Prepared in cooperation with the Colorado Department of Transportation

Probability and Volume of Potential Postwildfire Debris Flows in the 2011 Indian Gulch Burn Area, near Golden, Colorado

By Barbara C. Ruddy

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Conversion Factors

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)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)

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)"

Probability and Volume of Potential Postwildfire Debris Flows in the 2011 Indian Gulch Burn Area, Near Golden, Colorado

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Abstract

This report presents an assessment of the debris-flow hazards from drainage basins burned in 2011 by the Indian Gulch wildfire near Golden, Colorado. Empirical models derived from statistical evaluation of data collected from recently burned drainage basins throughout the intermountain western United States were used to estimate the probability of debris-flow occurrence and debris-flow volumes for selected drainage basins. Input for the models include measures of burn severity, topographic characteristics, soil properties, and rainfall total and intensity for a (1) 2-year-recurrence, 1-hour-duration rainfall, (2) 10-year-recurrence, 1-hour-duration rainfall, and (3) 25-year-recurrence, 1-hour-duration rainfall.

Estimated debris-flow probabilities in the drainage basins of interest ranged from 2 percent in response to the 2-year-recurrence, 1-hour-duration rainfall to a high of 76 percent in response to the 25-year-recurrence, 1-hour-duration rainfall. Estimated debris-flow volumes ranged from a low of 840 cubic meters to a high of 26,000 cubic meters, indicating a considerable hazard should debris flows occur.

Introduction

Debris flows, fast-moving slurries of sediment and water, have been documented after many wildfires in the western United States (Cannon and others, 2010) and can threaten lives, property, infrastructure, aquatic habitats, and water supplies. Wildfires can denude hillslopes of vegetation and can change soil properties that affect watershed hydrology and sediment-transport processes. Even small rainstorms after a fire can increase overland runoff that erodes soil, rock, ash, and vegetative debris from hillslopes (Cannon and others, 2008). This increased runoff concentrates in drainage networks and entrains additional sediment that may lead to the generation of destructive debris flows. Debris-flow hazards are most significant from 1 to 3 years following wildfires (Susan Cannon, U.S. Geological Survey, written commun., 2010). Deposition from debris flows is evident in the area burned by the Indian Gulch fire, but it is unknown whether these debris flows occurred postwildfire. On July 26, 1923, a thunderstorm in the foothills above Golden, Colo., resulted in flooding and a deposition of gravel and boulders across Clear Creek at the mouth of Indian Gulch (formerly known as Magpie Gulch) (Grover, 1925).

This report presents an assessment of the debris-flow hazards from drainage basins burned in 2011 by the Indian Gulch wildfire in near Golden, Colorado (figs. 1 through 7, table 1). This assessment was done by the U.S. Geological Survey (USGS) in cooperation with the Colorado Department of Transportation. Estimates are provided of the predicted probability of debris-flow occurrence and volume of debris that could flow from 11 drainage-basin outlets in response to three design storms: (1) 2-year-recurrence, 1-hour-duration rainfall of 25 millimeters (mm) (a 50 percent chance of occurrence in any given year), (2) 10-year-recurrence, 1-hour-duration rainfall of 41 mm (a 10 percent chance of occurrence in any given year), and (3) 25-year-recurrence, 1-hour-duration rainfall of 46 mm (a 4 percent chance of occurrence in any given year). The methods used for this assessment are based on the work by Cannon and others (2007; 2010) and Ruddy and others (2010).

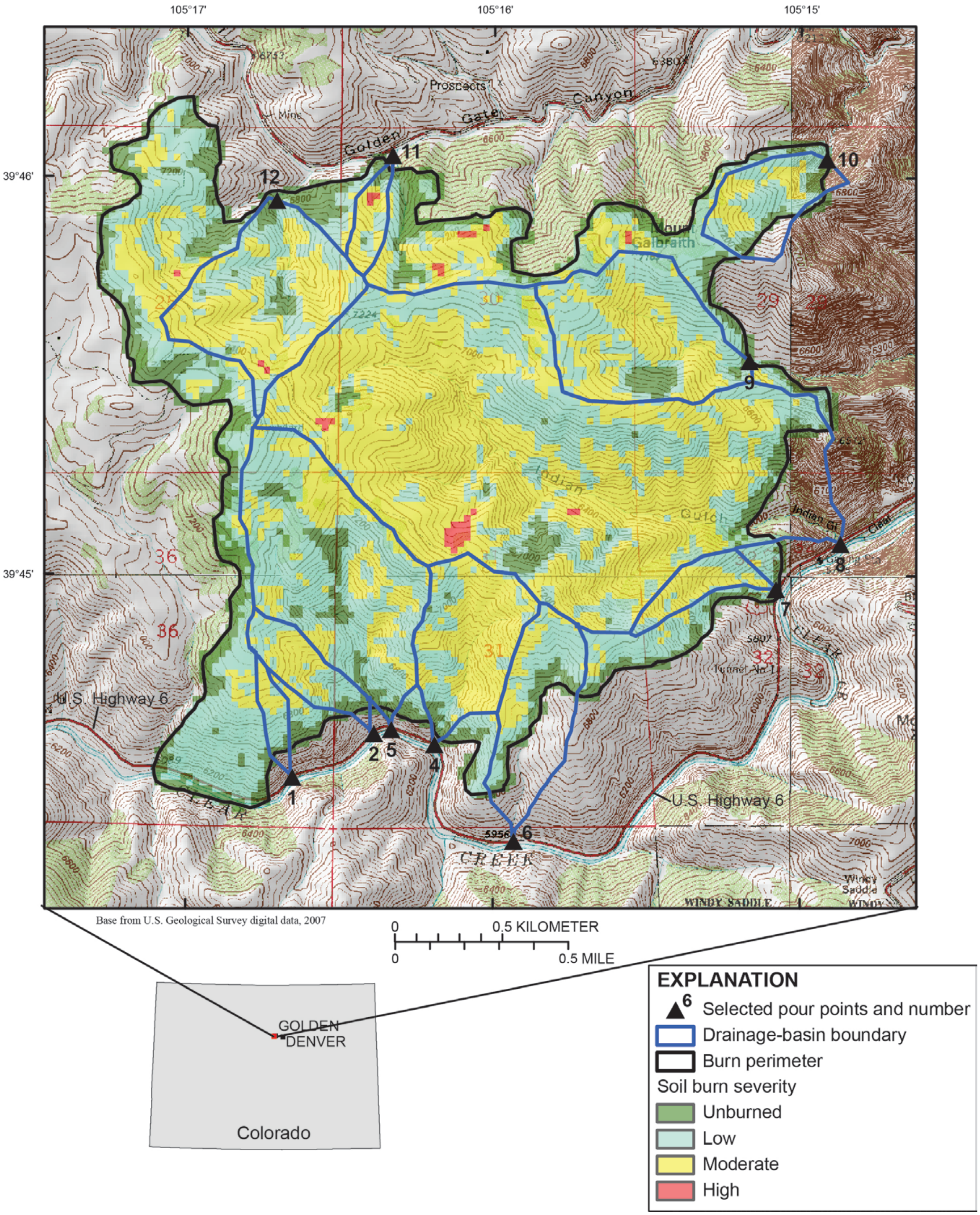

Figure 1. Location of drainage basins of interest and soil burn severity map of the 2011 Indian Gulch burn area, near Golden, Colorado.

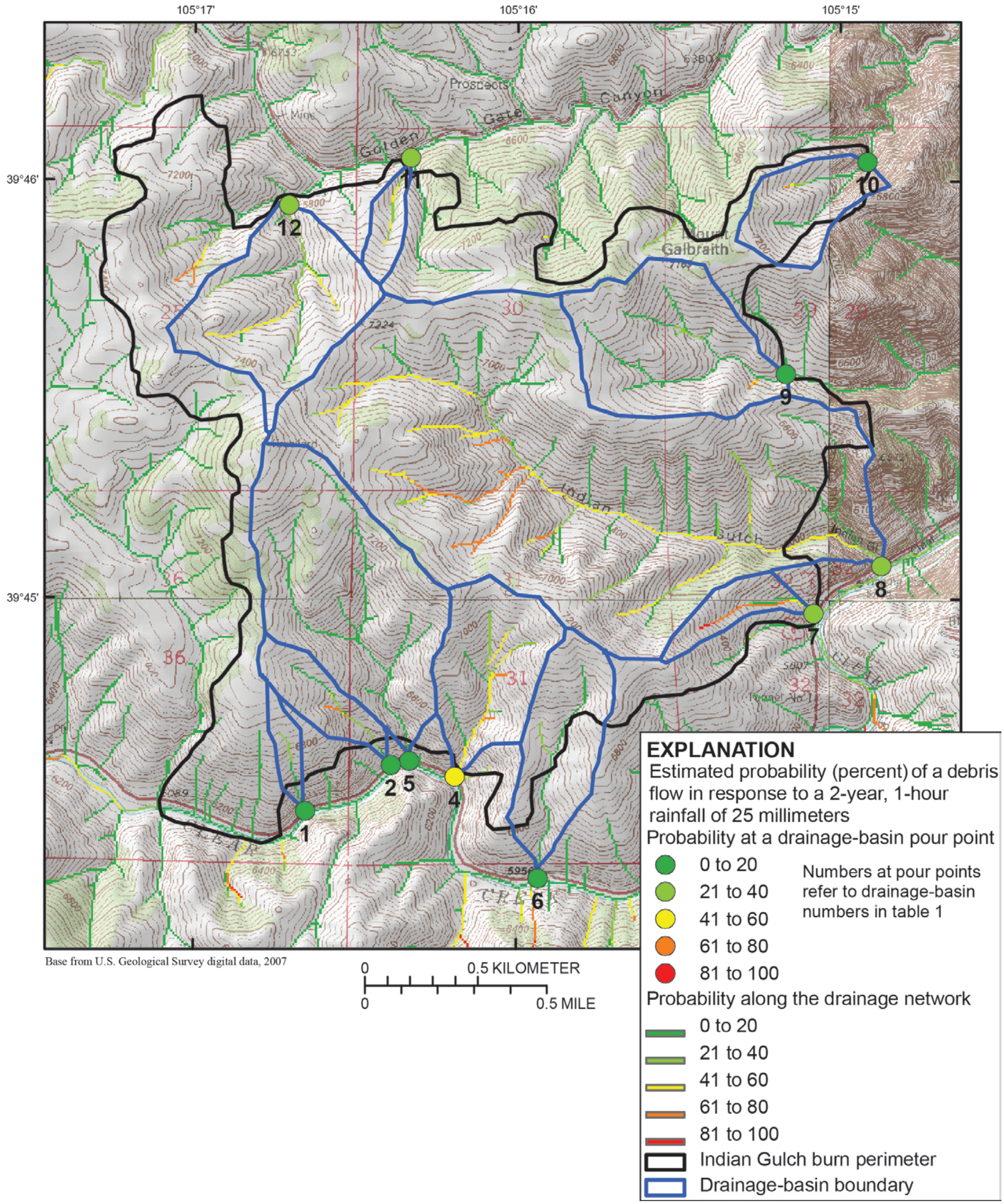

Figure 2. Estimated probability of potential postwildfire debris flows in the 2011 Indian Gulch burn area, near Golden, Colorado, in response to a 2-year-recurrence, 1-hour-duration rainfall of 25 millimeters.

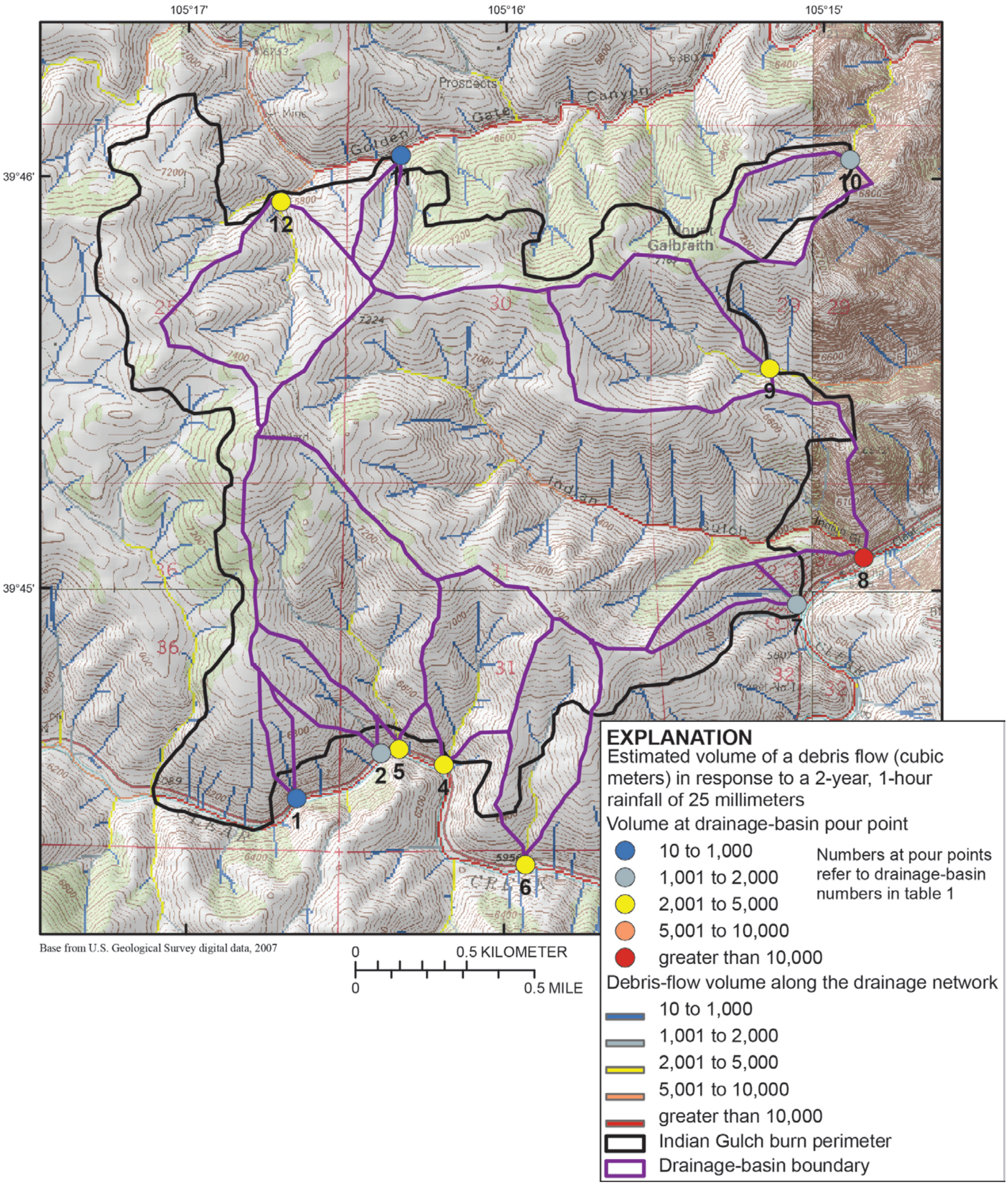

Figure 3. Estimated volumes of potential postwildfire debris flows in the 2011 Indian Gulch burn area, near Golden, Colorado, in response to a 2-year-recurrence, 1-hour-duration rainfall of 25 millimeters.

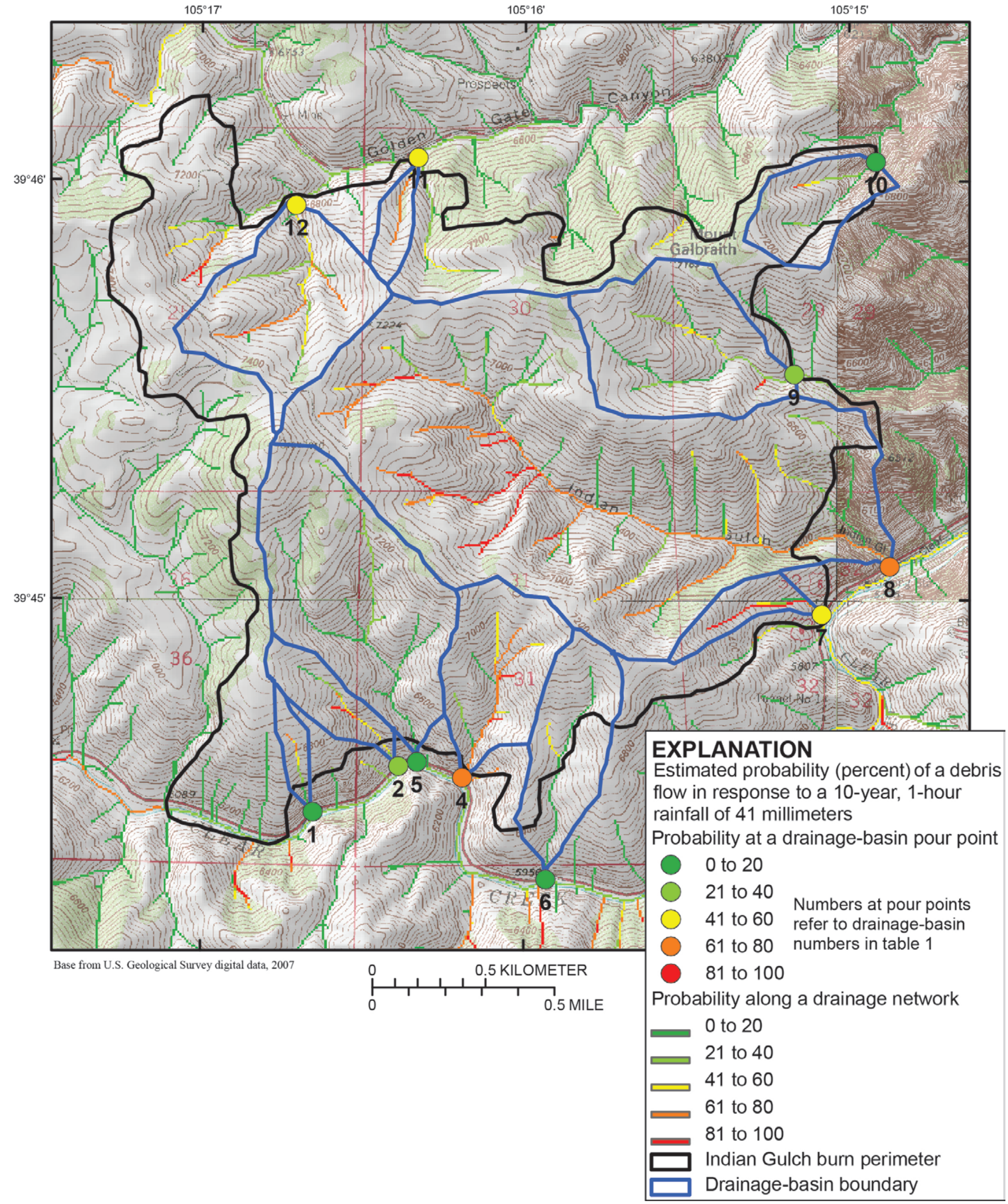

Figure 4. Estimated probability of potential postwildfire debris flows in the 2011 Indian Gulch burn area, near Golden, Colorado, in response to a 10-year-recurrence, 1-hour-duration rainfall of 41 millimeters.

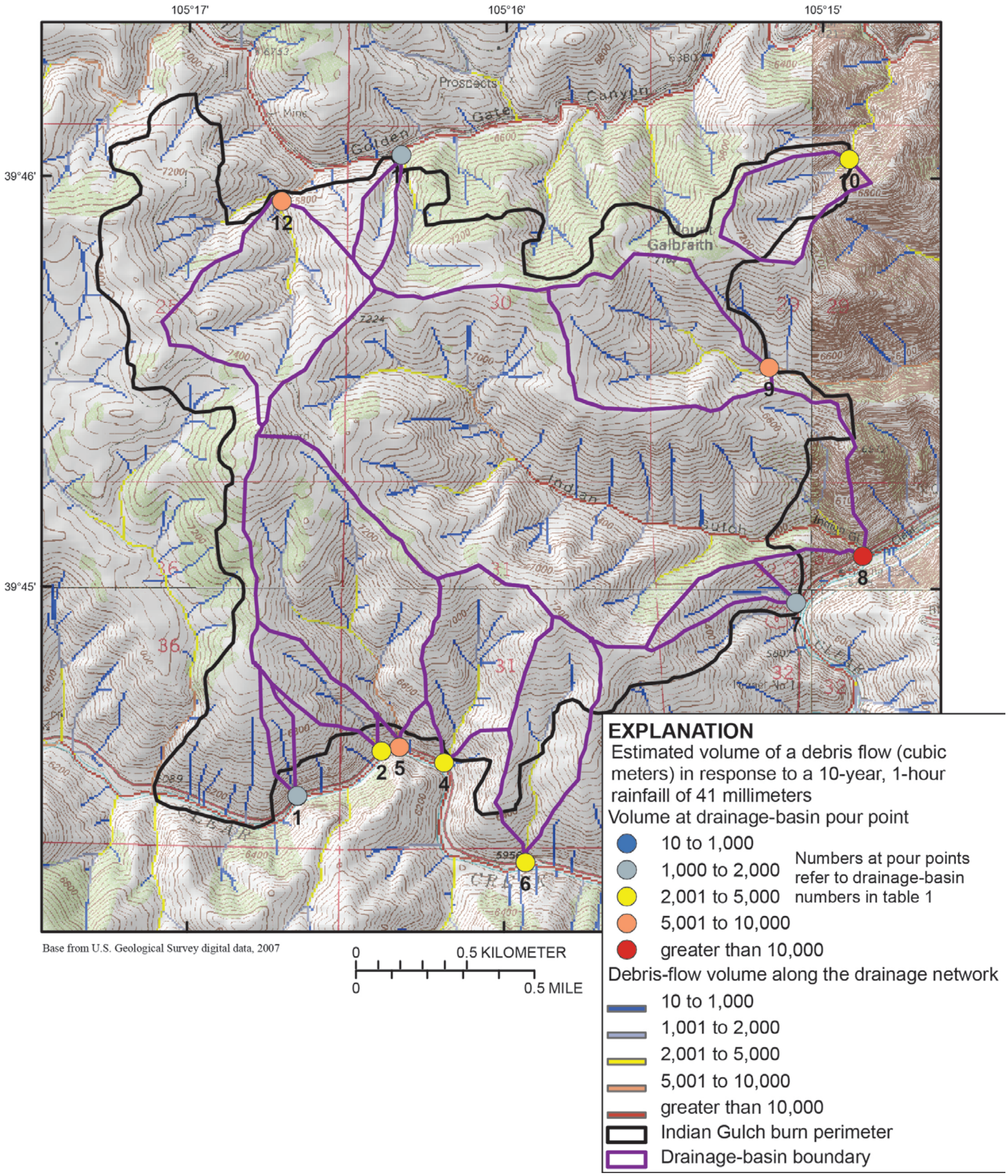

Figure 5. Estimated volumes of potential postwildfire debris flows in the 2011 Indian Gulch burn area, near Golden, Colorado, in response to a 10-year-recurrence, 1-hour-duration rainfall of 41 millimeters.

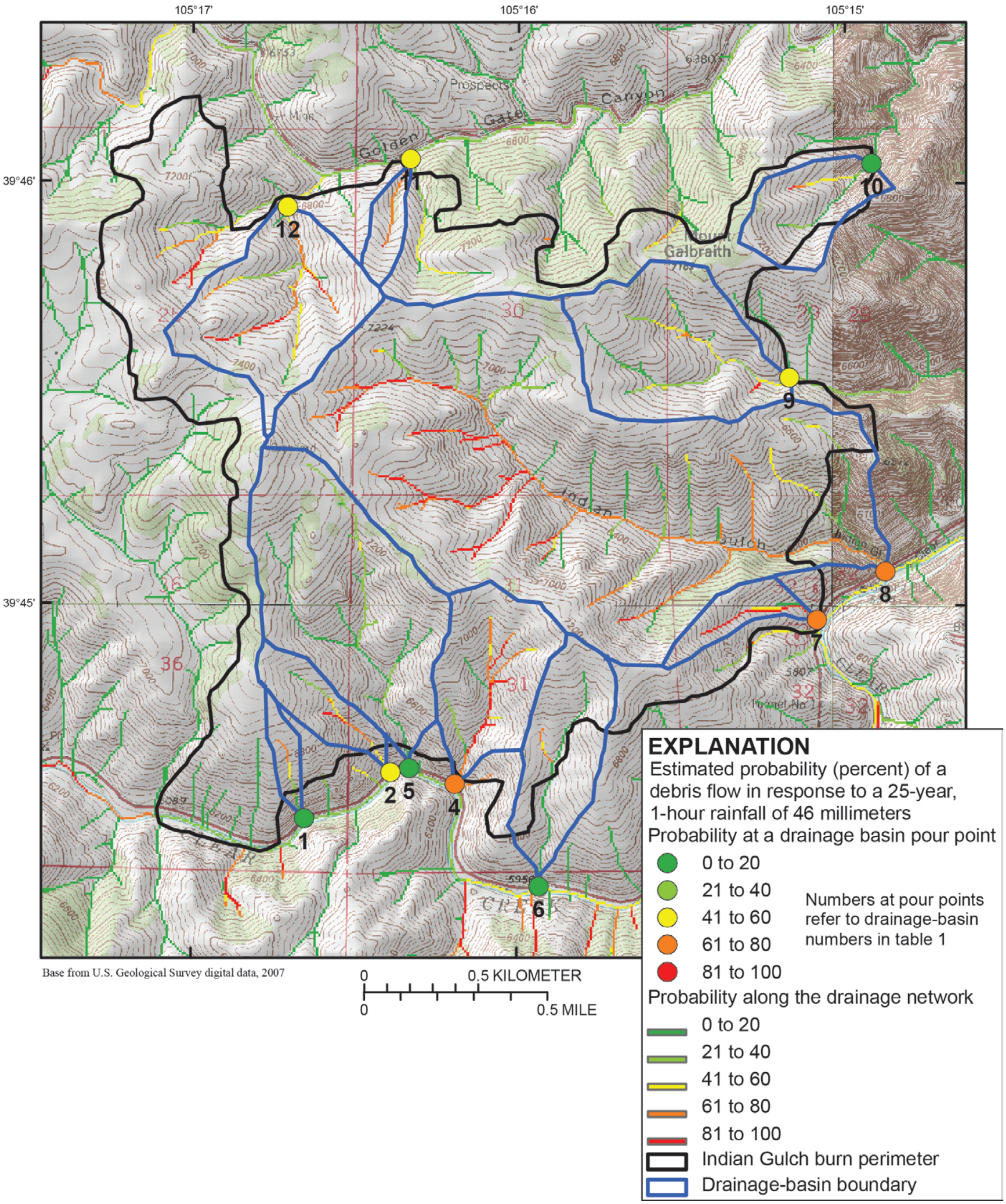

Figure 6. Estimated probability of potential postwildfire debris flows in the 2011 Indian Gulch burn area, near Golden, Colorado, in response to a 25-year-recurrence, 1-hour-duration rainfall of 46 millimeters.

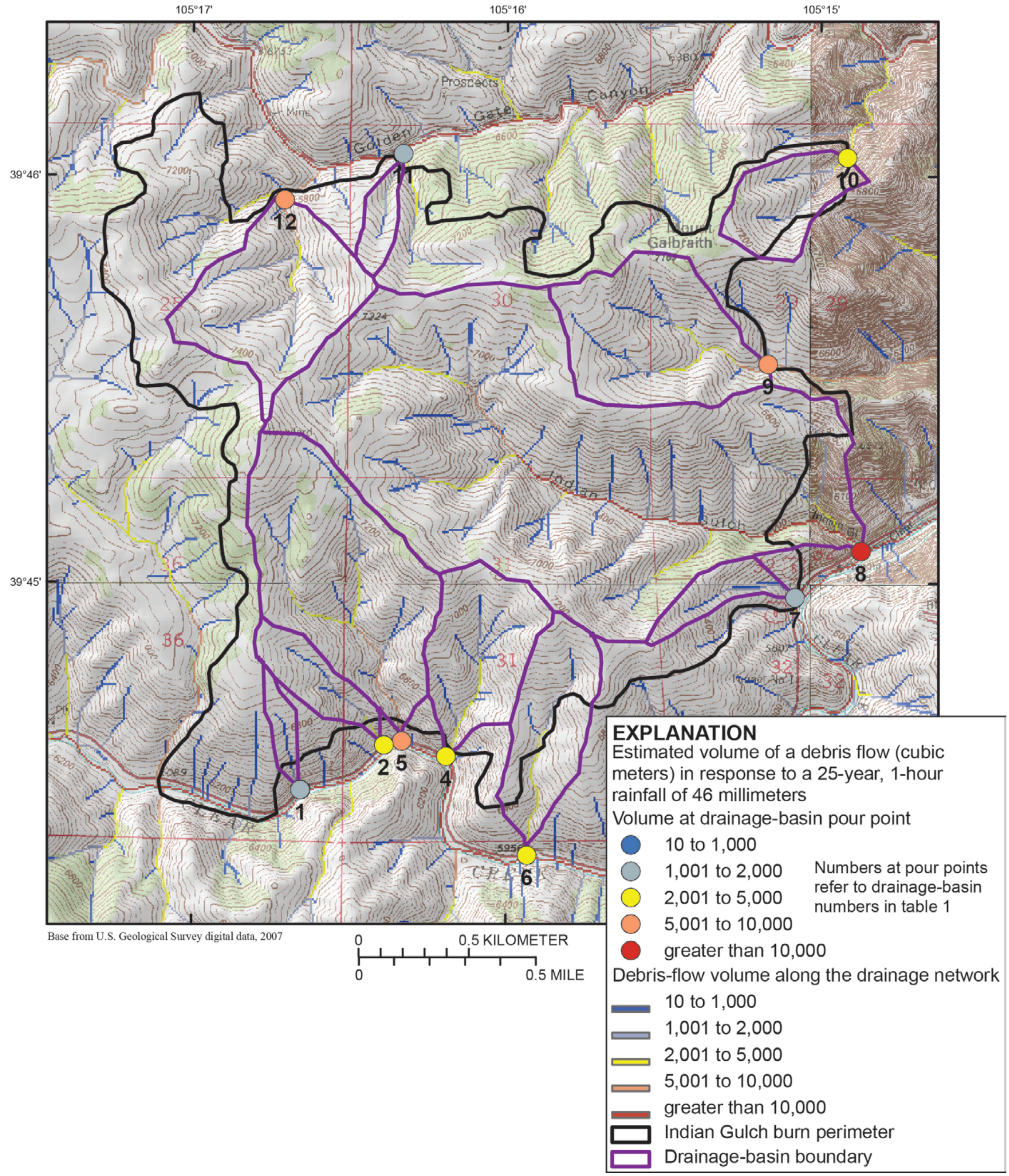

Figure 7. Estimated volumes of potential postwildfire debris flows in the 2011 Indian Gulch burn area, near Golden, Colorado, in response to a 25-year-recurrence, 1-hour-duration rainfall of 46 millimeters.

Table 1. Estimated debris-flow probabilities and volumes for the 2011 Indian Gulch burn area, near Golden, Colorado.

Drainage-basin number for pour point (fig.1–7)	Description	Latitude	Longitude	Drainage-basin area	Debris flow in response to a 2-year, 1-hour rainfall of 25 millimeters		Debris flow in response to a 10-year, 1-hour rainfall of 41 millimeters		Debris flow in response to a 25-year, 1-hour rainfall of 46 millimeters	
		degrees, minutes, seconds	degrees, minutes, seconds	square kilometers	Probability (percent)	Volume (cubic meters)	Probability (percent)	Volume (cubic meters)	Probability (percent)	Volume (cubic meters)
1	Small watershed south of Indian Gulch	39°44'29"	105°16'41"	0.05	2	840	5	1,100	7	1,200
2	Small watershed south of Indian Gulch	39°44'36"	105°16'23"	0.13	14	1,600	33	2,100	41	2,300
4	Small watershed south of Indian Gulch	39°44'34"	105°16'12"	0.32	41	3,300	68	4,400	76	4,800
5	Small watershed south of Indian Gulch	39°44'37"	105°16'19"	0.70	4	4,900	13	6,500	17	7,000
6	Small watershed south of Indian Gulch	39°44'20"	105°15'58"	0.29	2	2,600	6	3,400	8	3,700
7	Small watershed south of Indian Gulch	39°44'58"	105°15'04"	0.09	30	1,400	56	1,800	65	2,000
8	Indian Gulch	39°45'05"	105°14'53"	2.45	35	18,000	62	24,000	70	26,000
9	Small watershed northeast of Indian Gulch	39°45'32"	105°15'11"	0.49	14	3,900	33	5,100	41	5,500
10	Small watershed northeast of Indian Gulch	39°46'03"	105°14'56"	0.19	5	1,900	13	2,600	18	2,800
11	Small watershed north of Indian Gulch	39°46'03"	105°16'19"	0.06	25	1,000	51	1,300	59	1,400
12	Small watershed northwest of Indian Gulch	39°45'57"	105°16'41"	0.46	23	3,900	47	5,100	56	5,500

A set of statistical-empirical models was used to estimate the probability of debris-flow occurrence and volumes of debris flows for selected drainage basins. These models were developed by Cannon and others (2010) and were derived from statistical evaluation of data collected from recently burned drainage basins throughout the intermountain western United States. The regression model (eq. 1) of debris-flow probability is based on empirical data described by Cannon and others (2010, equation A). The model for debris-flow probability is as follows:

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

where P is the probability of debris-flow occurrence in fractional form and e is the mathematical constant (approximately 2.718…); and

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

where,

%SG30 is the percentage of the drainage-basin area with slope equal to or greater than 30 percent;

R is drainage-basin ruggedness, the change in drainage-basin elevation (meters) divided by the square root of the drainage basin area (square meters) (Melton, 1965);

%AB is the percentage of drainage-basin area burned at moderate and high severity (data for this assessment provided by Jess Clark, U.S. Department of Agriculture Forest Service, written commun., 2011);

I is average storm intensity (calculated by dividing total storm rainfall (Urban Drainage and Flood Control District, 2001) by the storm duration, in millimeters per hour);

%*C* is clay content of the soil (in percent) (U.S. Department of Agriculture, Soil Conservation Service, 1984); and

LL is the liquid limit of the soil at which the soil changes from plastic to liquid behavior (percentage of soil moisture by weight) (U.S. Department of Agriculture, Soil Conservation Service, 1984).

Cannon and others (2010) also developed an empirical model that can be used to estimate the volume of debris flow that would likely be produced from recently burned drainage basins:

$$\ln V = 7.2 + 0.6(\ln SG30) + 0.7(AB)^{0.5} + 0.2(T)^{0.5} + 0.3, \tag{2}$$

where,

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

SG30 is the area of the drainage basin with slopes equal to or greater than 30 percent (square kilometers);

AB is the drainage-basin area burned at moderate to high severity (square kilometers);

T is the total storm rainfall depth (millimeters) (Urban Drainage and Flood Control District, 2001); and

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

Each of the 11 evaluated drainage basins was identified by a single outlet (pour point) located at the drainage-basin mouth (table 1 and figure 1). Conditions within the drainage-basin area upstream from the identified pour point were used to estimate debris-flow probability and volume for a specific design storm (Cannon and others, 2010). Locations of drainage-basin pour points were selected based on the proximity to U.S. Highway 6 and Golden Gate Canyon Road and were intended to cover the majority of area burned by the fire (indicated by drainage-basin numbers in figures 1 through 7 and table 1).

In addition to the hazard assessments for the discrete drainage basins identified by pour points, a continuous parameterization technique was used to map potential debris-flow hazards along the drainage network of each basin. With this technique estimates of debris-flow probability and volume (Cannon and others, 2010) were obtained continuously along the drainage network (Verdin and Greenlee, 2003; Verdin and Worstell, 2008). This technique was developed as an alternative to traditional basin characterization approaches, which require “a priori” definition of drainage-basin outlets (pour points) and their corresponding basins.

Using the 1/3-arc-second National Elevation Dataset (Gesch and others, 2002) (10-meter (m) nominal resolution) for the study area and the flow structure inherent in the digital elevation model (DEM), the independent variables driving the probability and volume models were evaluated for every 10-m grid cell within the extent of the DEM. Rainfall totals and rainfall intensities were taken from Urban Drainage and Flood Control District Criteria Manual (2001). Values for all of the independent variables driving the predictive models were obtained using the continuous parameterization approach in a geographic information system (GIS). Once the surfaces of the independent variables were evaluated for every grid cell within the study area, the probability and volume models were solved using simple map algebra for the entire study area. Because the equations are valid only along drainage paths with contributing areas of at least 0.01 km^2 (Cannon and others, 2010), the probability and volume surfaces were then constrained to only those areas along the drainage network. Identification of the probability or volume of a debris flow along the drainage networks within the study area is possible by querying the derived surfaces. For this assessment, a raster-sampling technique (Verdin and Greenlee, 2003; Verdin and Worstell, 2008) was used to identify the values of debris-flow probability and volume at selected locations along the drainage network derived from a DEM.

The continuous parameterization technique allows for faster parameter characterization and the ability to characterize debris-flow hazard upstream from any location, not just at predefined basin outlets. This technique provides a synoptic view of the entire study area, which aids in the identification of smaller basins with high probabilities of debris flows within a larger basin. This allows for rapid evaluation of potential hot spots within the burned area—locations with potentially high probabilities of large debris flows. Although modeled probabilities and volumes at the pour point of a predefined basin might be relatively low, locations within the drainage basin might have substantially higher potential for debris flow. These can be easily identified with the continuous parameterization technique.

Estimated Debris-Flow Probabilities and Volumes

The estimated debris-flow probabilities and volumes in response to the three rainfall scenarios are presented in table 1. The 11 modeled drainage basins ranged in size from 0.05 square kilometers (km^2) to 2.45 km2. Estimated debris-flow probabilities in these drainage basins ranged from 2 percent in response to the 2-year-recurrence, 1-hour-duration rainfall to a high of 76 percent in response to the 25-year-recurrence, 1-hour-duration rainfall. The largest probabilities of debris flows are in drainage basin 4, most likely due to more than 90 percent of the basin having greater than 30 percent slope and about two-thirds of the basin being burned at moderate severity. The Indian Gulch burn area is very steep with the majority of the area having slopes greater than 30 percent. Only the areas adjacent to the stream channels or near the drainage-basin divides had slopes less than 30 percent. The steep slopes had a large influence on the debris-flow probabilities. About 44 percent of the burned area was burned at a moderate to high severity.

The largest estimates of debris-flow volumes were for Indian Gulch itself, which is 3.5 times larger than any of the modeled drainage basins (table 1). The other drainage basins flow into Clear Creek along U.S. Highway 6 or into Golden Gate Canyon. Evidence of debris flows, not necessarily postwildfire, was present at many of the pour points and along the drainages upstream from the pour points. The estimated probabilities of debris flows for the designated basins varied but the potential for debris-flow impacts to roads and other infrastructure is very high. It is important to recognize that even small debris flows at the drainage-basin outlets could cause considerable damage to infrastructure.

Estimated debris-flow volumes ranged from 840 cubic meters (m^3) for drainage basin 1 in response to a 2-year, 1-hour rainfall to 26,000 m^3 at Indian Gulch (drainage basin 8) in response to a 25-year, 1-hour rainfall. Generally, drainage basins with the largest areas had the largest estimated debris-flow volumes.

Hazardous areas of potential debris flows within several drainage basins, specifically, Indian Gulch, are shown on figures 4 and 6. The red channel reaches upstream from the pour point indicate debris-flow probabilities as high as 81–100 percent. Although the probabilities of a debris flow occurring in response to the 10-year-recurrence, 1-hour duration rainfall and the 25-year-recurrence, 1-hour duration rainfall at the pour point of drainage basin 8 are 62 and 70 percent, respectively (table 1), the continuous parameterization technique indicates locations along specific channel reaches where the probabilities are much higher.

Use and Limitations of the Assessment

This assessment presents estimates of debris-flow probability and volume for selected drainage basins and along their channels (or drainage networks) in the area burned by the 2011 Indian Gulch wildfire. Estimates were made in response to three design storms: (1) a 2-year-recurrence, 1-hour-duration rainfall of 25 millimeters (a 50 percent chance of occurrence in any given year), (2) a 10-year-recurrence, 1-hour-duration rainfall of 41 millimeters (a 10 percent chance of occurrence in any given year), and (3) a 25-year-recurrence, 1-hour-duration rainfall of 46 millimeters (a 4 percent chance of occurrence in any given year). Some areas within the selected drainage basins may have higher debris-flow probabilities than those shown at the drainage-basin outlet, or pour point, shown in figures 2, 4, and 6, and debris flows may not be produced from all basins during the modeled rainfalls. The estimates are likely valid for up to 3 years after the wildfire occurred (Susan Cannon, U.S. Geological Survey, written commun., 2010). The maps may be used to prioritize areas where emergency hazard warnings or erosion mitigation may be needed prior to rainstorms within these basins, at their outlets, or in areas downstream from these basins. This assessment evaluates only postwildfire debris flows (Cannon and others, 2007). Substantial hazards from flash floods without debris flow may remain for many years after a wildfire, but are beyond the scope of this assessment. The assessment is 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 assessment.

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