the basin area (square meters) (Melton, 1965); $\%AB$ is the percentage of basin area burned at moderate to high severity, which is a subset of the percentage of forested area in the basin; I is average storm intensity (in millimeters per hour); $\%C$ is clay content of the soil (in percent); and LL is the liquid limit of the soil (percentage of soil moisture by weight), which is the water content at which a soil changes from a plastic to a liquid state. The debris-flow probability model was developed using logistic regression (Hosmer and Lemeshow, 2000). Logistic regression calculates McFadden's rho, which is similar to the r-squared of linear regression (SPSS, Inc., 2000), but rho tends to be smaller than r-squared and ranges from 0 to 1.0. Values between 0.20 and 0.40 indicate significant correlation (SPSS, Inc., 2000). McFadden's rho calculated for this debris-flow probability model is 0.35.

DEBRIS-FLOW VOLUME

A regression equation developed by Gartner (2005) was used to estimate the volume of debris flow that would likely be produced in subbasins of the Three Lakes watershed following wildfire. The equation is:

$$Ln\ V = 0.65(\ln SG30) + 0.86(AB)^{1/2} + 0.22(T)^{1/2} + 6.46,$$

where, V is the debris-flow volume (including water, sediment, and debris) in cubic meters; $SG30$ is the area of basin with slopes equal to or greater than 30 percent (square kilometers); AB is the basin area burned at moderate to high severity (square kilometers), which is a subset of the percentage of forested area; and T is the total storm rainfall (millimeters). The debris-flow volume equation has an r^2 of 0.83 and a standard error of 0.90. In model validation, the volume equation predicted 71 percent of the debris-flow volumes within one standard error and within one order of magnitude (Gartner, 2005).

INPUT DATA AND ASSUMPTIONS

Input data for the predictions in the Three Lakes watershed were obtained from a variety of sources. From 30-m digital elevation maps (DEMs) within the Three Lakes watershed, 109 subbasins were delineated using the GIS Weasel, a Geographic Information System tool developed by Viger and Leavesley (2007). Subbasin sizes range from about 0.10 km^2 (0.04 mi^2) to about 25 km^2 (10 mi^2), which is consistent with the range of subbasin areas used in the development of the debris-flow models. The subbasin delineation approach delineated large subbasins and progressed to smaller basins until the remaining undelineated areas (those areas without an identifiable drainage or channel) were less than 0.1 km^2. The delineated subbasins cover 82 percent of the total Three Lakes watershed. Some small, undelineated watershed areas adjacent to Grand Lake, Shadow Mountain Lake, and Lake Granby were aggregated into computational areas in order to assess the likelihood of debris flows in these areas.

Forested areas were used as a surrogate for areas of medium- to high-burn severity. For the purpose of estimating debris probabilities and volumes, it was assumed that all of the forest cover, which was defined from the National Land Cover Database (U.S. Geological Survey, 1992), would burn at moderate- to high-burn severity within each of the subbasins. Although this assumption may characterize only very large wildfires, it provides a consistent basis for comparison of debris-flow hazards among subbasins in the Three Lakes watershed and provides a worst-case scenario for debris-flow prediction. High-burn severity is defined by Lindsey (2002) as the complete consumption of the forest litter and duff and combustion of all fine fuels in the canopy. A deep ash layer may be present on the forest floor, and the top layer of the mineral soil may be changed in color due to substantial soil heating where large-diameter fuels were consumed. Moderate-burn severity is defined as the consumption of forest litter and duff in discontinuous patches. Leaves or needles, although scorched, may remain on trees. Foliage and twigs on the forest floor are consumed, and some heating of the mineral soils may occur if the soil organic layer was thin.

Rainfall is an essential element in the generation of post-wildfire debris flows. The storm intensity used in the equations was a 5-year recurrence interval, 1-hour rainstorm (20 mm) for this area that occurred uniformly over each subbasin. The 5-year storm intensity for the study area was determined from the National Oceanic and Atmospheric Administration Atlas II for Colorado (Miller and others, 1973). A 5-year rainfall event has a 20-percent probability of occurring in any given year. It is estimated that the 4- to 6-year period following a wildfire is the period when burned basins are the most vulnerable to extensive erosion and potential debris flows (Elliott and others, 2005); thus, the 5-year rainfall event is reasonably likely to occur while the burned area is most vulnerable, but does not approach a worst-case scenario.

The subbasin areas and percentage of areas with 30 percent or greater slopes were determined using ArcMap with 30-m DEMs. Raw data for soil properties were compiled from the State Soil Geographic (STATSGO) database (U.S. Department of Agriculture, 1991), which was processed by Schwartz and Alexander (1995) to obtain clay content and liquid limit.

RESULTS OF DEBRIS-FLOW MODELS

The debris-flow probability model indicated a probability greater than 80 percent for post-wildfire debris flow in 86 of the 109 subbasins of the Three Lakes watershed. The debris-flow volume model estimated post-wildfire debris-flow volumes exceeding 200,000 m^3 in four of the subbasins.

DEBRIS-FLOW PROBABILITY

The estimated probabilities for post-wildfire debris flows in the 109 subbasins in the Three Lakes watershed ranged from less than 1 percent to about 100 percent (fig. 2), with the assumption that 100 percent of the forested area in each subbasin is burned at moderate to high severity and that the burn is followed by a 5-year storm event (20 mm of rainfall in 1 hour). Eighty-six of the 109 subbasins had an estimated probability of debris flow greater than 80 percent.

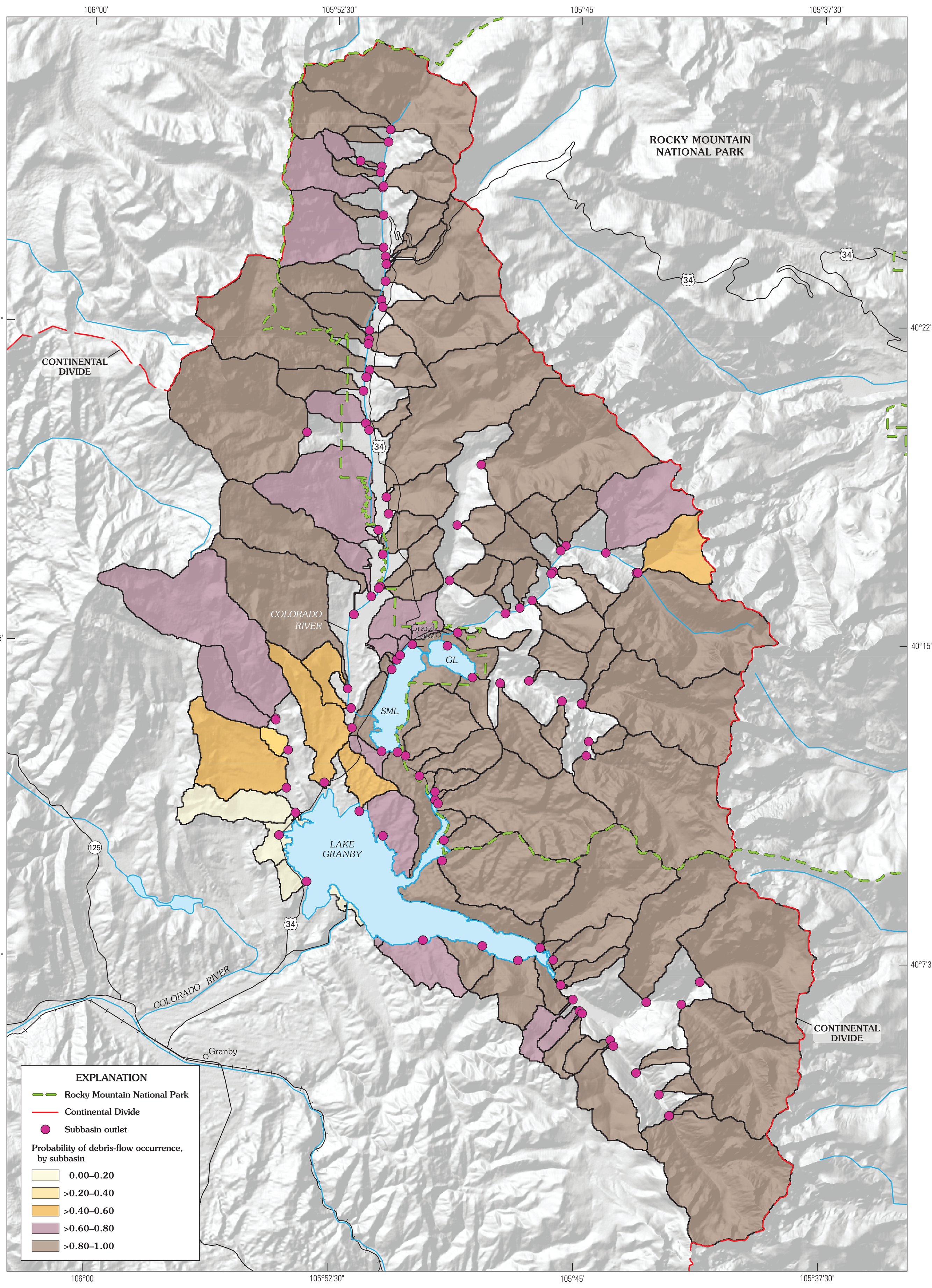
The debris-flow probability equation is relatively insensitive to the percentage of forested area burned in the study area. If the percentage of forested area burned in each of the subbasins is reduced to 75, 50, or 25 percent and other variables are held constant, about one-half of the subbasins have a greater than 40-percent probability of debris flow. This result indicates that many of the subbasins have some risk of debris flow in their unburned state and also indicates that non-fire variables in the equation such as basin slope, ruggedness, and soil properties are important factors in the occurrence of debris flow.

DEBRIS-FLOW VOLUME

Estimated post-wildfire debris-flow volumes for the 109 subbasins ranged from about 30 m^3 to more than 308,000 m^3 (fig. 3), assuming 100 percent of the forested areas in each subbasin burned at a moderate to high severity, followed by a 5-year storm event. The median debris-flow volume was about 6,800 m^3, and about 25 percent of the subbasins are predicted to yield more than 17,000 m^3 of debris-flow material.

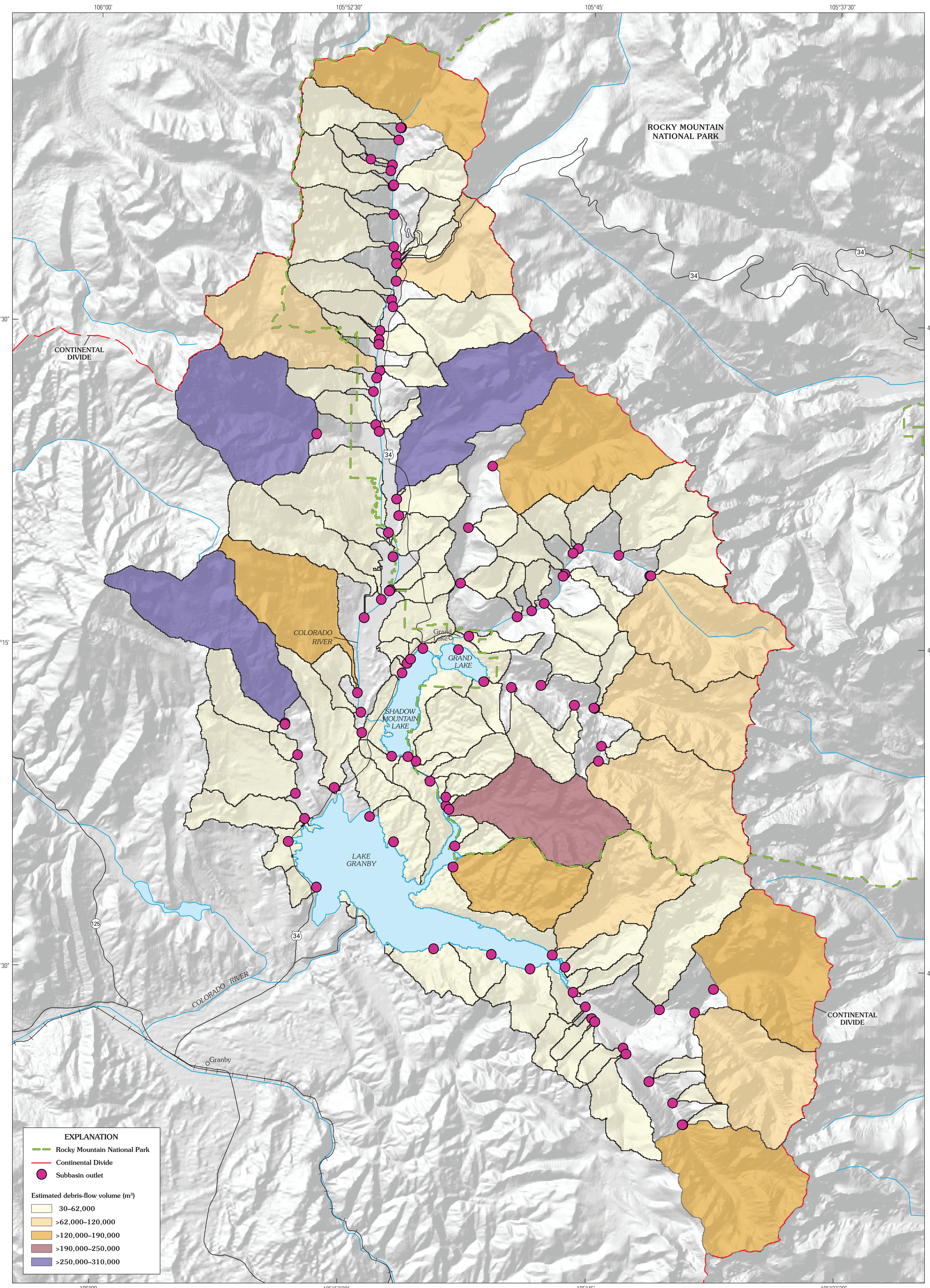
Predicted volumes of debris flow are proportional to the percentage of forested area burned, which in the study area is strongly related to subbasin area. Potential volumes of debris flow predicted by the volume equation are shown in table 1 for 0, 25, 50, 75, and 100 percent of burned forested area grouped by basin size. The volume of predicted debris flow increases with the percentage of forested area burned for small, medium, large, and very large subbasins.

It is important to recognize that although very large and severely burned subbasins in the study area may produce large volumes (200,000 to 300,000 m^3) of debris-flow material (water, sediment, and debris), determining where that material may be deposited below the subbasin outlets is beyond the scope of this study. Although the location of subbasin outlets may be near important water-supply infrastructure such as dams, pumping stations, tunnels, and roads, this study cannot indicate if that infrastructure will be reached or affected by a debris flow. Wide, low-gradient stream valleys such as the Colorado River Valley in Rocky Mountain National Park in the northern part of the study area (fig. 3) may intercept and capture debris-flow material before it reaches the infrastructure of the Three Lakes water supply.



Base from U.S. Geological Survey digital data, scale 1:24,000
Universal Transverse Mercator projection, zone 13
North American Datum 1983

Figure 2. Estimated probability of debris-flow occurrence, Three Lakes watershed, Grand County, Colorado. SML—Shadow Mountain Lake; GL—Grand Lake



Base from U.S. Geological Survey digital data, scale 1:24,000
Universal Transverse Mercator projection, zone 13
North American Datum 1983

Figure 3. Estimated debris-flow volume in cubic meters, Three Lakes watershed, Grand County, Colorado.

Table 1. Estimated medians and ranges of predicted debris-flow volumes for subbasins, by subbasin size

[Debris-flow median volumes and range of volumes are in cubic meters. Range of volumes is shown in parentheses; %, percent; km², square kilometer]

Subbasin size	Subbasin area (km^2)	Percentage of forested area burned at moderate to high severity				
		0%	25%	50%	75%	100%
Small	0.12–1.46	900 (5–1,700)	1,300 (20–2,300)	1,500 (24–2,700)	1,700 (27–3,100)	1,800 (30–3,500)
Medium	1.58–2.75	1,700 (200–2,400)	3,000 (340–4,600)	3,700 (440–6,100)	4,400 (520–7,700)	5,200 (610–9,200)
Large	2.78–6.27	2,500 (300–4,300)	5,000 (650–10,200)	6,800 (880–15,500)	8,500 (1,100–21,300)	10,300 (1,300–27,900)
Very large	6.61–24.92	7,800 (2,000–12,000)	25,600 (5,600–48,900)	43,200 (8,700–104,700)	61,000 (12,300–188,100)	84,900 (15,300–308,300)

Example of debris-flow deposits following the Missionary Ridge fire in southwestern Colorado. Photograph by Butch Knowlton, La Plata County Office of Emergency Management, 2002.

SUMMARY AND CONCLUSIONS

Debris flows pose substantial threats to life, property, infrastructure, and water resources. Post-wildfire debris flows may be of catastrophic proportions compared to debris flows occurring in unburned areas. During 2006, the U.S. Geological Survey (USGS), in cooperation with the Northern Colorado Water Conservancy District, initiated a pre-wildfire study to determine the potential for post-wildfire debris flows in the Three Lakes watershed, Grand County, Colorado. The objective was to estimate the probability of post-wildfire debris flows and to estimate the approximate volumes of debris flows from 109 subbasins in the Three Lakes watershed in order to provide the Northern Colorado Water Conservancy District with a relative measure of which subbasins might constitute the most serious debris-flow hazards. This report describes the results of the study and provides estimated probabilities of debris-flow occurrence and the estimated volumes of debris flow that could be produced in 109 subbasins of the watershed under an assumed moderate- to high-burn severity of all forested areas. The estimates are needed because the Three Lakes watershed includes communities and substantial water-resources and water-supply infrastructure that are important to residents both east and west of the Continental Divide. Using information provided in this report, land and water-supply managers can consider where to concentrate pre-wildfire planning, pre-wildfire preparedness, and pre-wildfire mitigation in advance of wildfires. Also, in the event of a large wildfire, this information will help managers identify the watersheds with the greatest post-wildfire debris-flow hazards.

The maps show pre-wildfire estimates of the probability that post-wildfire debris flow will occur and estimates of the volumes that could be generated by debris flows from 109 subbasins, ranging in size from about 0.1 km^2 to 25 km^2. Although the location, percentage of burned area, severity of wildfire, and storm intensity and duration after a fire cannot be known in advance, hypothetical or designed scenarios, such as those used in this report, are useful planning tools for conceptualizing potential wildfire effects. The estimates of debris-flow probability and volumes presented in this report are in response to a 5-year recurrence, 1-hour-duration rainstorm that might occur after a wildfire burned 100 percent of the forested areas in each subbasin at moderate to high severity. This is judged to be a reasonably likely scenario with which to estimate debris-flow probability and volume. The 5-year storm has a probability of occurring once in 5 years (20-percent probability in any given year) and approximates a period of time when the danger of post-wildfire debris flows is probably highest. Using this hypothetical scenario, the probabilities of debris-flow occurrence range from less than 1 to 100 percent in the subbasins, with a greater than 80 percent probability that debris flows would occur in 86 of 109 subbasins.

Estimates of debris-flow volume range between 30 m^3 and 308,300 m^3 with a median of 6,800 m^3, and about 25 percent of the subbasins might produce debris-flow volumes that exceed 17,000 m^3. The assumption that 100 percent of the forested area will burn is a worst-case burn scenario; therefore, estimated debris-flow volumes also are summarized in this report for burns of 0, 25, 50, 75, and 100 percent of the forested area in each basin. Using smaller percentages of burned areas produced smaller estimates of debris-flow volumes but nearly the same probabilities that the debris flow could occur.

Although the estimated probabilities of debris-flow occurrences are high and the estimated debris-flow volumes are large, this study did not consider whether the debris flows will reach basin outlets that are proximal to important infrastructure. The models used in this study were developed only to estimate debris-flow characteristics. Substantial flooding and other fluvial erosional processes that could cause substantial damage may also occur under post-wildfire conditions. Data collection and watershed modeling are needed to provide additional insight and refinements regarding post-wildfire debris-flow and flood hazards in the Three Lakes watershed.

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A PDF file for this map is available online at: http://pubs.usgs.gov/sim/3009

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