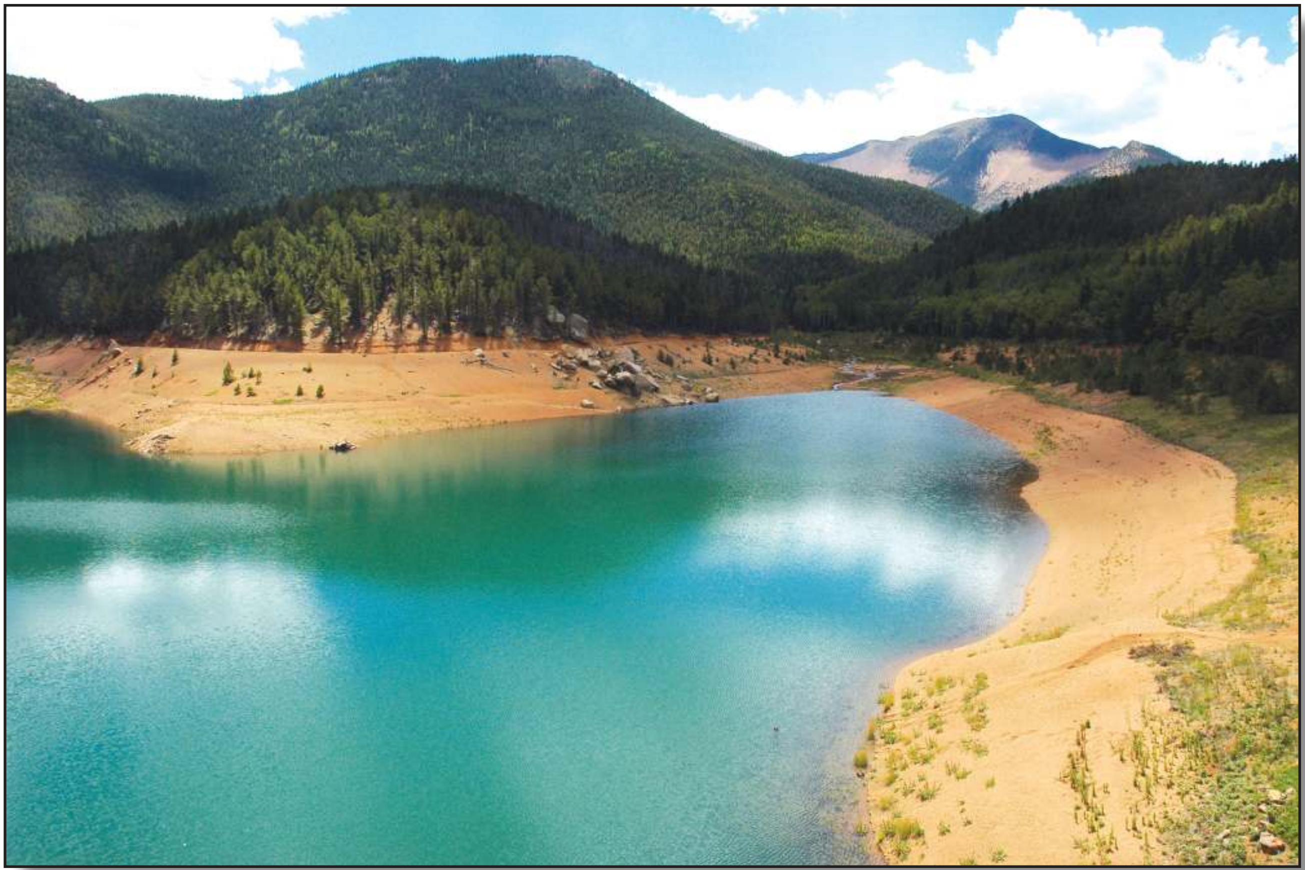
science for a changing world

Prepared in cooperation with the City of Colorado Springs, Colorado

Estimated Probabilities and Volumes of Postwildfire Debris Flows—A Prewildfire Evaluation for the Pikes Peak Area, El Paso and Teller Counties, Colorado



Scientific Investigations Report 2012–5104

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

COVER: Big Tooth Reservoir. View is south-southwest to South Ruxton Creek and Almagre Mountain, elevation 12,367 feet, in Pike National Forest.

Photograph by John G. Elliott, U.S. Geological Survey, August 27, 2010.

Estimated Probabilities and Volumes of Postwildfire Debris Flows—A Prewildfire Evaluation for the Pikes Peak area, El Paso and Teller Counties, Colorado

By John G. Elliott, Barbara C. Ruddy, Kristine L. Verdin, and Keelin R. Schaffrath

Prepared in cooperation with the City of Colorado Springs, Colorado

Scientific Investigations Report 2012–5104

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Elliott, J.G., Ruddy, B.C., Verdin, K.L., and Schaffrath, K.R., 2012, Estimated probabilities and volumes of postwildfire debris flows—A prewildfire evaluation for the Pikes Peak area, El Paso and Teller Counties, Colorado: U.S. Geological Survey Scientific Investigations Report 2012–5104, 26 p.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
	Pressure	
pound per square foot (lb/ft^2)	47.88	newton per square meter (N/m^2)
	Density	
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)
	Pressure	
newton per square meter (N/m^2)	0.02088	pound per square foot (lb/ft^2)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Estimated Probabilities and Volumes of Postwildfire Debris Flows—A Prewildfire Evaluation for the Pikes Peak Area, El Paso and Teller Counties, Colorado

By John G. Elliott, Barbara C. Ruddy, Kristine L. Verdin, and Keelin R. Schaffrath

Abstract

Debris flows are fast-moving, high-density slurries of water, sediment, and debris that can have enormous destructive power. Although debris flows, triggered by intense rainfall or rapid snowmelt on steep hillsides covered with erodible material, are a common geomorphic process in some unburned areas, a wildfire can transform conditions in a watershed with no recent history of debris flows into conditions that pose a substantial hazard to residents, communities, infrastructure, aquatic habitats, and water supply. The location, extent, and severity of wildfire and the subsequent rainfall intensity and duration cannot be known in advance; however, hypothetical scenarios based on empirical debris-flow models are useful planning tools for conceptualizing potential postwildfire debris flows. A prewildfire study to determine the potential for postwildfire debris flows in the Pikes Peak area in El Paso and Teller Counties, Colorado, was initiated in 2010 by the U.S. Geological Survey, in cooperation with the City of Colorado Springs, Colorado Springs Utilities. The study was conducted to provide a relative measure of which subwatersheds might constitute the most serious potential debris-flow hazards in the event of a large-scale wildfire and subsequent rainfall.

Potential postwildfire debris-flow probabilities and volumes for 14 primary watersheds upstream from critical municipal-water infrastructure and 170 selected subwatersheds located within the primary watersheds were estimated by using empirical debris-flow models. The debris-flow models assumed that all of the forest and shrub cover in the watershed would burn at moderate- to high-burn severity. Three postwildfire precipitation scenarios were used to represent a range of likely precipitation that could occur within 4 to 6 years after a wildfire: (1) a 2-year recurrence, 1-hour duration rainfall , referred to as a 2-year storm; (2) a 10-year recurrence, 1-hour duration rainfall , referred to as a 10-year storm; and (3) a 25-year recurrence, 1-hour duration rainfall, referred to as a 25-year storm. Each of the precipitation scenarios indicated the possibility of debris flows from the hypothetically burned watersheds.

Estimated probabilities for postwildfire debris flows in the 170 subwatersheds range from less than 1 to 46 percent in response to the 2-year storm, from 1 to 67 percent in response to the 10-year storm, and from 1 to 72 percent in response to the 25-year storm. Forty of the 170 subwatersheds have a greater than 60-percent probability of producing a debris flow in response to the 25-year storm. Subwatersheds with the lowest postwildfire debris-flow probabilities tend to have large areas of alpine and subalpine vegetation or other areas with sparse forest cover that would be minimally affected by wildfire. Subwatersheds with the highest debris-flow probabilities tend to have steep slopes and heavy forest cover. Postwildfire debris-flow probabilities for the 14 primary watersheds range from 4 to 42 percent in response to the 2-year storm, from 8 to 64 percent in response to the 10-year storm, and from 10 to 70 percent in response to the 25-year storm.

Estimated volumes for postwildfire debris flows in the 170 subwatersheds range from less than 100 m^3 to greater than 100,000 m^3 in response to the 2-year storm, the 10-year storm, and the 25-year storm. Estimated debris-flow volumes for each subwatershed increase as the storm recurrence interval increases. Subwatersheds with the smallest estimated postwildfire debris-flow volumes tend to have small drainage areas, have a small percent area of steep hillslopes, and (or) be located in alpine and subalpine zones. Subwatersheds with the largest estimated debris-flow volumes are those with the largest drainage areas. Estimated debris-flow volumes for the 14 primary watersheds range from about 11,000 to greater than 100,000 m^3 in response to the 2-year storm, from about 14,000 to greater than 100,000 m^3 in response to the 10-year storm, and from about 15,000 to greater than 100,000 m^3 in response to the 25-year storm.

The subwatersheds associated with the greatest potential postwildfire and postprecipitation debris-flow hazards are those with a combination of a high probability of debris-flow occurrence and a large estimated volume of debris-flow material. The ten subwatersheds with the greatest combined relative debris-flow hazard rankings are in the watersheds of Cascade, South Ruxton, Ruxton, Gould, East Beaver, North Cheyenne, and South Cheyenne Creeks.

Introduction

One of the most devastating potential postwildfire hazards is a debris flow (Cannon, 2001; Cannon and others, 1998). Debris flows are fast-moving, high-density slurries of water, sediment, and debris that can have enormous destructive power (Costa and Jarrett, 1981; Hungr and others, 1984; Pierson and Costa, 1987; Costa, 1988). Debris flows typically are triggered by intense rainfall or rapid snowmelt on steep hillsides covered with erodible material (Griffiths and others, 1996; Gartner and others, 2008). Although debris flows are a common geomorphic process in some unburned areas, a wildfire can transform conditions in a watershed with no recent history of debris flows into conditions that pose a substantial hazard to residents, communities, infrastructure, aquatic habitats, and water supply. Researchers have developed new techniques to estimate potential postwildfire debris-flow hazards (Cannon and others, 2010). These techniques can be used in a prewildfire analysis to estimate debris-flow hazards to life, property, infrastructure, and water resources before wildfires occur (Stevens and others, 2008; Elliott and others, 2011).

Several watersheds located to the north, east, and south of Pikes Peak are critical sources of municipal water for the cities of Colorado Springs and Manitou Springs, Colo. (fig. 1). Water collection systems located in these watersheds include reservoirs, tunnels, and diversion intake structures (table 1), which are all susceptible to damage or reduced operational efficiency from accelerated erosion and sedimentation that can occur following a wildfire.

Colorado experienced severe drought conditions in the late 20th and early 21st centuries (Kuhn, 2005) which, when combined with the accumulation of forest fuel, can lead to increased wildfire activity. Widespread Colorado wildfires in 2002 were associated with a prolonged period of below-average spring and summer precipitation, high temperatures, and low humidity (Pielke and others, 2005). In 2010, the U.S. Geological Survey (USGS), in cooperation with the City of Colorado Springs, Colorado Springs Utilities (CSU), initiated a prewildfire study to determine the potential for postwildfire debris flows in 14 primary watersheds and 170 selected subwatersheds located within the primary watersheds with infrastructure of concern to CSU (table 1).

The objective of this study was to estimate the probability of postwildfire debris flows and to estimate the approximate volumes of debris flows that could be delivered from watersheds upstream from critical CSU infrastructure in order to provide a relative measure of which watersheds might constitute the most serious postwildfire debris-flow hazards. Although the location, percentage of burned area, severity of wildfire, and storm intensity and duration after a wildfire cannot be known in advance, hypothetical or design scenarios, such as those used in this report, are useful planning tools for conceptualizing potential postwildfire effects (Elliott and others, 2011). Flooding and other fluvial erosion processes that could cause substantial damage also can occur under postwildfire conditions, but were beyond the scope of this study.

This report provides estimates of probabilities and volumes of postwildfire debris-flows that could be produced within a few years after an assumed moderate- to high-severity wildfire. For each of the 14 primary watersheds (fig. 1) and 170 selected subwatersheds within these primary watersheds (table 1), it was assumed that the hypothetical wildfire would burn all forest- and shrub-covered areas. Using information provided in this report, CSU water-resource managers can plan prevention and mitigation strategies in advance of the occurrence of wildfires. Also, in the event of a large wildfire, this information will help managers identify the watersheds and subwatersheds with the greatest postwildfire debris-flow hazards (Ruddy and others, 2010).

Pikes Peak Study Area

The Pikes Peak study area encompasses 229 square kilometers (km^2) (88.4 square miles (mi^2)) of rugged, mostly National Forest land in Teller and El Paso Counties (fig. 1). Elevation in the study area ranges from about 1,975 meters (m) (6,480 feet (ft)) at the outflow of the South Cheyenne Creek primary watershed (SCH00, table 1) to 4,301 m (14,110 ft) at the summit of Pikes Peak (U.S. Geological Survey, 2010). The majority of the study area is above 2,290 m (7,500 ft) elevation, except for small areas near the outflow of primary watersheds Ruxton Creek (MAN00, table 1), North Cheyenne Creek (NCH00, table 1), and South Cheyenne Creek (SCH00, table 1). The majority of the study area is composed of granite of Middle Proterozoic age with a few isolated areas of glacial drift of Quaternary age (Green, 1992). The study area is forested below an elevation of approximately 3,500 m (11,500 ft), and above this elevation, it is vegetated by alpine tundra.

Mean annual precipitation (1971–2000) varies throughout the study area and, when extrapolated to the area of the primary watersheds, ranges from about 570 millimeters (mm) (22.4 inches (in.)) in the South Catamount Creek watershed (SCT00, table 1) to 775 mm (30.5 in.) in the Mason Reservoir portion of the Boehmer Creek watershed (MAS00, table 1) (U.S. Geological Survey, 2010). Much of the precipitation occurs in the summer as afternoon thunderstorms or as winter snow.

Debris-Flow Regression Models

Equations developed by Cannon and others (2010) were used to estimate the probability of debris-flow occurrence and estimate the volumes of debris flows that might occur, if fires of moderate to high severity consumed all forest- and shrub-covered areas in the 14 primary watersheds (figure 1 and table 1) and in the 170 selected subwatersheds within these larger primary watersheds. Primary watersheds and subwatersheds hereinafter are referred to collectively as watersheds. The probability and volume equations are based

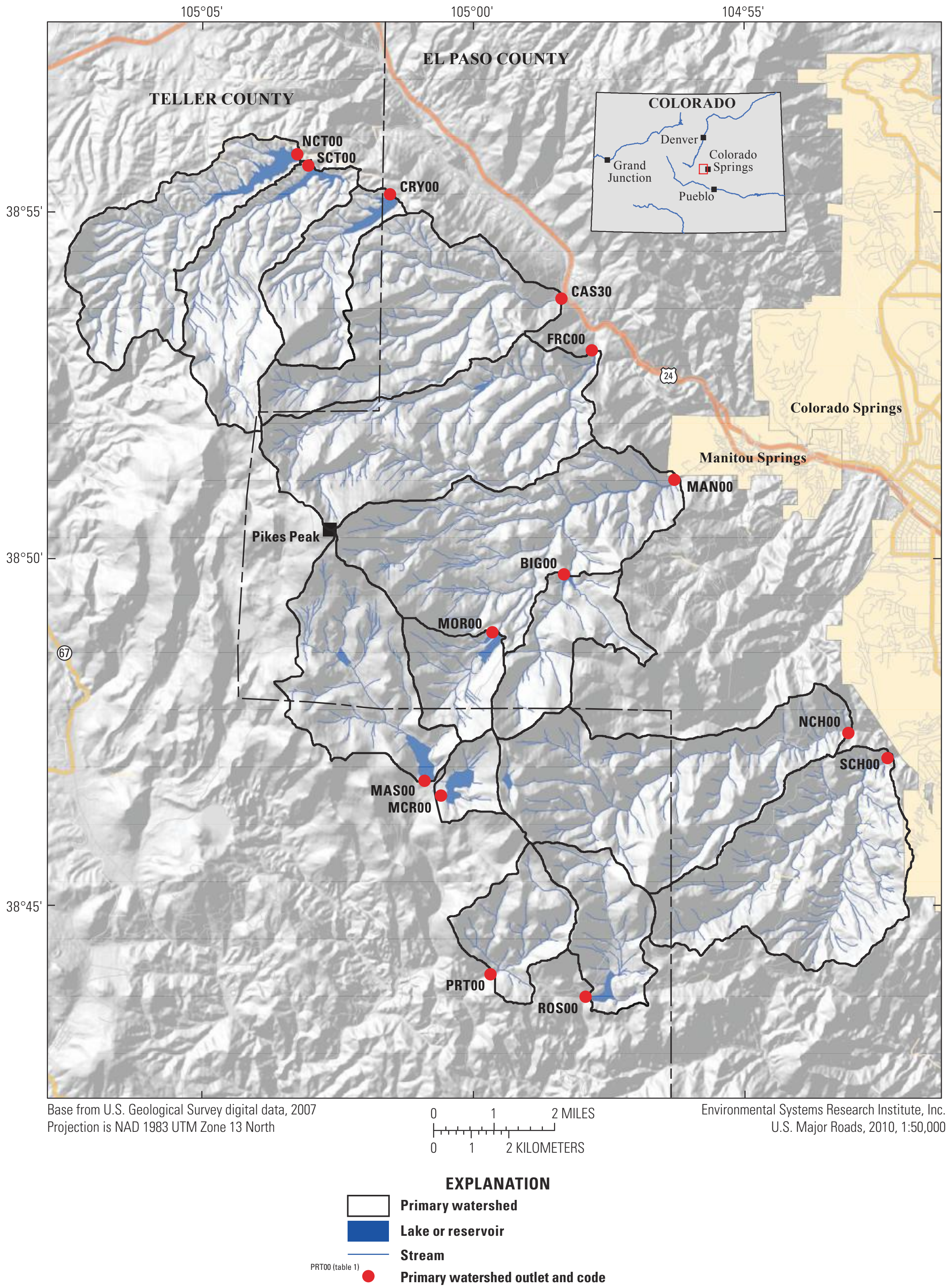


Figure 1. Shaded relief map of the Pikes Peak area showing topography, primary watersheds, and drainage networks.

Table 1. Infrastructure of concern to Colorado Springs Utilities and primary watersheds.

[D M S, degrees, minutes, seconds; km^2, square kilometers; mi^2, square miles; No., number]

Infrastructure	Primary watershed	Watershed code	Latitude (D M S)	Longitude (D M S)	Basin area (km^2)	Basin area (mi^2)	Mean annual precipitation (1971–2000) (mm)
North Slope Collection System							
North Catamount Reservoir	North Catamount Creek watershed	NCT00	38 55 50	105 03 09	16.31	6.30	568.5
South Catamount Reservoir	South Catamount Creek watershed	SCT00	38 55 38	105 02 57	13.43	5.19	656.1
Crystal Creek Reservoir	Crystal Creek watershed	CRY00	38 55 15	105 01 29	8.46	3.27	656.1
[1]Cascade Creek Intake	Cascade Creek watershed	CAS30	38 53 47	104 58 19	21.64	8.36	637.5
French Creek Intake	French Creek watershed	FRC00	38 53 01	104 57 45	25.66	9.91	683.5
South Slope Collection System							
Mason Reservoir	Boehmer Creek watershed	MAS00	38 46 48	105 00 46	15.96	6.16	774.2
McReynolds Reservoir	Middle Beaver Creek watershed	MCR00	38 46 38	105 00 45	3.20	1.24	753.4
[2]Lake Moraine	Ruxton Creek watershed headwaters	MOR00	38 48 56	104 59 32	6.22	2.40	752.3
[2]Big Tooth Reservoir	South Ruxton Creek watershed	BIG00	38 49 47	104 58 18	6.30	2.43	696.2
Manitou No. 1 Intake	Ruxton Creek watershed	MAN00	38 51 10	104 56 13	42.65	16.47	694.7
Rosement Collection System							
Platte Rogers Tunnel Intake	Gould Creek watershed	PRT00	38 44 01	104 59 37	7.54	2.91	688.3
Rosemont Reservoir	East Beaver Creek watershed	ROS00	38 43 39	104 57 51	8.32	3.21	683.8
South Suburban Collection System							
North Cheyenne Creek Intake	North Cheyenne Creek watershed	NCH00	38 47 30	104 53 02	27.36	10.56	653.0
South Cheyenne Creek Intake	South Cheyenne Creek watershed	SCH00	38 47 08	104 52 17	25.78	9.95	573.8

[1]Cascade Creek Intake was numbered subsequent to the assignment of watershed code CAS00 at a different location; hence the use of CAS30 for this intake location.

[2]Lake Moraine and Big Tooth Reservoir are located within the greater Ruxton Creek watershed and upstream from the Manitou No. 1 Intake.

on results from extensive studies of postwildfire debris flows that occurred in recently burned watersheds in the intermountain western United States, including Colorado, Utah, and California (Gartner and others, 2005; Gartner and others, 2008). The debris-flow equations are applicable only to areas where confined, channelized runoff is likely to occur (Cannon and others, 2010). The method of applying these equations to unburned watersheds to estimate the potential debris-flow hazards resulting from hypothetical wildfires was used by Elliott and others (2011) in the upper Blue River watershed in Summit County, Colorado.

The 14 primary watersheds in this study range in size from 3.20 to 42.65 km^2 (1.24 to 16.47 mi^2), and the 170 subwatersheds range in size from 0.01 to 26.04 km^2 (0.004 to 10.05 mi^2) (table 2). The watersheds examined by Cannon and others (2010) ranged in size from 0.01 to 103 km^2; however, they found that postwildfire debris flows were not observed in watersheds with contributing drainage areas greater than approximately 30 km^2. The 14 primary watersheds include the combined areas of multiple modeled subwatersheds within them as well as other areas within the primary watershed, such as large, laterally planar hillslopes, that were not modeled as a single landform. One primary watershed, Ruxton Creek (MAN00) has a drainage area that is greater than the maximum drainage area (30 km^2) that produced a debris flow in Cannon and others (2010) because it includes the areas upstream from Lake Moraine (MOR00) and Big Tooth Reservoir (BIG00) (figure 1). Although greater in area than that observed by Cannon and others (2010), MAN00 is included in this analysis for the purpose of comparison.

Debris-Flow Probability

The regression equation of debris-flow probability is based on empirical data described by Cannon and others (2010, their model A). The equation is

$$P = e^x /(1 + e^x), \tag{1}$$

where,

P is the probability of debris-flow occurrence in fractional form,

and

$$x = -0.7 + 0.03(\%SG30) - 1.6(R) + 0.06(\%AB) + 0.07(I) + 0.2(\%C) - 0.4(LL), \tag{2}$$

where,

$\%SG30$ is the percentage of the watershed area with slopes equal to or greater than 30 percent;

R is watershed ruggedness, calculated as the change in watershed elevation (in meters) divided by the square root of the watershed area (in meters) (Melton, 1965);

$\%AB$ is the percentage of watershed area burned at moderate to high severity;

I is average storm intensity (in millimeters per hour);

$\%C$ is the 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 (Das, 1983).

The debris-flow probability model of Cannon and others (2010) was developed using multiple logistic regression (Hosmer and Lemeshow, 2000) of data from postwildfire debris flows collected throughout the intermountain west. Logistic regression calculates McFadden's rho-squared, which is similar to the coefficient of determination, or r-squared (r^2), of linear regression (SPSS, Inc., 2000), but rho-squared tends to be smaller than r-squared and also ranges from 0 to 1.0. Values of rho-squared between 0.20 and 0.40 indicate significant correlation (SPSS, Inc., 2000). McFadden's rho-squared calculated for this debris-flow probability model (Cannon and others, 2010, their model A) is 0.35.

Cannon and others (2010) evaluated the sensitivity of their model as the number of watersheds known to have produced debris flows to the number of watersheds predicted by the model to have a probability of occurrence greater than 50 percent. The sensitivity of their model A, used in this report, was 44 percent (Cannon and others, 2010, their table 2).

Debris-Flow Volume

The multivariate regression equation for debris-flow volume developed by Cannon and others (2010, their equation 2) was used to estimate a mean volume of debris-flow material deposited at the outlet of a recently burned watershed in the upper Blue River watershed (Elliott and others, 2011), and was used in this study. The equation is

$$ln\ V = 7.2 + 0.6(ln\ SG30) + 0.7(AB)^{0.5} + 0.2(T)^{0.5} + 0.3, \qquad (3)$$

where,

ln is the natural logarithm;

V is the debris-flow volume (including water, sediment, and debris) in cubic meters;

*SG*30 is the area of watershed with slopes equal to or greater than 30 percent (in square kilometers);

AB is the watershed area burned at moderate to high severity (in square kilometers);

T is the total storm rainfall (in millimeters);

and

0.3 is a bias correction that changes the predicted estimate from a median to a mean value (Helsel and Hirsch, 2002).

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 87 percent of the debris-flow volumes within the 95-percent prediction interval; all reported volumes were within one order of magnitude of predicted volumes (Cannon and others, 2010).

Input Data for Debris-Flow Models and Assumptions

Input data for postwildfire debris-flow probability and volume estimates in the Pikes Peak area were obtained from a variety of sources. The primary input variables of the debris-flow models used in this study, developed by Cannon and others (2010), are the extent of the burned area, rainfall volumes and intensity, and soil and topographic characteristics.

Forested area was used as a surrogate for the extent of burned area, and it was assumed that all of the forest and shrub cover, which was defined from the 1992 Enhanced National Land Cover Database (Nakagaki and others, 2007), would burn at moderate- to high-burn severity. Although this assumption may characterize only extensive and severe wildfires, it provides a consistent basis for comparison of debris-flow hazards among watersheds in the Pikes Peak area as well as providing 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 the combustion of all fine fuels in the canopy. A deep ash layer may be present on the forest floor in areas of high-burn severity, 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 is thin.

Rainfall, in terms of both storm recurrence and precipitation duration, is an essential element in the generation of postwildfire debris flows. The debris flows studied by Cannon and others (2010) to develop equations 1 and 2 were generated by short-duration (up to 1-hour) convective rainstorms with recurrence intervals ranging from less than 2 years to as many as 10 years. Another researcher noted that the 25-year recurrence rainfall might be more representative of storms that generate other debris flows because a more frequently occurring storm might deliver too little rainfall runoff to sustain a debris flow, whereas a less frequently occurring storm might deliver too much rainfall runoff, creating a sediment-laden water flood rather than a debris flow (J.S. O'Brien, FLO Engineering, Inc., oral commun., 2002).

Postwildfire studies of the 2002 Hayman, Coal Seam, and Missionary Ridge burned areas estimated that burned watersheds were the most vulnerable to extensive erosion and potential debris flows for a 4- to 6-year period following those wildfires (Elliott and others, 2005), whereas Cannon and others (2010) found that most postwildfire debris-flow activity occurred within about 2 years after the wildfire. Therefore, a 2-year recurrence rainfall is likely to occur while the burned area is most vulnerable to erosion, but such a storm might not represent a worst-case scenario. To represent weather conditions that might result in more severe postwildfire erosion, debris-flow probabilities and volumes in response to the 10-year and 25-year recurrence rainfall events also were simulated for the Pikes Peak area watersheds.

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.

[D M S, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Input									
	Latitude (D M S)	Longitude (D M S)	Watershed area (km²)	Percentage of watershed with slopes greater than or equal to 30 percent (percent)	Area with slopes greater than or equal to 30 percent (km²)	Ruggedness (m/m)	Percentage of watershed with medium and high burn severity (percent)	Area of medium and high burn severity (km²)	Soil clay content (percent)	Soil liquid limit (percent)
North Catamount Reservoir Watershed (Primary Watershed Code NCT00). 2-year RI, 1-hour rainfall = 19 mm. 10-year RI, 1-hour rainfall = 30 mm. 25-year RI, 1-hour rainfall = 38 mm.										
NCT00	38 55 50	105 03 09	16.31	5.8	0.94	0.17	92.8	15.13	8.4	23.6
NCT01	38 55 51	105 03 50	0.36	0.1	0.00	0.13	97.2	0.35	8.4	23.6
NCT02	38 55 33	105 04 21	0.29	0.5	0.00	0.14	100.0	0.29	8.4	23.6
NCT03	38 55 14	105 04 50	0.32	0.1	0.00	0.16	99.7	0.32	8.4	23.6
NCT04	38 55 03	105 04 46	0.52	0.1	0.00	0.19	100.0	0.52	8.4	23.6
NCT05	38 54 56	105 05 22	0.78	0.2	0.00	0.17	100.0	0.78	8.4	23.6
NCT06	38 54 58	105 05 30	0.37	0.1	0.00	0.15	100.0	0.37	8.4	23.6
NCT07	38 54 46	105 05 60	1.59	0.8	0.01	0.27	99.9	1.59	8.4	23.5
NCT08	38 54 42	105 06 03	1.08	3.2	0.03	0.35	99.8	1.08	8.4	23.6
NCT09	38 54 21	105 06 07	3.49	9.0	0.32	0.24	99.8	3.48	8.4	23.6
NCT10	38 54 18	105 06 05	1.55	19.4	0.30	0.49	98.5	1.53	8.4	23.6
NCT11	38 54 18	105 06 05	1.11	19.3	0.22	0.41	99.3	1.10	8.4	23.6
NCT12	38 54 07	105 06 24	2.48	12.2	0.30	0.27	99.7	2.47	8.4	23.6
NCT13	38 54 07	105 06 24	0.78	1.6	0.01	0.26	100.0	0.78	8.4	23.6
NCT30	38 54 55	105 05 18	0.20	1.3	0.00	0.25	100.0	0.20	8.4	23.6
South Catamount Reservoir Watershed (Primary Watershed Code SCT00). 2-year RI, 1-hour rainfall = 22 mm. 10-year RI, 1-hour rainfall = 34 mm. 25-year RI, 1-hour rainfall = 39 mm.										
SCT00	38 55 38	105 02 57	13.43	8.7	1.17	0.32	82.3	11.05	10.0	24.8
SCT01	38 55 08	105 03 22	1.34	2.0	0.03	0.20	99.2	1.33	8.4	23.6
SCT02	38 55 09	105 03 45	0.49	3.1	0.02	0.32	99.9	0.49	8.4	23.6
SCT03	38 55 07	105 03 50	10.74	10.5	1.12	0.36	79.6	8.54	10.4	25.1
SCT04	38 54 25	105 04 41	3.59	16.6	0.60	0.57	60.5	2.17	11.1	25.7
SCT05	38 53 46	105 04 32	2.44	23.4	0.57	0.62	42.1	1.03	12.3	26.6
SCT06	38 54 16	105 04 55	2.78	13.5	0.38	0.54	91.0	2.53	9.8	24.7
SCT07	38 53 44	105 05 09	1.72	21.7	0.37	0.61	85.5	1.47	10.6	25.3
SCT30	38 55 08	105 03 46	10.77	10.4	1.12	0.36	79.7	8.58	10.4	25.1
Crysyal Creek Reservoir Watershed (Primary Watershed Code CRY00). 2-year RI, 1-hour rainfall = 24 mm. 10-year RI, 1-hour rainfall = 37 mm. 25-year RI, 1-hour rainfall = 44 mm.										
CRY00	38 55 15	105 01 29	8.46	6.9	0.59	0.27	96.1	8.12	8.7	23.8
CRY01	38 54 32	105 02 43	0.64	7.0	0.04	0.32	99.8	0.64	8.4	23.6
CRY02	38 54 17	105 02 47	5.00	10.2	0.51	0.34	96.7	4.83	8.9	24.0
CRY03	38 54 11	105 02 45	0.01	0.0	0.00	0.54	100.0	0.01	8.4	23.6
CRY04	38 53 18	105 02 30	0.61	12.0	0.07	0.45	98.8	0.60	8.4	23.6
CRY05	38 53 19	105 02 30	1.20	12.6	0.15	0.49	89.5	1.07	10.2	25.0
CRY30	38 54 33	105 02 42	6.25	9.1	0.57	0.31	97.3	6.08	8.8	23.9
Cascade Creek Watershed (Primary Watershed Code CAS30). 2-year RI, 1-hour rainfall = 26 mm. 10-year RI, 1-hour rainfall = 38 mm. 25-year RI, 1-hour rainfall = 44 mm.										
CAS30	38 53 47	104 58 19	21.64	13.8	2.99	0.37	95.2	20.60	8.9	24.0
CAS00	38 53 49	104 59 11	20.10	11.0	2.21	0.32	94.9	19.08	8.9	24.0
CAS01	38 53 46	104 59 08	0.01	24.6	0.00	1.49	100.0	0.01	8.4	23.6
CAS02	38 53 51	104 59 15	9.04	13.6	1.23	0.47	89.7	8.11	9.5	24.4
CAS03	38 53 44	104 59 41	1.01	15.6	0.16	0.28	99.6	1.01	8.4	23.6
CAS04	38 54 01	104 59 26	10.83	8.1	0.88	0.21	99.1	10.74	8.4	23.6
CAS05	38 54 01	104 59 49	4.97	6.3	0.31	0.26	99.2	4.93	8.4	23.6
CAS06	38 53 21	105 00 05	1.50	4.7	0.07	0.44	99.7	1.49	8.4	23.6
CAS07	38 53 22	105 00 06	5.61	15.3	0.86	0.56	83.6	4.69	10.1	24.9
CAS08	38 53 50	105 00 14	1.05	5.3	0.06	0.39	98.5	1.04	8.4	23.6
CAS09	38 53 29	105 00 34	0.82	4.6	0.04	0.44	99.6	0.82	8.4	23.6
CAS10	38 53 20	105 00 48	2.18	16.9	0.37	0.38	98.9	2.16	8.4	23.6
CAS11	38 53 12	105 01 23	0.24	25.9	0.06	0.84	99.6	0.24	8.4	23.6
CAS12	38 53 13	105 01 33	1.24	23.0	0.29	0.45	98.5	1.22	8.4	23.6
CAS13	38 54 12	105 00 47	2.68	6.0	0.16	0.31	99.8	2.68	8.4	23.6
CAS14	38 54 13	105 00 46	1.39	2.0	0.03	0.18	99.6	1.39	8.4	23.6
CAS15	38 54 16	105 00 60	0.57	5.6	0.03	0.42	99.8	0.57	8.4	23.6
CAS16	38 52 35	105 02 22	2.53	16.3	0.41	0.55	66.1	1.67	12.2	26.5
CAS31	38 53 50	105 00 12	1.05	5.3	0.06	0.39	98.5	1.04	8.4	23.6

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[DMS, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Output								
	2-year RI, 1-hour rainfall debris-flow probability (percent)	2-year RI, 1-hour rainfall debris-flow volume (m³)	10-year RI, 1-hour rainfall debris-flow probability (percent)	10-year RI, 1-hour rainfall debris-flow volume (m³)	25-year RI, 1-hour rainfall debris-flow probability (percent)	25-year RI, 1-hour rainfall debris-flow volume (m³)	25-year RI, 1-hour rainfall debris-flow probability rank	25-year RI, 1-hour rainfall debris-flow volume rank	25-year RI, 1-hour rainfall combined debris-flow hazard rank
North Catamount Reservoir Watershed (Primary Watershed Code NCT00). 2-year RI, 1-hour rainfall = 19 mm. 10-year RI, 1-hour rainfall = 30 mm. 25-year RI, 1-hour rainfall = 38 mm.									
NCT00	16	63,000	29	79,000	42	91,000	na	na	na
NCT01	18	<100	32	<100	46	<100	118	167	160
NCT02	21	100	36	200	50	200	98	162	146
NCT03	20	<100	35	<100	48	<100	105	168	156
NCT04	19	<100	34	100	47	100	111	164	158
NCT05	20	200	35	200	48	200	103	157	145
NCT06	20	<100	36	<100	49	<100	99	166	151
NCT07	18	800	32	1,000	45	1,100	119	141	143
NCT08	17	1,200	30	1,500	43	1,700	131	131	149
NCT09	22	8,000	38	10,000	52	11,000	87	35	49
NCT10	19	5,000	34	6,200	48	7,200	108	55	78
NCT11	22	3,600	38	4,500	52	5,100	86	69	69
NCT12	23	6,300	39	7,900	53	9,100	79	47	53
NCT13	18	600	33	700	46	800	117	148	150
NCT30	18	200	33	200	46	200	116	158	157
South Catamount Reservoir Watershed (Primary Watershed Code SCT00). 2-year RI, 1-hour rainfall = 22 mm. 10-year RI, 1-hour rainfall = 34 mm. 25-year RI, 1-hour rainfall = 39 mm.									
SCT00	8	52,000	17	65,000	23	71,000	na	na	na
SCT01	23	1,200	41	1,500	49	1,600	100	133	132
SCT02	21	600	38	800	46	800	114	146	144
SCT03	7	38,000	15	48,000	19	52,000	155	8	77
SCT04	2	9,500	4	12,000	6	13,000	167	33	113
SCT05	1	6,700	1	8,500	2	9,200	169	46	123
SCT06	11	7,800	23	9,800	29	11,000	144	40	98
SCT07	9	6,000	18	7,500	24	8,100	151	50	114
SCT30	7	39,000	15	48,000	19	53,000	154	7	75
Crysyal Creek Reservoir Watershed (Primary Watershed Code CRY00). 2-year RI, 1-hour rainfall = 24 mm. 10-year RI, 1-hour rainfall = 37 mm. 25-year RI, 1-hour rainfall = 44 mm.									
CRY00	22	26,000	41	33,000	53	36,000	na	na	na
CRY01	25	1,300	45	1,700	58	1,800	58	127	101
CRY02	22	15,000	41	19,000	53	21,000	78	23	30
CRY03	16	<100	32	<100	44	<100	126	170	167
CRY04	23	1,700	43	2,200	55	2,400	70	113	97
CRY05	12	3,200	25	4,100	35	4,500	137	74	122
CRY30	23	19,000	43	24,000	55	27,000	69	19	24
Cascade Creek Watershed (Primary Watershed Code CAS30). 2-year RI, 1-hour rainfall = 26 mm. 10-year RI, 1-hour rainfall = 38 mm. 25-year RI, 1-hour rainfall = 44 mm.									
CAS30	24	>100,000	42	>100,000	53	>100,000	na	na	na
CAS00	24	>100,000	42	>100,000	52	>100,000	85	2	21
CAS01	9	100	19	100	27	200	146	163	170
CAS02	15	42,000	29	52,000	39	57,000	134	6	59
CAS03	34	3,300	55	4,100	65	4,500	19	73	27
CAS04	31	46,000	51	57,000	62	63,000	32	4	4
CAS05	29	12,000	48	15,000	58	16,000	53	25	18
CAS06	23	2,400	41	3,000	51	3,300	95	95	105
CAS07	9	21,000	20	26,000	27	28,000	145	17	76
CAS08	23	1,800	41	2,200	51	2,500	92	112	116
CAS09	23	1,300	41	1,600	51	1,800	94	130	129
CAS10	31	7,700	51	9,500	61	10,000	35	41	16
CAS11	23	1,300	40	1,700	51	1,800	96	129	130
CAS12	32	5,100	52	6,300	62	7,000	30	57	22
CAS13	28	5,300	47	6,500	57	7,200	60	54	44
CAS14	29	1,300	49	1,700	59	1,800	47	128	91
CAS15	24	1,100	42	1,300	53	1,500	80	136	125
CAS16	3	7,300	7	9,000	10	9,900	162	43	118
CAS31	23	1,800	41	2,200	51	2,500	91	111	115

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[D M S, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Input									
	Latitude (D M S)	Longitude (D M S)	Watershed area (km²)	Percentage of watershed with slopes greater than or equal to 30 percent (percent)	Area with slopes greater than or equal to 30 percent (km²)	Ruggedness (m/m)	Percentage of watershed with medium and high burn severity (percent)	Area of medium and high burn severity (km²)	Soil clay content (percent)	Soil liquid limit (percent)
French Creek Watershed (Primary Watershed Code FRC00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 39 mm. 25-year RI, 1-hour rainfall = 45 mm.										
FRC00	38 53 01	104 57 45	25.66	25.1	6.45	0.41	79.5	20.40	9.8	24.6
FRC01	38 52 51	104 57 47	0.51	46.2	0.24	0.70	100.0	0.51	8.4	23.6
FRC02	38 52 39	104 58 41	0.28	17.3	0.05	0.38	100.0	0.28	8.4	23.6
FRC03	38 52 34	104 58 56	1.61	13.8	0.22	0.37	99.6	1.60	8.4	23.6
FRC04	38 52 38	104 59 05	0.40	3.2	0.01	0.28	100.0	0.40	8.4	23.6
FRC05	38 52 37	104 59 31	0.03	7.6	0.00	0.71	94.9	0.03	8.4	23.6
FRC06	38 51 15	105 00 09	0.57	8.8	0.05	0.77	100.0	0.57	11.6	26.0
FRC07	38 51 16	105 00 33	5.32	40.9	2.18	0.54	44.0	2.34	11.8	26.3
FRC08	38 52 15	105 01 07	5.32	36.6	1.95	0.53	59.5	3.17	11.0	25.6
FRC09	38 52 28	104 58 20	1.31	4.9	0.06	0.43	99.3	1.30	8.4	23.6
FRC10	38 52 12	104 58 13	0.71	8.8	0.06	0.33	100.0	0.71	8.4	23.6
FRC11	38 52 02	104 58 25	1.55	11.6	0.18	0.40	99.5	1.54	8.4	23.6
FRC12	38 52 01	104 58 25	8.06	31.7	2.56	0.59	62.9	5.07	10.9	25.5
FRC13	38 52 27	105 00 01	6.36	33.3	2.12	0.53	65.9	4.19	10.6	25.3
Mason Reservoir (Middle Beaver Creek) Watershed (Primary Watershed Code MAS00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 44 mm.										
MAS00	38 46 48	105 00 46	15.96	4.5	0.71	0.24	62.2	9.92	11.6	26.0
MAS01	38 47 16	105 00 48	0.51	2.6	0.01	0.30	95.8	0.49	8.4	23.6
MAS02	38 47 35	105 01 23	1.75	2.2	0.04	0.37	80.8	1.41	9.8	24.7
MAS03	38 47 38	105 01 42	2.49	1.7	0.04	0.26	84.0	2.09	12.6	26.9
MAS04	38 48 13	105 02 06	1.64	5.2	0.08	0.28	60.1	0.99	12.8	27.0
MAS05	38 48 38	105 02 33	2.74	3.3	0.09	0.51	31.7	0.87	12.8	27.0
MAS30	38 47 32	105 01 22	0.08	7.0	0.01	0.62	100.0	0.08	9.0	24.1
McReynolds Reservoir (Middle Beaver Creek) Watershed (Primary Watershed Code MCR00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.										
MCR00	38 46 38	105 00 45	3.20	19.8	0.63	0.22	64.7	2.07	8.4	23.6
MCR01	38 46 33	105 00 14	0.45	32.4	0.15	0.65	68.1	0.31	8.4	23.6
MCR30	38 46 27	105 00 21	0.14	2.4	0.00	0.38	85.6	0.12	8.4	23.6
MCR31	38 46 58	105 00 07	0.49	19.8	0.10	0.63	55.1	0.27	8.4	23.6
[1]Lake Moraine (Ruxton Creek) Watershed (Primary Watershed Code MOR00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.										
MOR00	38 48 56	104 59 32	6.22	17.4	1.08	0.28	86.2	5.36	8.8	23.9
MOR01	38 48 33	105 00 00	4.55	20.6	0.94	0.33	89.3	4.07	8.7	23.8
MOR02	38 48 23	105 00 11	0.98	19.2	0.19	0.55	92.6	0.90	9.0	24.1
MOR03	38 48 48	104 59 47	0.73	2.7	0.02	0.77	89.0	0.65	9.4	24.4
MOR30	38 48 03	105 00 27	0.76	20.5	0.16	0.41	98.0	0.75	8.4	23.6
[1]Big Tooth Reservoir (South Ruxton Creek) Watershed (Primary Watershed Code BIG00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.										
BIG00	38 49 47	104 58 18	6.30	15.6	0.98	0.36	85.1	5.36	8.4	23.6
BIG01	38 49 38	104 58 11	0.49	5.9	0.03	0.57	97.7	0.48	8.4	23.6
BIG02	38 49 38	104 58 12	2.08	16.1	0.33	0.33	99.9	2.08	8.4	23.6
BIG03	38 49 35	104 58 23	6.06	16.2	0.98	0.37	84.9	5.14	8.4	23.6
BIG04	38 49 23	104 58 22	0.62	26.6	0.16	0.55	100.0	0.62	8.4	23.6
BIG05	38 48 42	104 58 47	1.21	9.9	0.12	0.50	93.4	1.13	8.4	23.6
BIG06	38 48 41	104 58 47	2.66	21.6	0.57	0.47	69.7	1.86	8.4	23.6
[2]Manitou No. 1 Intake (Ruxton Creek) Watershed (Primary Watershed Code MAN00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.										
MAN00	38 51 10	104 56 13	42.65	20.4	8.70	0.34	85.3	36.38	9.7	24.5
MAN01	38 51 01	104 56 32	0.94	40.8	0.38	1.00	99.0	0.93	8.8	23.8
MAN02	38 51 05	104 56 38	0.24	28.9	0.07	1.10	99.0	0.24	20.8	30.8
MAN03	38 51 06	104 56 55	1.48	19.3	0.28	0.43	100.0	1.48	10.5	24.8
MAN04	38 50 58	104 57 09	1.15	57.9	0.67	0.78	95.2	1.09	8.4	23.6
MAN05	38 50 57	104 57 26	0.49	28.9	0.14	0.72	96.2	0.47	8.4	23.6
MAN06	38 50 54	104 57 43	0.30	20.4	0.06	0.54	98.6	0.29	8.4	23.6
MAN07	38 50 47	104 58 10	5.08	12.6	0.64	0.73	72.8	3.70	10.6	25.3

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[DMS, degrees, minutes, seconds; RI, recurrence interval: km^2, square kilometer; m/m, meter per meter; m^3, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Output								
	2-year RI, 1-hour rainfall debris-flow probability (percent)	2-year RI, 1-hour rainfall debris-flow volume (m^3)	10-year RI, 1-hour rainfall debris-flow probability (percent)	10-year RI, 1-hour rainfall debris-flow volume (m^3)	25-year RI, 1-hour rainfall debris-flow probability (percent)	25-year RI, 1-hour rainfall debris-flow volume (m^3)	25-year RI, 1-hour rainfall debris-flow probability rank	25-year RI, 1-hour rainfall debris-flow volume rank	25-year RI, 1-hour rainfall combined debris-flow hazard rank
French Creek Watershed (Primary Watershed Code FRC00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 39 mm. 25-year RI, 1-hour rainfall = 45 mm.									
FRC00	15	>100,000	27	>100,000	36	>100,000	na	na	na
FRC01	46	3,700	63	4,400	72	4,800	3	71	13
FRC02	37	1,300	55	1,500	65	1,600	20	132	66
FRC03	35	5,200	52	6,200	62	6,800	31	58	26
FRC04	31	600	48	700	58	800	55	151	120
FRC05	16	100	28	200	37	200	136	161	168
FRC06	15	1,500	26	1,800	35	1,900	138	124	148
FRC07	2	25,000	4	29,000	6	32,000	166	13	93
FRC08	5	28,000	10	33,000	15	36,000	159	11	85
FRC09	27	2,300	42	2,700	53	3,000	81	101	96
FRC10	33	1,800	50	2,200	61	2,400	39	114	67
FRC11	32	4,500	49	5,400	59	5,900	50	63	41
FRC12	5	45,000	10	54,000	14	59,000	160	5	79
FRC13	7	35,000	13	41,000	19	45,000	156	9	80
Mason Reservoir (Middle Beaver Creek) Watershed (Primary Watershed Code MAS00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 44 mm.									
MAS00	4	40,000	8	49,000	10	51,000	na	na	na
MAS01	27	700	46	800	49	800	101	147	139
MAS02	10	1,800	21	2,200	23	2,200	152	116	153
MAS03	11	2,200	21	2,700	24	2,800	148	104	141
MAS04	3	2,500	6	3,000	7	3,100	164	97	147
MAS05	<1	2,500	1	3,000	1	3,100	170	98	152
MAS30	23	300	41	400	44	400	125	153	159
McReynolds Reservoir (Middle Beaver Creek) Watershed (Primary Watershed Code MCR00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.									
MCR00	10	11,000	20	14,000	25	15,000	na	na	na
MCR01	9	2,500	18	3,100	23	3,300	153	94	138
MCR30	15	200	29	300	35	300	140	155	166
MCR31	3	1,900	7	2,400	9	2,500	163	110	154
[1]Lake Moraine (Ruxton Creek) Watershed (Primary Watershed Code MOR00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.									
MOR00	23	28,000	42	35,000	49	37,000	na	na	na
MOR01	27	21,000	48	26,000	54	28,000	71	18	25
MOR02	22	3,800	42	4,700	49	5,000	102	70	89
MOR03	9	900	19	1,100	24	1,200	149	140	163
MOR30	36	3,200	58	4,000	65	4,200	21	77	29
[1]Big Tooth Reservoir (South Ruxton Creek) Watershed (Primary Watershed Code BIG00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.									
BIG00	19	27,000	37	33,000	44	35,000	na	na	na
BIG01	21	1,000	40	1,300	47	1,400	112	137	140
BIG02	38	7,500	61	9,400	67	10,000	14	42	8
BIG03	19	26,000	37	32,000	44	34,000	129	12	60
BIG04	37	3,100	60	3,900	66	4,100	18	83	31
BIG05	21	3,100	40	3,900	47	4,100	113	82	109
BIG06	9	9,900	19	12,000	24	13,000	150	32	95
[2]Manitou No. 1 Intake (Ruxton Creek) Watershed (Primary Watershed Code MAN00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.									
MAN00	20	>100,000	39	>100,000	46	>100,000	na	na	na
MAN01	29	5,900	51	7,300	58	7,700	56	51	36
MAN02	14	1,500	29	1,900	35	2,000	139	121	142
MAN03	35	5,800	57	7,300	64	7,700	23	52	15
MAN04	44	8,600	67	11,000	72	11,000	2	36	6
MAN05	28	2,600	49	3,300	56	3,500	65	89	68
MAN06	32	1,400	54	1,800	61	1,900	40	125	82
MAN07	4	16,000	10	19,000	13	21,000	161	24	100

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[D M S, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Input									
	Latitude (D M S)	Longitude (D M S)	Watershed area (km²)	Percentage of watershed with slopes greater than or equal to 30 percent (percent)	Area with slopes greater than or equal to 30 percent (km²)	Ruggedness (m/m)	Percentage of watershed with medium and high burn severity (percent)	Area of medium and high burn severity (km²)	Soil clay content (percent)	Soil liquid limit (percent)
[2]Manitou No. 1 Intake (Ruxton Creek) Watershed (Primary Watershed Code MAN00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.—Continued										
MAN08	38 50 57	104 58 30	0.24	6.4	0.02	0.36	100.0	0.24	8.4	23.6
MAN09	38 50 48	104 59 00	1.09	3.2	0.03	0.28	99.8	1.09	8.5	23.7
MAN10	38 50 48	104 59 00	3.02	15.2	0.46	0.83	54.5	1.65	12.1	26.4
MAN11	38 50 35	104 58 20	26.04	15.0	3.92	0.22	89.4	23.28	9.0	24.1
MAN12	38 50 08	104 58 06	0.65	25.5	0.17	0.62	98.9	0.65	8.4	23.6
MAN13	38 50 28	104 58 22	15.50	13.7	2.13	0.28	88.6	13.73	9.4	24.4
MAN14	38 50 33	104 58 26	4.57	22.7	1.04	0.72	57.9	2.65	11.4	25.9
MAN15	38 50 10	104 58 40	3.29	16.0	0.53	0.57	87.0	2.86	10.7	25.4
MAN16	38 49 35	104 58 56	0.74	2.8	0.02	0.36	98.8	0.73	8.4	23.6
MAN17	38 49 35	104 59 01	3.43	11.1	0.38	0.51	87.1	2.98	10.0	24.8
MAN18	38 49 34	104 59 01	6.69	16.5	1.10	0.36	86.7	5.81	8.7	23.9
Platte Rogers Tunnel Intake (Gould Creek) Watershed (Primary Watershed Code PRT00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.										
PRT00	38 44 01	104 59 37	7.54	9.2	0.69	0.24	99.0	7.46	12.5	25.2
PRT01	38 44 05	104 59 33	2.65	7.7	0.20	0.30	99.5	2.63	13.3	25.5
PRT02	38 44 04	104 59 27	0.67	3.1	0.02	0.30	99.5	0.66	21.0	28.4
PRT03	38 44 17	104 59 47	0.85	9.8	0.08	0.41	100.0	0.85	11.9	24.9
PRT04	38 44 17	104 59 47	1.37	5.9	0.08	0.38	99.0	1.36	11.8	24.9
PRT05	38 44 50	104 59 36	0.26	1.0	0.00	0.40	100.0	0.26	8.4	23.6
PRT06	38 44 14	104 59 08	1.01	9.8	0.10	0.44	99.4	1.01	12.3	25.1
PRT07	38 44 36	104 58 37	0.13	21.9	0.03	0.86	100.0	0.13	8.4	23.6
PRT08	38 44 36	104 58 36	1.84	5.1	0.09	0.37	97.3	1.79	8.4	23.6
Rosement Reservoir (East Beaver Creek) Watershed (Primary Watershed Code ROS00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.										
ROS00	38 43 39	104 57 51	8.25	9.4	0.77	0.25	97.8	8.07	15.3	26.2
ROS01	38 43 37	104 57 20	0.36	5.5	0.02	0.38	98.3	0.35	21.0	28.4
ROS02	38 44 05	104 57 30	0.38	32.1	0.12	0.76	99.3	0.38	18.1	27.3
ROS03	38 44 05	104 57 31	0.23	9.9	0.02	0.72	100.0	0.23	21.0	28.4
ROS04	38 44 05	104 57 19	0.21	2.0	0.00	0.90	94.3	0.20	20.2	28.1
ROS05	38 44 05	104 57 18	5.60	9.7	0.54	0.29	98.5	5.51	12.8	25.3
ROS06	38 44 02	104 57 15	0.04	5.8	0.00	0.52	100.0	0.04	21.0	28.4
ROS07	38 44 28	104 57 14	0.64	12.9	0.08	0.65	94.6	0.60	15.2	26.2
ROS08	38 44 30	104 57 23	4.08	9.1	0.37	0.32	99.1	4.05	11.1	24.6
ROS09	38 45 34	104 57 37	1.17	10.3	0.12	0.48	97.4	1.14	8.4	23.6
ROS10	38 45 37	104 57 48	0.04	0.0	0.00	0.63	100.0	0.04	8.4	23.6
ROS30	38 44 03	104 57 15	0.23	1.9	0.00	0.33	100.0	0.23	21.0	28.4
ROS31	38 44 47	104 57 30	0.27	24.2	0.06	0.66	100.0	0.27	15.8	26.4
ROS32	38 44 58	104 57 33	0.32	20.9	0.07	0.76	99.2	0.32	8.9	23.8
ROS33	38 45 03	104 57 34	0.03	7.5	0.00	0.92	100.0	0.03	8.6	23.7
North Cheyenne Creek Watershed (Primary Watershed Code NCH00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 43 mm. 25-year RI, 1-hour rainfall = 47 mm.										
NCH00	38 47 30	104 53 02	27.36	32.1	8.80	0.33	88.6	24.26	9.8	24.4
NCH01	38 47 32	104 53 08	0.64	20.6	0.13	0.60	75.2	0.48	22.9	32.1
NCH02	38 47 25	104 53 35	0.66	44.1	0.29	0.51	85.3	0.57	19.0	29.8
NCH03	38 47 17	104 54 06	4.44	24.9	1.11	0.62	94.8	4.21	8.7	23.8
NCH04	38 46 43	104 54 25	0.18	44.8	0.08	1.04	87.3	0.16	8.4	23.6
NCH05	38 46 10	104 55 19	0.40	9.6	0.04	0.37	93.7	0.37	8.4	23.6
NCH06	38 45 53	104 55 46	0.47	10.4	0.05	0.66	99.7	0.47	8.4	23.6
NCH07	38 45 37	104 56 04	0.49	28.8	0.14	0.74	97.5	0.48	8.4	23.6
NCH08	38 45 37	104 56 04	0.27	14.4	0.04	0.76	98.1	0.27	8.4	23.6
NCH09	38 47 22	104 54 18	0.34	43.3	0.15	0.63	86.2	0.30	8.4	23.6
NCH10	38 47 10	104 54 55	0.15	86.3	0.13	1.30	89.8	0.13	8.4	23.6
NCH11	38 47 14	104 55 17	1.76	45.4	0.80	0.54	93.5	1.65	8.4	23.6
NCH12	38 47 11	104 55 48	0.19	40.6	0.08	1.10	100.0	0.19	8.4	23.6
NCH13	38 47 08	104 56 07	2.05	13.9	0.29	0.52	97.0	1.98	8.4	23.6

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[DMS, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Output: 2-year RI, 1-hour rainfall debris-flow probability (percent)	2-year RI, 1-hour rainfall debris-flow volume (m³)	10-year RI, 1-hour rainfall debris-flow probability (percent)	10-year RI, 1-hour rainfall debris-flow volume (m³)	25-year RI, 1-hour rainfall debris-flow probability (percent)	25-year RI, 1-hour rainfall debris-flow volume (m³)	25-year RI, 1-hour rainfall debris-flow probability rank	25-year RI, 1-hour rainfall debris-flow volume rank	25-year RI, 1-hour rainfall combined debris-flow hazard rank
[2]Manitou No. 1 Intake (Ruxton Creek) Watershed (Primary Watershed Code MAN00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.—Continued									
MAN08	31	600	52	800	59	800	49	149	112
MAN09	31	1,500	52	1,800	59	1,900	46	122	84
MAN10	1	8,200	3	10,000	4	11,000	168	37	117
MAN11	26	>100,000	47	>100,000	54	>100,000	74	1	14
MAN12	33	3,200	55	4,000	62	4,200	33	79	40
MAN13	22	>100,000	41	>100,000	48	>100,000	106	3	39
MAN14	2	17,000	5	21,000	7	22,000	165	21	102
MAN15	13	12,000	27	15,000	33	16,000	143	27	86
MAN16	27	1,000	48	1,200	55	1,300	68	138	119
MAN17	13	10,000	28	12,000	34	13,000	142	31	90
MAN18	21	30,000	39	38,000	46	40,000	115	10	50
Platte Rogers Tunnel Intake (Gould Creek) Watershed (Primary Watershed Code PRT00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.									
PRT00	42	29,000	62	36,000	69	38,000	na	na	na
PRT01	40	6,500	61	7,900	67	8,400	15	49	9
PRT02	45	900	66	1,100	72	1,200	5	139	62
PRT03	36	2,300	57	2,800	64	3,000	25	100	52
PRT04	34	2,700	54	3,300	61	3,500	37	88	51
PRT05	28	200	47	300	54	300	73	156	131
PRT06	35	2,700	56	3,300	62	3,500	29	87	45
PRT07	25	800	44	1,000	51	1,100	93	142	133
PRT08	28	3,300	47	4,100	54	4,300	72	76	63
Rosement Reservoir (East Beaver Creek) Watershed (Primary Watershed Code ROS00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 42 mm. 25-year RI, 1-hour rainfall = 46 mm.									
ROS00	41	33,000	64	41,000	70	44,000	na	na	na
ROS01	41	800	63	1,000	69	1,000	11	144	71
ROS02	43	2,300	66	2,900	72	3,100	6	99	35
ROS03	34	800	56	1,000	62	1,000	28	143	88
ROS04	17	300	34	300	40	400	133	154	161
ROS05	38	19,000	60	24,000	67	25,000	17	20	5
ROS06	38	200	60	200	67	200	16	160	92
ROS07	25	2,000	45	2,500	52	2,700	83	105	103
ROS08	35	12,000	58	15,000	64	16,000	22	26	7
ROS09	26	3,200	47	3,900	54	4,200	75	80	70
ROS10	19	<100	37	<100	44	<100	130	169	169
ROS30	42	300	65	400	71	400	8	152	74
ROS31	40	1,500	62	1,800	69	1,900	12	123	57
ROS32	26	1,500	46	1,900	53	2,000	77	120	111
ROS33	16	200	32	200	38	200	135	159	165
North Cheyenne Creek Watershed (Primary Watershed Code NCH00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 43 mm. 25-year RI, 1-hour rainfall = 47 mm.									
NCH00	33	>100,000	56	>100,000	63	>100,000	na	na	na
NCH01	6	2,600	14	3,300	18	3,500	157	90	137
NCH02	24	4,300	45	5,400	52	5,800	84	65	64
NCH03	27	24,000	50	30,000	57	32,000	63	14	17
NCH04	18	1,600	37	2,000	44	2,100	127	117	136
NCH05	25	1,100	47	1,400	54	1,500	76	134	121
NCH06	23	1,400	45	1,800	52	1,900	89	126	124
NCH07	29	2,700	52	3,400	59	3,600	51	86	58
NCH08	21	1,100	41	1,400	48	1,500	104	135	135
NCH09	27	2,500	50	3,100	57	3,300	61	91	65
NCH10	37	2,000	61	2,500	67	2,600	13	107	47
NCH11	42	11,000	66	14,000	72	15,000	4	28	3
NCH12	27	1,500	50	1,900	57	2,100	62	119	94
NCH13	26	6,700	49	8,500	56	9,000	66	48	43

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[D M S, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Input									
	Latitude (D M S)	Longitude (D M S)	Watershed area (km²)	Percentage of watershed with slopes greater than or equal to 30 percent (percent)	Area with slopes greater than or equal to 30 percent (km²)	Ruggedness (m/m)	Percentage of watershed with medium and high burn severity (percent)	Area of medium and high burn severity (km²)	Soil clay content (percent)	Soil liquid limit (percent)
North Cheyenne Creek Watershed (Primary Watershed Code NCH00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 43 mm. 25-year RI, 1-hour rainfall = 47 mm.—Continued										
NCH14	38 46 55	104 56 18	0.96	33.2	0.32	0.65	96.3	0.93	8.4	23.6
NCH15	38 46 37	104 56 58	0.34	42.4	0.14	1.00	99.2	0.33	8.4	23.6
NCH16	38 46 21	104 57 10	0.25	48.2	0.12	0.85	98.7	0.25	8.4	23.6
NCH17	38 46 23	104 57 17	1.30	22.8	0.30	0.57	96.6	1.25	8.4	23.6
NCH18	38 45 51	104 57 19	0.71	9.7	0.07	0.53	93.7	0.66	8.4	23.6
NCH19	38 46 26	104 57 26	3.26	25.8	0.84	0.49	93.1	3.04	8.4	23.6
NCH20	38 46 18	104 57 48	1.67	24.1	0.40	0.59	90.1	1.51	8.4	23.6
NCH21	38 46 12	104 57 49	0.47	12.3	0.06	0.43	98.4	0.46	8.4	23.6
NCH22	38 46 12	104 57 51	0.86	31.7	0.27	0.78	94.9	0.81	8.4	23.6
NCH23	38 46 40	104 57 40	1.88	30.9	0.58	0.58	57.9	1.09	8.4	23.6
NCH24	38 46 41	104 57 40	3.04	16.8	0.51	0.45	85.7	2.60	8.4	23.6
NCH25	38 47 04	104 58 02	2.45	15.3	0.38	0.41	83.4	2.04	8.4	23.6
NCH26	38 47 05	104 58 03	0.66	11.1	0.07	0.47	98.2	0.65	8.4	23.6
NCH30	38 47 08	104 54 24	4.21	23.6	0.99	0.56	94.8	4.00	8.4	23.6
South Cheyenne Creek Watershed (Primary Watershed Code SCH00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 43 mm. 25-year RI, 1-hour rainfall = 48 mm.										
SCH00	38 47 08	104 52 17	25.78	30.8	7.93	0.30	94.5	24.37	17.9	29.0
SCH01	38 46 55	104 52 49	0.33	68.6	0.23	0.77	68.6	0.23	22.9	32.1
SCH02	38 46 37	104 52 51	0.87	32.9	0.28	0.60	99.7	0.86	22.9	32.1
SCH03	38 45 56	104 52 52	0.63	42.0	0.26	0.78	99.0	0.62	22.9	32.1
SCH04	38 45 56	104 52 52	1.60	46.7	0.75	0.52	99.9	1.60	22.9	32.1
SCH05	38 45 52	104 53 05	0.87	9.6	0.08	0.38	100.0	0.87	22.9	32.1
SCH06	38 45 25	104 53 12	0.20	7.5	0.02	0.52	100.0	0.20	22.9	32.1
SCH07	38 45 21	104 53 12	0.51	26.7	0.14	0.80	100.0	0.51	22.9	32.1
SCH08	38 45 12	104 53 15	0.77	33.7	0.26	0.69	99.8	0.77	22.9	32.1
SCH09	38 45 11	104 53 15	0.31	33.4	0.10	0.69	95.8	0.29	21.4	31.2
SCH10	38 45 03	104 53 04	0.71	36.3	0.26	0.65	99.8	0.71	22.9	32.1
SCH11	38 44 50	104 53 27	0.02	3.8	0.00	0.46	100.0	0.02	22.9	32.1
SCH12	38 44 41	104 53 26	0.52	40.0	0.21	0.72	100.0	0.52	22.9	32.1
SCH13	38 44 41	104 53 27	0.33	23.5	0.08	0.83	100.0	0.33	22.9	32.1
SCH14	38 44 46	104 53 29	0.75	32.8	0.25	0.54	98.4	0.74	22.9	32.1
SCH15	38 44 46	104 53 30	0.67	33.9	0.23	0.59	93.6	0.63	18.0	29.2
SCH16	38 46 33	104 53 19	0.75	19.4	0.14	0.46	94.2	0.70	22.8	32.0
SCH17	38 46 32	104 53 24	0.37	4.5	0.02	0.64	87.2	0.32	17.4	28.9
SCH18	38 46 31	104 53 25	1.07	13.0	0.14	0.53	91.4	0.98	11.9	25.7
SCH19	38 45 58	104 53 55	1.18	9.8	0.12	0.56	99.1	1.17	13.6	26.6
SCH20	38 45 54	104 54 13	0.70	46.0	0.32	0.81	92.0	0.64	8.4	23.6
SCH21	38 45 37	104 54 30	1.01	53.8	0.54	0.61	83.1	0.84	8.4	23.6
SCH22	38 45 18	104 54 43	1.64	34.3	0.56	0.79	92.9	1.52	11.2	24.7
SCH23	38 44 38	104 56 05	0.41	27.2	0.11	0.90	83.3	0.34	19.2	27.7
SCH24	38 44 38	104 56 05	0.55	21.1	0.12	0.63	95.9	0.53	21.0	28.4
SCH30	38 45 17	104 54 43	3.44	38.3	1.32	0.53	90.2	3.10	14.2	25.8

Table 2. Debris-flow model input variables and estimated debris-flow probabilities and volumes for primary watersheds and subwatersheds.—Continued

[DMS, degrees, minutes, seconds; RI, recurrence interval: km², square kilometer; m/m, meter per meter; m³, cubic meter; mm, millimeter; na, not applicable; <, less than; >, greater than]

Watershed code	Output								
	2-year RI, 1-hour rainfall debris-flow probability (percent)	2-year RI, 1-hour rainfall debris-flow volume (m³)	10-year RI, 1-hour rainfall debris-flow probability (percent)	10-year RI, 1-hour rainfall debris-flow volume (m³)	25-year RI, 1-hour rainfall debris-flow probability (percent)	25-year RI, 1-hour rainfall debris-flow volume (m³)	25-year RI, 1-hour rainfall debris-flow probability rank	25-year RI, 1-hour rainfall debris-flow volume rank	25-year RI, 1-hour rainfall combined debris-flow hazard rank
North Cheyenne Creek Watershed (Primary Watershed Code NCH00). 2-year RI, 1-hour rainfall = 29 mm. 10-year RI, 1-hour rainfall = 43 mm. 25-year RI, 1-hour rainfall = 47 mm.—Continued									
NCH14	33	5,300	57	6,600	64	7,000	24	56	19
NCH15	31	2,500	54	3,100	61	3,300	34	92	54
NCH16	40	2,100	64	2,700	70	2,800	10	103	42
NCH17	30	5,600	53	7,100	60	7,500	45	53	28
NCH18	20	1,900	41	2,400	48	2,500	109	109	126
NCH19	30	16,000	53	20,000	60	22,000	43	22	10
NCH20	22	7,300	43	9,200	50	9,700	97	44	61
NCH21	30	1,500	54	2,000	60	2,100	41	118	73
NCH22	26	4,600	49	5,800	56	6,100	67	61	55
NCH23	5	8,000	12	10,000	16	11,000	158	39	110
NCH24	18	11,000	37	14,000	44	15,000	128	29	72
NCH25	17	8,000	35	10,000	41	11,000	132	38	87
NCH26	28	1,900	51	2,500	58	2,600	57	108	81
NCH30	28	21,000	51	27,000	58	29,000	54	16	11
South Cheyenne Creek Watershed (Primary Watershed Code SCH00). 2-year RI, 1-hour rainfall = 30 mm. 10-year RI, 1-hour rainfall = 43 mm. 25-year RI, 1-hour rainfall = 48 mm.									
SCH00	38	>100,000	60	>100,000	68	>100,000	na	na	na
SCH01	13	3,100	27	3,900	34	4,200	141	81	127
SCH02	30	4,900	51	6,100	60	6,500	44	59	34
SCH03	29	4,200	50	5,200	59	5,600	52	67	46
SCH04	43	11,000	65	14,000	72	15,000	1	30	2
SCH05	23	2,400	43	2,900	52	3,100	88	96	99
SCH06	19	600	36	700	45	800	123	150	155
SCH07	21	2,700	39	3,300	48	3,600	107	85	106
SCH08	28	4,400	49	5,500	57	5,900	59	62	48
SCH09	24	2,000	44	2,500	52	2,700	82	106	104
SCH10	30	4,300	52	5,400	61	5,800	38	64	32
SCH11	19	<100	36	100	45	100	122	165	162
SCH12	31	3,500	52	4,400	61	4,700	36	72	38
SCH13	19	1,700	36	2,100	44	2,300	124	115	134
SCH14	30	4,200	52	5,300	60	5,700	42	66	37
SCH15	27	3,900	48	4,800	56	5,200	64	68	56
SCH16	20	3,000	39	3,800	48	4,100	110	84	107
SCH17	9	700	20	800	26	900	147	145	164
SCH18	19	3,300	37	4,100	45	4,400	120	75	108
SCH19	23	3,100	43	3,900	52	4,200	90	78	83
SCH20	32	4,800	54	6,000	62	6,400	27	60	23
SCH21	32	7,100	54	8,800	63	9,500	26	45	12
SCH22	29	9,100	51	11,000	59	12,000	48	34	20
SCH23	19	2,200	36	2,700	45	2,900	121	102	128
SCH24	41	2,500	63	3,100	71	3,300	9	93	33
SCH30	41	22,000	63	27,000	71	29,000	7	15	1

[1]Lake Moraine and Big Tooth Reservoir are located within the greater Ruxton Creek watershed and upstream from the Manitou #1 Intake.

[2]Ruxton Creek main-stem (MAN00) probability and volume estimates include the areas upstream from Lake Moraine (MOR00) and Big Tooth Reservoir (BIG00); however, model assumes no reservoir effect. Ruxton Creek drainage area at MAN00 is greater than the maximum drainage area that produced a debris flow in Cannon and others, 2010 (30 km²). See text p. 4 for explanation.

Three postwildfire precipitation scenarios and recurrence intervals were used for the postwildfire debris-flow analysis in the Pikes Peak area watersheds. These scenarios were (1) a 2-year recurrence (50-percent annual exceedance probability), 1-hour duration rainfall; (2) a 10-year recurrence (10-percent annual exceedance probability), 1-hour duration rainfall; and (3) a 25-year recurrence (4-percent annual exceedance probability), 1-hour duration rainfall. In this report, the precipitation scenarios will be referred to as the “2-, 10-, and 25-year storms.” Rainfall totals for the Pikes Peak area watersheds were extrapolated from the National Oceanic and Atmospheric Administration (NOAA) Atlas II for Colorado (Miller and others, 1973). A 1-hour rainfall duration was chosen for the scenarios because it is a relatively short-lived event, and because it was the longest rainfall period for which rainfall intensity was calculated when the debris-flow models were derived (Cannon and others, 2010, their table 2). The total storm rainfall for each scenario was assumed to occur uniformly over each primary watershed.

Other input variables for the debris-flow model were determined from a variety of sources. The watershed area and percentage of watershed area with hillslopes of 30 percent or greater were determined using ArcMap (Environmental Systems Research Institute, Inc., 2009) with topography from 10-m digital-elevation models (DEMs) (Gesch and others, 2002). 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 soil clay content and liquid limit. Soil properties were spatially averaged when more than one value occurred in a watershed. Because tools were not available in the standard ArcGIS toolbox to evaluate ruggedness in a spatially explicit manner, a python script was written to evaluate the ruggedness variable for each grid cell in the study area.

Watershed Characterization

Debris-flow probabilities and volumes for this study were estimated using two watershed-characterization methods. First, a conventional watershed-characterization approach was used. Secondly, the debris-flow probabilities and volumes were estimated using a continuous-parameterization technique (Verdin and Greenlee, 2003; Verdin and Worstell, 2008).

For the conventional watershed characterization approach, 14 primary watersheds (identified by Colorado Springs Utilities) and 170 selected subwatersheds within the primary watersheds (tables 1 and 2) were delineated using Streamstats (U.S. Geological Survey, 2010). The 170 subwatersheds were selected based on (1) topographic characteristics and vegetation distribution as displayed in the Streamstats interface, and (2) geomorphic field evidence of previous debris flows. Watershed sizes in the analysis ranged from 0.01 to 42.65 km^2 (0.004 to 16.47 mi^2) (table 2), which is consistent with the range of watershed areas used in the debris-flow models developed by Cannon and others (2010), 0.01 to 103 km^2 (0.004 to 39.77 mi^2). The 14 primary watersheds and 170 subwatersheds were evaluated by averaging the input variables over the watershed area and using those values in the debris-flow equations.

Whereas the conventional watershed-characterization method allows evaluation of the debris-flow probability and volume equations at predefined locations only (generally at the watershed outlet), the continuous-parameterization technique, using the 1/3-arc-second National Elevation Dataset (Gesch and others, 2002) (10-m nominal resolution) and its derived flow-direction grid as a base, evaluates the debris-flow equations for every pixel within the 10-m DEM. This technique provides a synoptic view of the entire study area, providing estimates of debris-flow volume and probability in a continuous manner for the entire channel length within a watershed. Examination of the derived probabilities and volumes along all stream channels facilitates identification of areas of high or low potential for debris flows.

Evaluation of the debris-flow equations using the continuous-parameterization technique requires that surfaces of all of the independent variables used as input to the predictive equations be developed. Through use of the flow-direction grid and techniques detailed in Verdin and Worstell (2008), surfaces were developed for all of the independent variables. Once the surfaces of the independent variables were developed, the probability and volume equations were solved using map algebra for each grid cell and the 2-year, 10-year , and 25-year storms. Identification of the probability or volume of a debris flow at any location within the study area is possible by querying the derived surfaces. In this assessment, a raster sampling technique was used to identify the values of debris-flow probability and volume at selected locations along the drainage network derived from a digital-elevation model. The results from the continuous-parameterization approach were identical to the results of the conventional watershed-characterization approach at the watershed outlet, or pour point, of the 14 primary watersheds and 170 subwatersheds defined within the study area. The advantage of the continuous-parameterization technique is that it provides the capability to rapidly evaluate and assess subwatershed probability and volume estimates at specific drainage-network locations within a watershed, as well as at the watershed outlet.

Verification of Debris-Flow Model Results

Preliminary estimates of debris-flow probability made with the Cannon and others (2010) model were checked against geomorphic evidence onsite for selected watersheds in the study area during a reconnaissance visit. The presence of older debris-flow deposits or debris-flow-scoured channels in these watersheds was considered to be geomorphic evidence that debris flows had occurred at some time in the past, and that the debris-flow models of Cannon and others (2010) were appropriate for use in the Pikes Peak area watersheds. The purpose of the reconnaissance was to verify historical debris-flow activity, and no attempt was made to determine what watershed conditions (postwildfire or unburned) existed at the time the debris flows occurred.

The debris-flow probability model was run for each watershed with the assumptions that (1) all trees and shrubs in the watershed had been burned with a moderate to high severity, and that the fire soon was followed by (2) a 2-year recurrence, 1-hour storm. This scenario represented a relatively rare wildfire (a moderate- to high-burn severity of the entire watershed) and a relatively common rainfall (50-percent annual-exceedance probability) likely to occur soon after a wildfire.

Debris-flow probabilities for all watersheds in the study area ranged from less than 1 to 46 percent for the assumed burn severity and extent and the assumed 2-year storm. USGS personnel performed reconnaissance and onsite verification in 47 study-area watersheds in August 2010. Forty-two of these watersheds had an estimated debris-flow probability of 20 percent or greater as a result of the assumed burn severity and extents followed by a 2-year storm. Eighteen of these 42 high-probability watersheds (43 percent) and one watershed with a 19-percent probability (SCH-13) showed geomorphic evidence of previous debris-flow activity including lateral, or marginal, levees (figs. 2 and 3), terminal lobes, debris-flow fans, or debris-flow-scoured channels (Costa, 1988; Pierson, 2005). Fourteen of these watersheds (33 percent) had inconclusive geomorphic evidence; such as lobe-shaped deposits of colluvium or reworked glacial till that could have been formed by hillslope creep, landslide, earthflow, solifluction, rockfall, debris flow, or combinations thereof (Keefer and Johnson, 1983). Ten of these watersheds (24 percent) showed no geomorphic evidence of previous debris-flow activity.

Figure 2. Debris-flow marginal levee near the outlet of subwatershed SCH13, a tributary in the South Cheyenne Creek watershed. View is looking upstream; arrows indicate direction of debris flow. Photograph by Keelin R. Schaffrath, U.S. Geological Survey, August 24, 2010.

Figure 3. Debris-flow marginal levees bordering East Beaver Creek in subwatershed ROS08, a tributary that flows into the Penrose-Rosemont Reservoir. View is looking upstream; arrows indicate direction of debris flow. Photograph by John G. Elliott, U.S. Geological Survey, August 25, 2010.

No attempt was made to correlate any observed debris-flow deposit with a previous wildfire, a specific storm characteristic, or a date. However, in watersheds for which the model predicted a greater than 20-percent probability of debris-flow activity for the 2-year storm, corroborative geomorphic evidence typically was found. The geomorphic evidence of debris-flow activity was subtle in most observed watersheds and debris-flow deposits commonly were found in heavily forested locations, indicating that the most recent debris-flow activity was at least several decades old (figs. 2 and 3). Although it was not determined whether any of the observed debris flows in the reconnaissance subwatersheds were the result of previous wildfires, the field evidence indicated that debris-flow processes had been active in these locations. Therefore, it was concluded that the Cannon and others (2010) models were appropriate to estimate the probability and volume of postwildfire debris flows in these watersheds for a range of postwildfire rainfall scenarios.

Estimated Probabilities and Volumes of Postwildfire Debris Flows

Potential postwildfire debris-flow probabilities and volumes for 14 primary watersheds and 170 subwatersheds located within the primary watersheds were estimated by using the empirical debris-flow models of Cannon and others (2010), equations 1, 2, and 3. The debris-flow models assumed that a moderate to severe wildfire burned 100 percent of the forest and shrub stands within the watershed, and that rainstorms occurred within 4 to 6 years following the hypothetical wildfire (Elliott and others, 2005). Three postwildfire precipitation scenarios were used to represent a range of precipitation scenarios that could occur shortly after a wildfire in the Pikes Peak region: (1) a 2-year recurrence, 1-hour duration rainfall (2-year storm); (2) a 10-year recurrence, 1-hour duration rainfall (10-year storm); and (3) a 25-year recurrence, 1-hour duration rainfall (25-year storm).

The estimated probabilities and volumes are hypothetical and have been made due to the need for timely best science information. The estimates are provided on the condition that neither the U.S. Geological Survey nor the United States Government may be held liable for any damages resulting from the authorized or unauthorized use of the estimates.

Pikes Peak Area Watershed Debris-Flow Probabilities

Results of the debris-flow probability modeling are shown graphically as color-coded map symbols at primary watershed and subwatershed outlets in figures 4, 5, and 6; the corresponding numerical values are presented in table 2. The color-coded map symbols represent the probability of a debris flow occurring in the channel at the primary watershed or subwatershed outlet estimated using the conventional watershed-characterization approach discussed in the “Watershed Characterization” section.

In addition to the color coded map symbols, the maps in figures 4, 5, and 6 include color-coded shaded areas representing the debris-flow probabilities in third-order streams in the study area. Stream order is a method of classifying the components of the drainage network and is a measure of the position of a stream in the hierarchy of tributaries within a watershed (Horton, 1945). The Strahler order (Strahler, 1957) is one such method and was used in this analysis. Strahler third-order watersheds were assessed for debris-flow probability using the continuous-parameterization technique described in the “Watershed Characterization” section. Although the contributing area upstream from the outlet of each Strahler third-order watershed is entirely shaded by a color representing the debris-flow estimated probability, the estimated probability is applicable only for a debris flow occurring at the point at which smaller channels converge to form a Strahler third-order channel, and not for every channel segment upstream from that point. The shaded areas give a detailed breakdown of the debris-flow estimated probability in smaller areas of the subwatersheds, providing useful information for resource managers and emergency responders.

The estimated probabilities for postwildfire debris flows in the 170 subwatersheds in the Pikes Peak study area ranged from less than 1 to 46 percent in response to the 2-year storm, 1 to 67 percent in response to the 10-year storm, and 1 to 72 percent in response to the 25-year storm (table 2). Subwatersheds with the lowest postwildfire debris-flow probabilities tended to have large areas of alpine and subalpine vegetation or other large areas with sparse forest cover (figs. 4–6).

Subwatersheds with the highest probabilities tended to be heavily forested and tended to have a large percent area of steep slopes (table 2). Forty of the 170 subwatersheds had a greater than 60 percent probability of producing a debris flow in response to the 25-year storm (fig. 6 and table 2). The drainage areas of these 40 high-probability subwatersheds ranged from 0.04 to 10.83 km^2 and averaged 1.38 km^2. Cannon and others (2010) found that “low-order tributaries” with a mean area of 1.7 km^2 produced most of the debris flows in their study areas. Many of the subwatersheds with the highest debris-flow probabilities in this study were in the eastern and southeastern part of the study area, notably tributaries in the Gould Creek (Platte Rogers Tunnel Intake, PRT), East Beaver Creek (Rosemont Reservoir, ROS), North Cheyenne Creek (NCH), and South Cheyenne Creek (SCH) primary watersheds (fig. 6 and table 2).

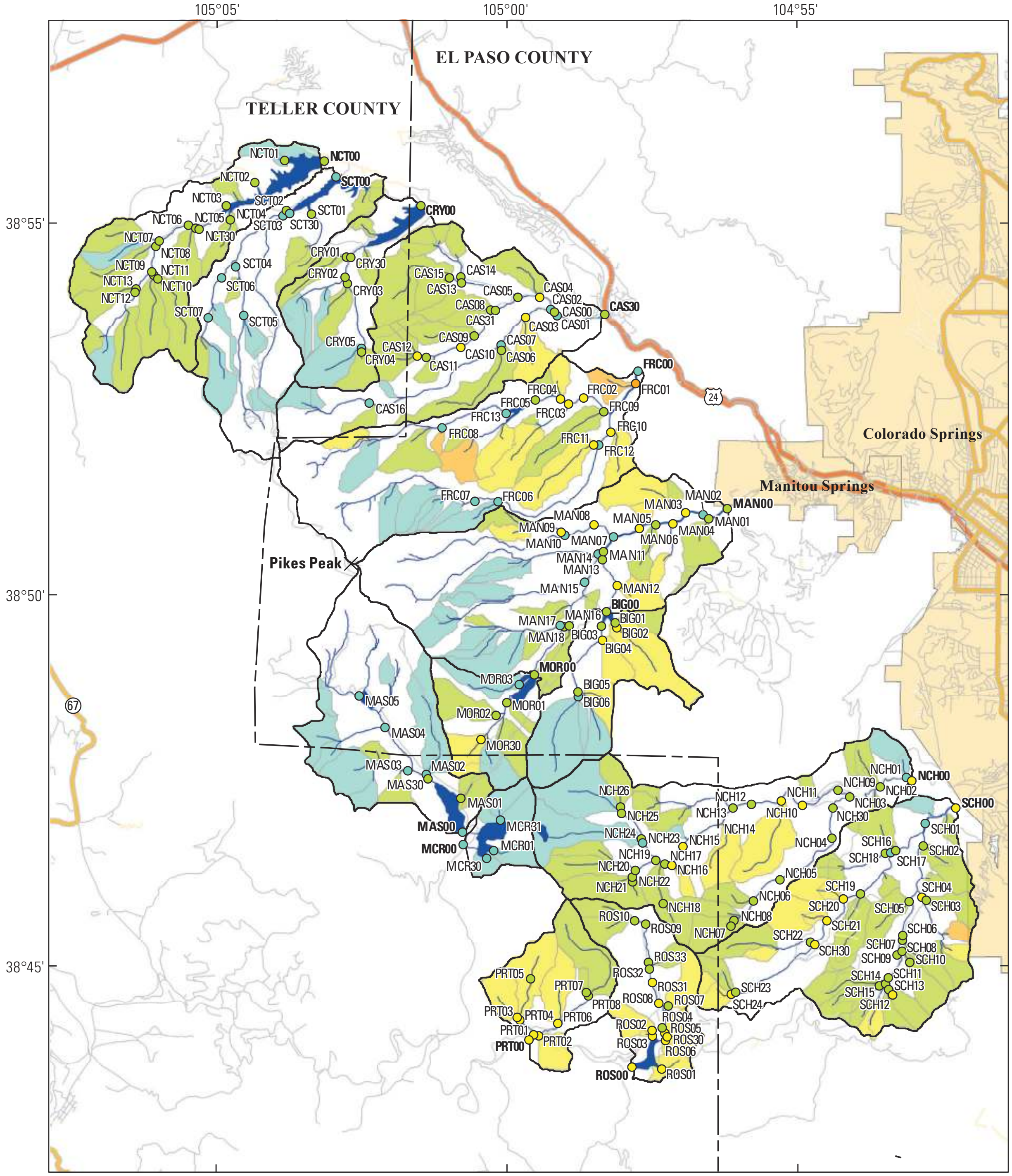
The 14 primary watersheds were evaluated separately because they consisted of nested subwatersheds, and any potential debris flow reaching the primary watershed outlet could be the result of debris-flow contributions from the nested subwatersheds and also could include runoff from other contributing land surfaces (for example, laterally planar hillslopes) within the primary watershed (figs. 4, 5, 6). Postwildfire debris-flow probabilities for the primary watersheds ranged from 4 to 42 percent in response to the 2-year storm, 8 to 64 percent in response to the 10-year storm, and 10 to 70 percent in response to the 25-year storm (table 2).

The PRT, ROS, NCH, and SCH primary watersheds each had a greater than 60-percent probability of producing a debris flow at the watershed outlet in response to a 25-year storm (table 2) if the entire forested part of the watershed was moderately to severely burned. The PRT and ROS primary watersheds had a greater than 40-percent probability of producing a debris flow in response to as little as a 2-year storm.

It is possible for a large primary watershed to have a very small percent probability of a debris flow reaching the watershed outlet even though debris flows were possible in some subwatersheds within the primary watershed This possibility occurs in some primary watersheds because of limited transport potential downstream from a subwatershed outlet or because of the relatively small size of the debris-flow contributing area within the primary watershed. Cannon and others (2010) found that “debris flows were not observed at the outlets of watersheds greater than about 30 km^2 (12 mi^2) in area.”

Pikes Peak Area Watershed Debris-Flow Volumes

Results of the debris-flow volume models are shown graphically as color-coded map symbols at primary watershed and subwatershed outlets in figures 7, 8, and 9: the corresponding numerical values are presented in tables 2. The color-coded map symbols represent the estimated volume of a debris flow occurring in the channel at the primary watershed or subwatershed outlet estimated using the conventional watershed-characterization approach discussed in the “Watershed Characterization” section.



Base from U.S. Geological Survey digital data, 2007
Projection is NAD 1983 UTM Zone 13 North

0 1 2 MILES
0 1 2 KILOMETERS

Environmental Systems Research Institute, Inc.
U.S. Major Roads, 2010, 1:50,000

EXPLANATION

Estimated probability of debris flow at outlet of Strahler 3rd-order watershed (percent)

- 0 to 15
- 16 to 30
- 31 to 45
- 46 to 60

MCR00 Primary watershed code
MCR30 Subwatershed code

Primary watershed boundary
Lake or reservoir
Stream

Estimated probability of debris flow at outlet of watershed of interest (percent)

- 0 to 15
- 16 to 30
- 31 to 45
- 46 to 60

Figure 4. Map of primary watersheds and subwatersheds showing estimated debris-flow probabilities in response to the 2-year-recurrence, 1-hour-duration rainfall. See table 2 for watershed and subwatershed codes.

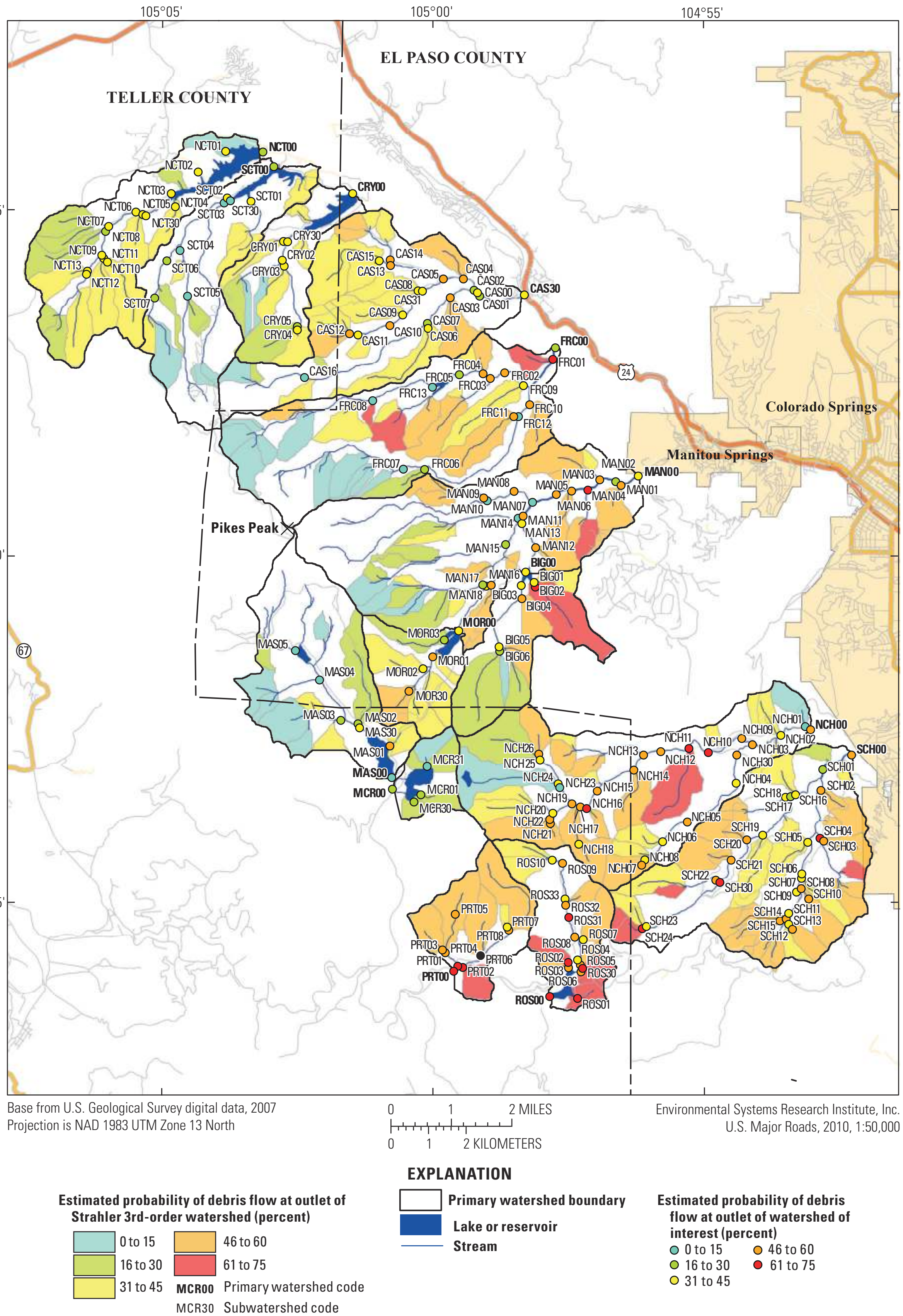


Figure 5. Map of primary watersheds and subwatersheds showing estimated debris-flow probabilities in response to the 10-year-recurrence, 1-hour-duration rainfall. See table 2 for watershed and subwatershed codes.

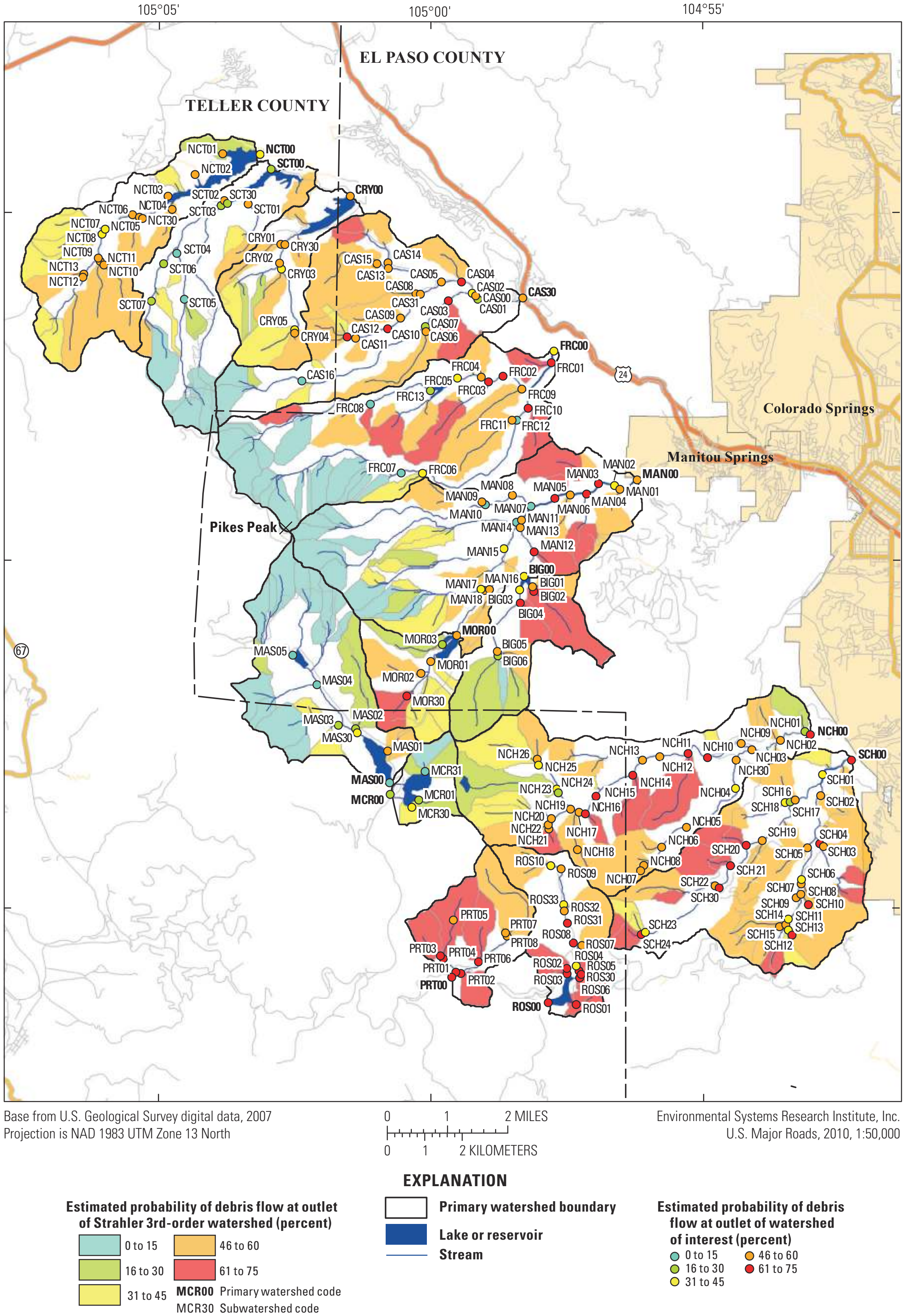
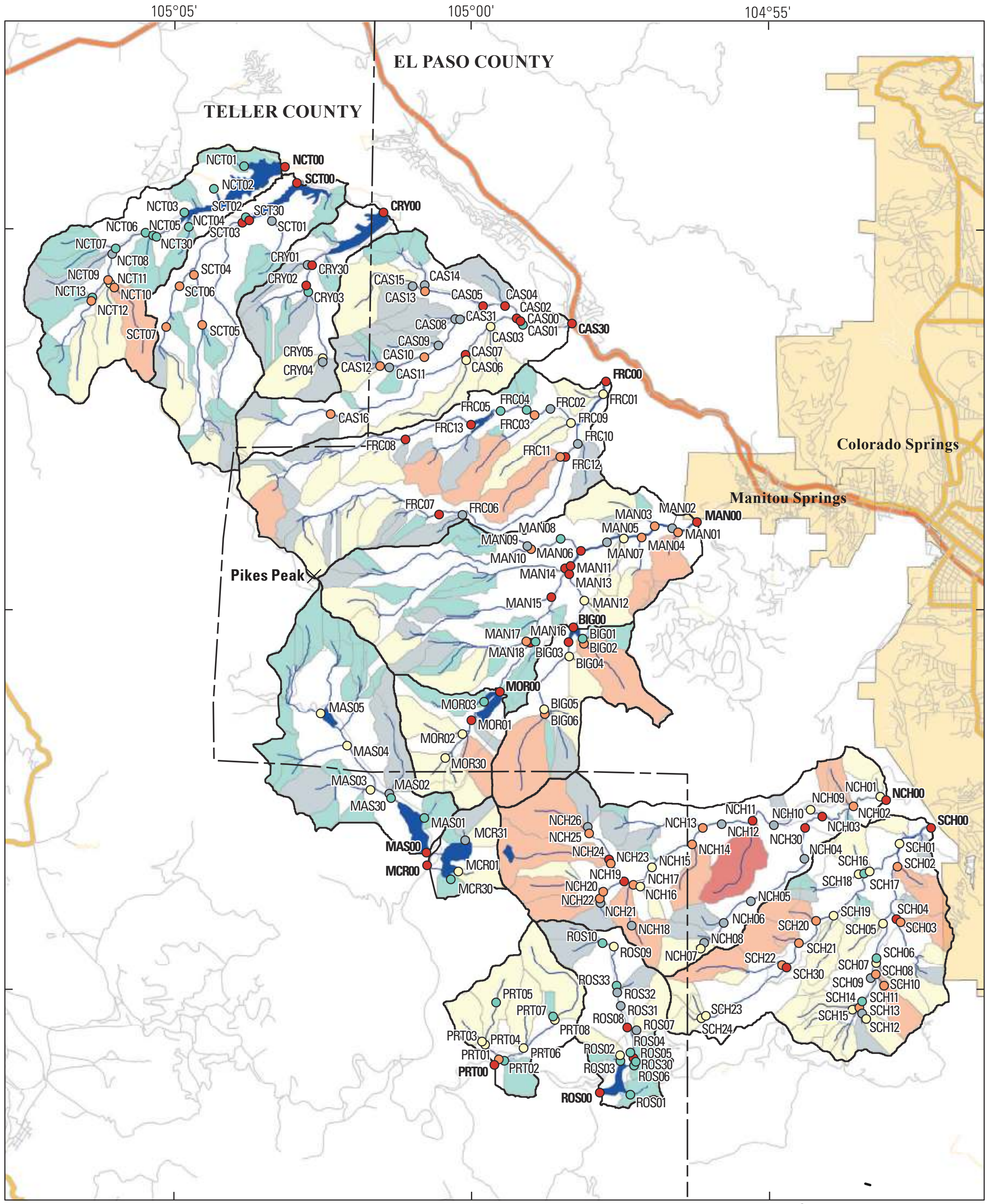


Figure 6. Map of primary watersheds and subwatersheds showing estimated debris-flow probabilities in response to the 25-year-recurrence, 1-hour-duration rainfall. See table 2 for watershed and subwatershed codes.



Base from U.S. Geological Survey digital data, 2007
Projection is NAD 1983 UTM Zone 13 North

0 1 2 MILES
0 1 2 KILOMETERS

Environmental Systems Research Institute, Inc.
U.S. Major Roads, 2010, 1:50,000

EXPLANATION

Estimated volume of debris flow at outlet of Strahler 3rd-order watershed (cubic meters)

- Less than 1,000
- Greater than 1,000 to 2,000
- Greater than 2,000 to 4,000
- Greater than 4,000 to 10,000
- Greater than 10,000

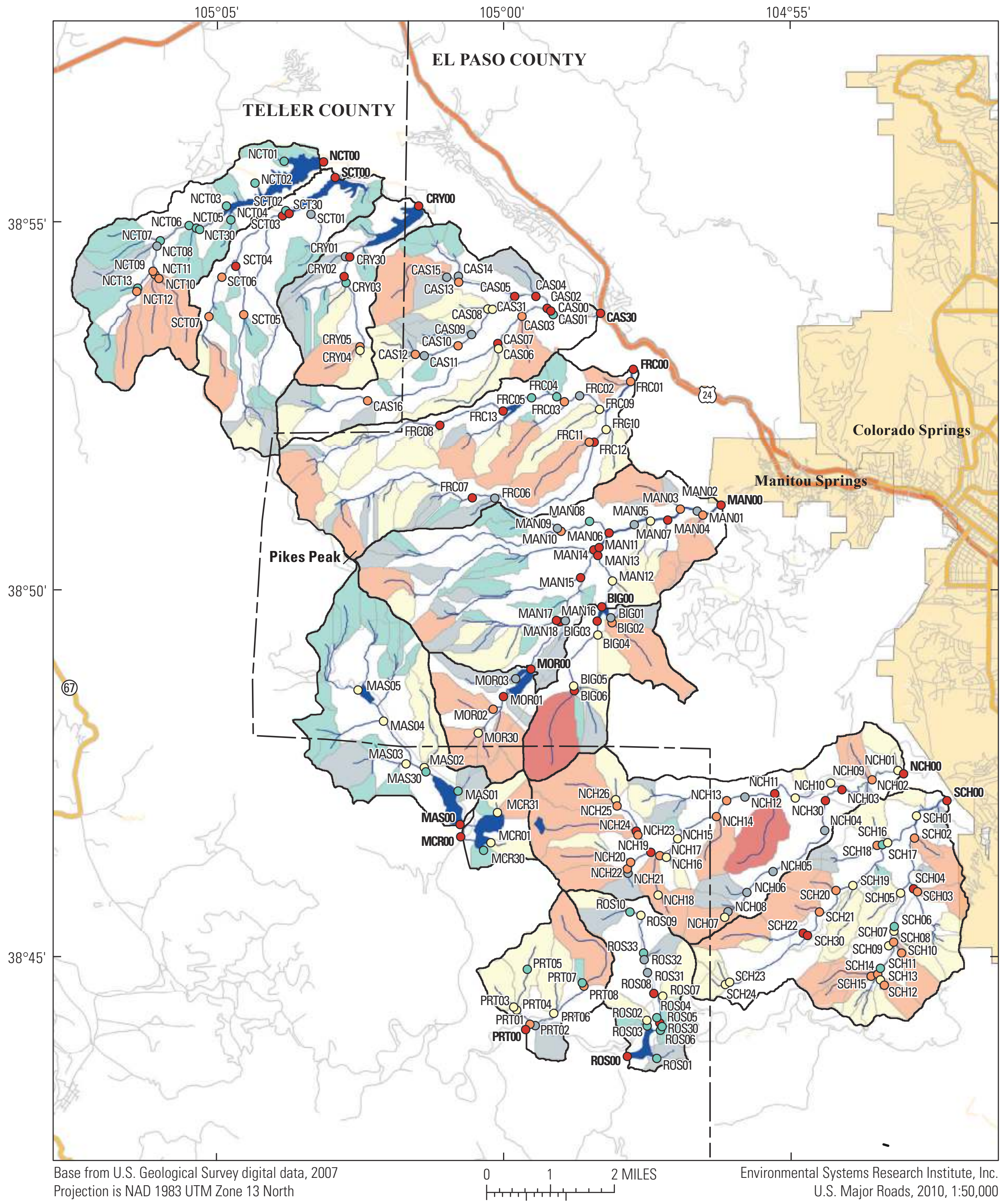
MCR00 Primary watershed code
MCR30 Subwatershed code

Primary watershed boundary
Lake or reservoir
Stream

Estimated volume of debris flow at outlet of watershed of interest (cubic meters)

- Less than 1,000
- Greater than 1,000 to 2,000
- Greater than 2,000 to 4,000
- Greater than 4,000 to 10,000
- Greater than 10,000

Figure 7. Map of primary watersheds and subwatersheds showing estimated debris-flow volumes in response to the 2-year-recurrence, 1-hour-duration rainfall. See table 2 for watershed and subwatershed codes.



Base from U.S. Geological Survey digital data, 2007
Projection is NAD 1983 UTM Zone 13 North

0 1 2 MILES
0 1 2 KILOMETERS

Environmental Systems Research Institute, Inc.
U.S. Major Roads, 2010, 1:50,000

EXPLANATION

Estimated volume of debris flow at outlet of Strahler 3rd-order watershed (cubic meters)

- Less than 1,000
- Greater than 1,000 to 2,000
- Greater than 2,000 to 4,000
- Greater than 4,000 to 10,000
- Greater than 10,000

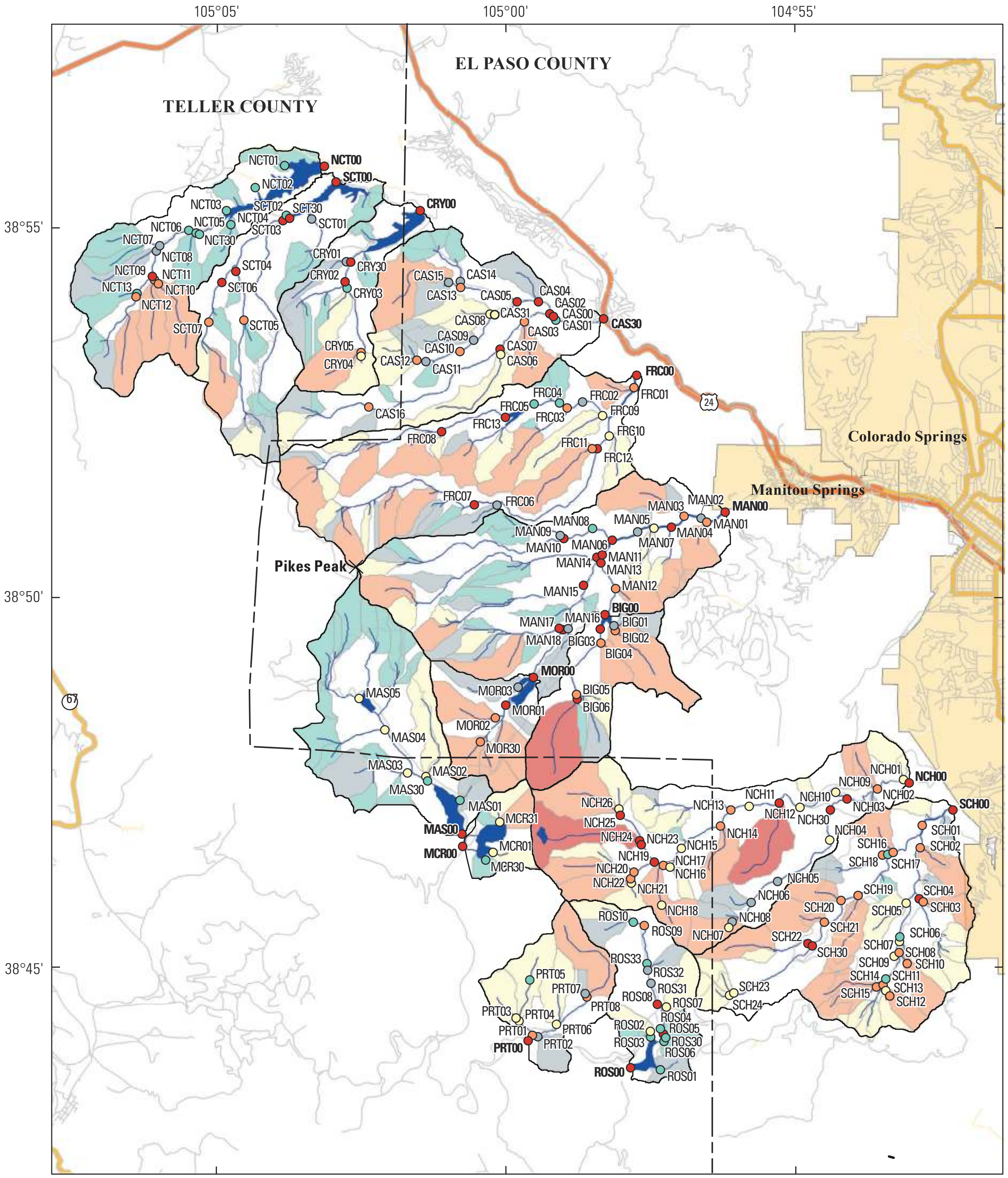
MCR00 Primary watershed code
MCR30 Subwatershed code

Primary watershed boundary
Lake or reservoir
Stream

Estimated volume of debris flow at outlet of watershed of interest (cubic meters)

- Less than 1,000
- Greater than 1,000 to 2,000
- Greater than 2,000 to 4,000
- Greater than 4,000 to 10,000
- Greater than 10,000

Figure 8. Map of primary watersheds and subwatersheds showing estimated debris-flow volumes in response to the 10-year-recurrence, 1-hour-duration rainfall. See table 2 for watershed and subwatershed codes.



Base from U.S. Geological Survey digital data, 2007
Projection is NAD 1983 UTM Zone 13 North

0 1 2 MILES
0 1 2 KILOMETERS

Environmental Systems Research Institute, Inc.
U.S. Major Roads, 2010, 1:50,000

EXPLANATION

Estimated volume of debris flow at outlet of Strahler 3rd-order watershed (cubic meters)

- Less than 1,000
- Greater than 1,000 to 2,000
- Greater than 2,000 to 4,000
- Greater than 4,000 to 10,000
- Greater than 10,000

MCR00 Primary watershed code
MCR30 Subwatershed code

Primary watershed boundary
Lake or reservoir
Stream

Estimated volume of debris flow at outlet of watershed of interest (cubic meters)

- Less than 1,000
- Greater than 1,000 to 2,000
- Greater than 2,000 to 4,000
- Greater than 4,000 to 10,000
- Greater than 10,000

Figure 9. Map of primary watersheds and subwatersheds showing estimated debris-flow volumes in response to the 25-year-recurrence, 1-hour-duration rainfall. See table 2 for watershed and subwatershed codes.

In addition to the color-coded map symbols, the maps in figures 7, 8, and 9 include color-coded shaded areas representing the debris-flow volumes in Strahler third-order streams within the 170 subwatersheds. Although the contribution area upstream from the outlet of each Strahler third-order watershed is entirely shaded by a color representing the debris-flow estimated volume, the estimated volume is applicable only for a debris flow delivering sediment to the point at which smaller channels converge to form a Strahler third-order channel, and not for every channel segment upstream from that point. The shaded areas give a detailed breakdown of the debris-flow estimated volume in smaller areas of the subwatersheds, providing useful information for resource managers and emergency responders.

The debris-flow volume verification data presented in Cannon and others (2010, their figure 4) ranged between 100 and 100,000 m^3 with predicted volumes within one order of magnitude of measured volumes. Using the precedent established by Cannon and others (2010), debris-flow volume estimates for the Pikes Peak study area are presented in table 2 as follows: (1) estimated volumes less than 100 m^3 are reported as less than 100 m^3, (2) estimated volumes greater than 100,000 m^3 are reported as greater than 100,000 m^3, (3) estimated volumes between 100 m^3 and 1,000 m^3 are rounded to the nearest hundred, and (4) estimated volumes between 1,000 m^3 and 100,000 m^3 are rounded to two significant digits.

The estimated volumes for potential postwildfire debris flows in the 170 subwatersheds in the Pikes Peak study area ranged from less than 100 m^3 to greater than 100,000 m^3 in response to the 2-year storm, the 10-year storm, and the 25-year storm (table 2). Estimated debris-flow volumes for each subwatershed increased as the storm recurrence interval increased. Subwatersheds with the smallest estimated postwildfire debris-flow volumes tended to have small drainage areas, have a small percent area of steep hillslopes (table 2), and (or) be located in alpine and subalpine zones (figs. 7, 8, and 9). Subwatersheds with the largest estimated debris-flow volumes were those with the largest drainage areas. Forty-two subwatersheds had estimated debris-flow volumes equal to or greater than 10,000 m^3 in response to a 25-year storm and, of those, three had estimated debris-flow volumes greater than 100,000 m^3 (table 2).

As with the probability estimates, debris-flow volume estimates for the 14 primary watersheds were evaluated separately because they consisted of nested subwatersheds (figs. 7–9). Postwildfire debris-flow volume estimates for the primary watersheds ranged from about 11,000 to greater than 100,000 m^3 in response to the 2-year storm, from about 14,000 to greater than 100,000 m^3 in response to the 10-year storm, and from about 15,000 to greater than 100,000 m^3 in response to the 25-year storm (table 1). The Cascade Creek (CAS), French Creek (FRC), Ruxton Creek (Manitou No. 1 Intake, MAN), NCH, and SCH primary watersheds each had estimated debris-flow volumes greater than 100,000 m^3 in response to a 25-year storm (fig. 9 and table 2). These were the five largest primary watersheds, each having a watershed area greater than 20 km^2.

Although some moderately to severely burned watersheds in the study area potentially can produce large volumes of debris-flow material (water, sediment, and other debris), determining where that material could be deposited below the watershed outlet is beyond the scope of this study. Wide and relatively low-gradient main-stem valleys in the primary watersheds, such as the lower reaches of Cascade Creek (CAS05, CAS13, CAS15) (fig. 9), potentially could intercept and capture some debris-flow material produced in tributaries before the material reaches the primary watershed outlet (CAS30) (fig. 9). The numerous reservoirs in the study area also would likely or almost certainly intercept debris-flow material from upstream areas before it could be transported to the primary watershed outlet.

Combined Relative Debris-Flow Hazard Ranking

The watersheds with the greatest potential postwildfire and postprecipitation debris-flow hazards are those with both high estimated probabilities of debris-flow occurrence and large estimated volumes of debris-flow material (Cannon and others, 2010). Results from the 25-year storm debris-flow probability and volume equations were merged to produce a combined relative debris-flow hazard ranking for the 170 subwatersheds in the Pikes Peak study area to provide an overall indicator of the relative hazards associated with each subwatershed.

For each subwatershed, the debris-flow probability rank, with 1 associated with the highest probability (table 2), was added to the debris-flow volume rank, with 1 associated with the largest volume (table 2), to derive a preliminary combined rank sum. The preliminary combined rank sums for the 170 subwatersheds ranged from 22 (highest combined hazard) to 309 (lowest combined hazard). The preliminary combined rank sums for each subwatershed were renumbered with 1 assigned to the subwatershed with the highest combined hazard, 2 assigned to the subwatershed with the second-highest combined hazard, and so forth through 170 for the subwatershed with the lowest combined hazard.

The 10 subwatersheds with the highest combined relative debris-flow hazard rankings for the 25-year storm, listed generally from north to south, are

- CAS04 (rank 4) in the Cascade Creek watershed;
- BIG02 (rank 8) in the South Ruxton Creek watershed;
- MAN04 (rank 6) in the Ruxton Creek watershed;
- PRT01 (rank 9) in the Gould Creek watershed;
- ROS05 (rank 5) and ROS08 (rank 7) in the East Beaver Creek watershed;
- NCH11 (rank 3) and NCH19 (rank 10) in the North Cheyenne Creek watershed; and
- SCHO4 (rank 2) and SCH30 (rank 1) in the South Cheyenne Creek watershed (table 2).

Combined relative debris-flow hazard rankings were not calculated for the 14 primary watersheds because the direct comparison of primary watershed rankings with the subwatershed rankings would be misleading. The primary watersheds were composite areas that generally consisted of the following: (1) multiple subwatersheds, for which individual debris-flow probabilities and volumes were estimated, and (2) interspersed, laterally planar hillslope areas, for which no individual debris-flow probability and volume estimates were made. Additionally, the outlets of several primary watersheds were located downstream from reservoirs.

Summary and Conclusions

Debris flows are fast-moving, high-density slurries of water, sediment, and debris that can have enormous destructive power. Debris flows typically are triggered by intense rainfall or rapid snowmelt on steep hillsides covered with erodible material. Although debris flows are a common geomorphic process in some unburned areas, a wildfire can transform conditions in a watershed with no recent history of debris flows into conditions that pose a substantial hazard to residents, communities, infrastructure, aquatic habitats, and water supply. In 2010, the U.S. Geological Survey, in cooperation with the City of Colorado Springs, Colorado Springs Utilities (CSU), initiated a prewildfire study to determine the potential for postwildfire debris flows in selected Pikes Peak area watersheds of El Paso and Teller Counties, Colo. The study objective was to estimate the probability of postwildfire debris flows and to estimate the approximate volumes of debris flows that could be delivered from 14 primary watersheds and 170 selected subwatersheds located within the primary watersheds with infrastructure of concern to CSU. This report presents the results of that study.

Debris-flow probabilities and volumes were estimated for 170 selected subwatersheds within the 14 primary watersheds in order to provide CSU with a relative measure of which subwatersheds might constitute the most serious debris-flow hazards in the event of a large-scale wildfire and subsequent rainfall. In addition to the outlets of these primary watersheds and subwatersheds, debris-flow probabilities and volumes at the outlets of Strahler third-order streams and their associated watersheds were estimated, providing useful information for resource managers and emergency responders. Presented graphically only, the shaded third-order watersheds give a visually detailed breakdown of the debris-flow probability and volume in smaller areas of the subwatersheds.

Using information provided in this report, CSU water-resource managers can plan prevention and mitigation strategies in advance of the occurrence of wildfires. Also, in the event of a large wildfire, this information will help managers identify the watersheds and subwatersheds with the greatest postwildfire debris-flow hazards. These estimates are hypothetical and neither the U.S. Geological Survey nor the United States Government may be held liable for any damages resulting from the authorized or unauthorized use of the estimates.

Potential postwildfire debris-flow probabilities and volumes in the study area were based on empirical equations. The 14 primary watersheds range in size from 3.20 to 42.65 km^2 (1.24 to 16.47 mi^2), and the 170 subwatersheds range in size from 0.01 to 26.04 km^2 (0.004 to 10.06 mi^2). The models assumed that all of the forest and shrub cover in the watershed would burn at moderate- to high-burn severity. Three postwildfire precipitation scenarios were used to represent a range of likely precipitation scenarios that could occur within 4 to 6 years after a wildfire: (1) a 2-year recurrence (50-percent annual exceedance probability), 1-hour-duration rainfall; (2) a 10-year recurrence (10-percent annual exceedance probability), 1-hour-duration rainfall; and (3) a 25-year recurrence (4-percent annual exceedance probability), 1-hour-duration rainfall. Rainfall totals for Pikes Peak study area watersheds were determined from the National Oceanic and Atmospheric Administration and were considered to occur uniformly over each primary watershed.

The estimated probabilities for postwildfire debris flows in the 170 subwatersheds ranged from less than 1 to 46 percent in response to the 2-year storm (2-year recurrence, 1-hour duration rainfall), 1 to 67 percent in response to the 10-year storm (10-year recurrence, 1-hour duration rainfall), and 1 to 72 percent in response to the 25-year storm (25-year recurrence, 1-hour duration rainfall). Postwildfire debris-flow probabilities for the 14 primary watersheds ranged from 4 to 42 percent in response to the 2-year storm, 8 to 64 percent in response to the 10-year storm, and 10 to 70 percent in response to the 25-year storm.

Subwatersheds with the lowest postwildfire debris-flow probabilities tended to have large areas of alpine and subalpine vegetation or other large areas with sparse forest cover. Forty of the 170 subwatersheds had a greater than 60-percent probability of producing a debris flow in response to the 25-year storm. Subwatersheds with the highest probabilities tended to be heavily forested and tended to have a large percent area of steep slopes. Many of the subwatersheds with the highest debris-flow probabilities were tributaries in the Gould Creek (Platte Rogers Tunnel Intake, PRT), East Beaver Creek (Rosemont Reservoir, ROS), North Cheyenne Creek (NCH), and South Cheyenne Creek (SCH) primary watersheds.

The estimated volumes for potential postwildfire debris flows in the 170 subwatersheds in the Pikes Peak study area ranged from less than 100 m^3 to greater than 100,000 m^3 in response to the 2-year storm, the 10-year storm, and the 25-year storm . Estimated debris-flow volumes for each subwatershed increased as the storm recurrence interval increased. Postwildfire debris-flow volume estimates for the 14 primary watersheds ranged from about 11,000 to greater than 100,000 m^3 in response to the 2-year storm, from about 14,000 to greater than 100,000 m^3 in response to the 10-year storm, and from about 15,000 to greater than 100,000 m^3 in response to the 25-year storm. Subwatersheds with the smallest estimated postwildfire debris flow volumes tended to have small drainage areas, have a small percent area of steep hillslopes, and (or) be located in alpine and subalpine zones. Subwatersheds with the largest estimated debris-flow volumes were those with the largest drainage areas.

The watersheds with the greatest potential postwildfire and post-precipitation hazards are those with both high estimated probabilities of debris-flow occurrence and large estimated volumes of debris-flow material. The 10 subwatersheds with the greatest combined relative debris-flow hazard rankings for the 25-year storm are CAS04 in the Cascade Creek watershed, BIG02 in the South Ruxton Creek watershed, MAN04 in the Ruxton Creek watershed, PRT01 in the Gould Creek watershed, ROS05 and ROS08 in the East Beaver Creek watershed, NCH11 and NCH19 in the North Cheyenne Creek watershed, and SCHO4 and SCH30 in the South Cheyenne Creek watershed.

Although the location, percentage of burned area, severity of wildfire, and subsequent storm intensity and duration cannot be known in advance, hypothetical scenarios, such as those used in this report, are useful planning tools for conceptualizing potential postwildfire debris-flow hazards. The models in this study were used only to estimate postwildfire debris-flow characteristics at a specific location: the watershed outlet. No attempt was made in this study to model the transport of debris-flow material downstream from the watershed outlet. Substantial flooding and other fluvial-erosion processes that could cause substantial damage also can occur under postwildfire conditions, but were beyond the scope of this study.

Acknowledgments

This study was performed by the U.S. Geological Survey in cooperation with the City of Colorado Springs, Colo., Colorado Springs Utilities. Earl Cassidy and Katherine Chase of the USGS, performed technical reviews of the report. Photographs were taken by John G. Elliott and Keelin R. Schaffrath, USGS.

References Cited

Cannon, S.H., 2001, Debris-flow generation from recently burned drainage basins: Environmental and Engineering Geoscience, v. 7 no. 4, p. 321–341.

Cannon, S.H., Powers, P.S., and Savage, W.Z., 1998, Fire-related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA: Environmental Geology, v. 34, no. 2–3, p. 210–218.

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., and Parrett, C., 2010, Predicting the probability and volume of postwildfire debris flows in the intermountain western United States: Geological Society of America Bulletin, v. 122, p. 127–144.

Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, *in* Flood geomorphology: New York, John Wiley and Sons, p. 113–122.

Costa, J.E., and Jarrett, R.D., 1981, Debris flows in small mountain stream channels of Colorado and their hydrologic impacts: Bulletin of the Association of Engineering Geologists, v. XVIII, no. 3, p. 309–322.

Das, B.M., 1983, Advanced soil mechanics: New York, McGraw-Hill, 511 p.

Elliott, J.G., Flynn, J.L., Bossong, C.R., and Char, S.J., 2011, Estimated probabilities and volumes of postwildfire debris flows, a prewildfire evaluation for the Upper Blue River watershed, Summit County, Colorado: U.S. Geological Survey Scientific Investigations Report 2006–5039, 22 p. *http://pubs.usgs.gov/sir/2011/5039/*

Elliott, J.G., Smith, M.E., Friedel, M.J., Stevens, M.R., Bossong, C.R., Litke, D.W., Parker, R.S., Costello, Catherine, Wagner, Jason, Char, S.J., Bauer, M.A., and Wilds, S.R., 2005, Analysis and mapping of post-wildfire hydrologic hazards for the 2002 Hayman, Coal Seam, and Missionary Ridge wildfires, Colorado: U.S. Geological Survey Scientific Investigations Report 2004–5300, 104 p.

Environmental Systems Research Institute, Inc., 2009, ArcGIS Desktop (v. 9.3.1, Service Pack 1): Redlands, Calif.

Gartner, J.E., Cannon, S. H., Bigio, E.R., Davis, N.K., Parrett, C., Pierce, K.L., Rupert, M.R., Thurston, B.L., Trebish, M.J., Garcia, S.P., and Rea, A.H., 2005, Compilation of data relating to the erosive response of 606 recently burned basins in the Western U.S.: U.S. Geological Survey Open-File Report 05–1218, *http://pubs.usgs.gov/of/2005/1218*.

Gartner, J.E., Cannon, S. H., Santi, P.M., and Dewolfe, V.G., 2008, Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S.: Geomorphology, v. 96, p. 339–354, doi: 10.1016/j.geomorph.2007.02.033.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D., 2002, The national elevation dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, p. 5–11.

Green, G.N., 1992, The Digital Geologic Map of Colorado in ARC/INFO Format: U.S. Geological Survey Open-File Report 92–0507, 9 p.; *http://pubs.usgs.gov/of/1992/ofr-92-0507*

Griffiths, P.G., Webb. R.H., and Melis, T.S., 1996, Initiation and frequency of debris flows in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 96–491, 35 p.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 510 p., *http://pubs.usgs.gov/twri/twri4a3/html/pdf_new.html* (accessed February 26, 2010).

Horton, R.E., 1945, Erosional developments of streams and their drainage basins; hydrophysical approach to quantitative morphology: Geol. Soc. Am. Bull., v. 56, p. 275–370.

Hosmer, D.W., and Lemeshow, Stanley, 2000, Applied logistic regression, 2d ed.: New York, John Wiley & Sons, Inc., 375 p.

Hungr, O., Morgan, G.C., and Kellerhals, R., 1984, Quantitative analysis of debris-torrent hazards for design of remedial measures: Canadian Geotechnical Journal, v. 21, p. 663–677.

Keefer, D.K., and Johnson, A.M., 1983, Earth flows—Morphology, mobilization, and movement: U.S. Geological Survey Professional Paper 1264, 56 p.

Kuhn, Gerhard, 2005, Historical perspective of statewide streamflows during the 2002 and 1977 droughts in Colorado: U.S. Geological Survey Scientific Investigations Report 2005–5174, 84 p.

Lindsey, Rebecca, 2002, Satellites aid burn area rehabilitation: National Aeronautic and Space Administration online report, various pagination, available online at *http://earthobservatory.nasa.gov/Study/BAER/* (accessed February 15, 2007).

Melton, M.A., 1965, The geomorphic and paleoclimate significance of alluvial deposits in southern Arizona: Journal of Geology, v. 73, p. 1–38.

Miller, J.F., Frederick, R.H., and Tracey, R.J., 1973, Precipitation-frequency atlas of the western United States, v. 3—Colorado: Silver Spring, Md., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service.

Nakagaki, N., Price, C.V., Falcone, J.A., Hitt, K.J., and Ruddy, B.C., 2007, Enhanced National Land Cover 1992 (NLCDe 92), U.S. Geological Survey Sacramento, CA [online-only digital data set] *http://water.usgs.gov/lookup/getspatial?nlcde92*.

Pielke, R.A., Sr., Doeskin, N., Bliss, O., Green, T., Chaffin, C., Salas, J.D., Woodhouse, C.A., Lukas, J., and Wolter, K., 2005, Drought 2002 in Colorado—An unprecedented drought or a routine drought?: Pure and Applied Geophysics, v. 162, p. 1455–1479.

Pierson, T.P., 2005, Distinguishing between debris flows and floods from field evidence in small watersheds: U.S. Geological Survey Fact Sheet 2004–3142, 4 p.

Pierson, T.C., and Costa, J.E., 1987, A rheological classification of subaerial sediment-water flows: Geological Society of America, Reviews in Engineering Geology, v. VII, 12 p.

Ruddy, B.C., Stevens, M.R., Verdin, K.L., and Elliott, J.G., 2010, Probability and volume of potential postwildfire debris flows in the 2010 Fourmile burn area, Boulder County, Colorado: U.S. Geological Survey Open-File Report 2010–1244, 5 p.

Schwartz, G.E., and Alexander, R.B., 1995, State Soil Geographic (STATSGO) data base for the conterminous United States: U.S. Geological Survey Open-File Report 95–449.

SPSS, Inc., 2000, SYSTAT 10, Statistics I—Software documentation: Chicago, SPSS, Inc., 663 p.

Strahler, A.N., 1957, Quantitative analysis of watershed geomorphology: American Geophysical Union Transactions, v. 38, p. 913–920.

Stevens, M.R., Bossong, C.R., Litke, D.W., Viger, R.J., Rupert, M.G., and Char, S.J., 2008, Estimated probability of post-wildfire debris-flow occurrence and estimated volume of debris flows from a pre-wildfire analysis in the Three Lakes Watershed, Grand County, Colorado: U.S. Geological Survey Scientific Investigations Map 3009, 1 sheet.

U.S. Department of Agriculture, National Resources Conservation Service, National Soil Survey Center, 1991, State Soil Geographic (STATSGO) database: Data use information, Miscellaneous Publication Number 1492, 110 p. (Revised July 1994.)

U.S. Geological Survey, 2010, Streamstats—A water resources web application, accessed July 19, 2010, *http://water.usgs.gov/osw/streamstats/colorado.html*.

Verdin, K.L. and Greenlee, S., 2003, Continuous parameterization using EDNA, *in* Proceedings of the 2003 ESRI User's Conference, July 7–11, 2003, San Diego, California. URL: *http://gis.esri.com/library/userconf/proc03/p0617.pdf*, accessed May 2007.

Verdin, K. L. and Worstell, B., 2008, A fully distributed implementation of mean annual streamflow regional regression equations: Journal of the American Water Resources Association, v. 44, p. 1537–1547. doi: 10.1111/j.1752-1688.2008.00258.x

Publishing support provided by:
Denver Publishing Service Center, Denver, Colorado

For more information concerning this publication, contact:
Director, USGS Colorado Water Science Center
Box 25046, Mail Stop 415
Denver, CO 80225
(303) 236-4882

Or visit the Colorado Water Science Center Web site at:
http://co.water.usgs.gov/

This report is available at: *http://pubs.usgs.gov/sir/2012/5104/*

USGS

Elliott and others—**A Prefire Evaluation for the Pikes Peak Area, El Paso and Teller Counties, Colorado**—USGS/SIR 2012–5104