EMERGENCY ASSESSMENT OF DEBRIS-FLOW HAZARDS FROM BASINS BURNED BY THE PADUA FIRE OF 2003, SOUTHERN CALIFORNIA

By Susan H. Cannon, Joseph E. Gartner, Michael G. Rupert, *and* John A. Michael

U.S. Geological Survey
Box 25046, DFC, MS 966
Denver, CO 80225
(303) 273-8604, cannon@usgs.gov

U.S. Geological Survey Open-File Report 2004-1072

Prepared in Cooperation with Federal Emergency Management Agency (FEMA) and Environmental Systems Research Institute, Inc.

These maps are not to be used for flood insurance rating purposes under the National Flood Insurance Program. For insurance rating purposes, please refer to the currently effective Flood Insurance Rate Maps (FIRM) published by the Federal Emergency Management Agency (FEMA). To obtain a copy of the FIRM, contact the FEMA Map Service Center at 1-800-385-9616, or at http://store/mcs.fema.gov.

2004
U.S. Department of the Interior
U.S. Geological Survey

ABSTRACT

Results of a present preliminary assessment of the probability of debris-flow activity and estimates of peak discharges that can potentially be generated by debris flows issuing from basins burned by the Padua Fire of October 2003 in southern California in response to 25-year, 10-year, and 2-year recurrence, 1-hour duration rain storms are presented. The resulting probability maps are based on the application of a logistic multiple-regression model (Cannon and others, 2004) that describes the percent chance of debris-flow production from an individual basin as a function of burned extent, soil properties, basin gradients, and storm rainfall. The resulting peak discharge maps are based on application of a multiple-regression model (Cannon and others, 2004) that can be used to estimate debris-flow peak discharge at a basin outlet as a function of basin gradient, burn extent, and storm rainfall. Probabilities of debris-flow occurrence for the Padua Fire range between 0 and 99% and estimates of debris-flow peak discharges range between 1211 and 6,096 ft^3/s (34 to 173 m^3/s). These maps are intended to identify those basins that are most prone to the largest debris-flow events and provide information for the preliminary design of mitigation measures and for the planning of evacuation timing and routes.

INTRODUCTION

The objective of this report is to present a preliminary emergency assessment of the potential for debris-flow generation from basins burned by the Padua Fire in southern California for selected rainfall events (Fig. 1). The assessment identifies those basins most likely to produce debris flows, and estimates the magnitude, in terms of peak discharge, of the possible debris-flow response at the outlets of the basins. Identification of potential debris-flow hazards from burned drainage basins is necessary to make effective and appropriate mitigation decisions, and can aid in decisions about evacuation timing and routes.

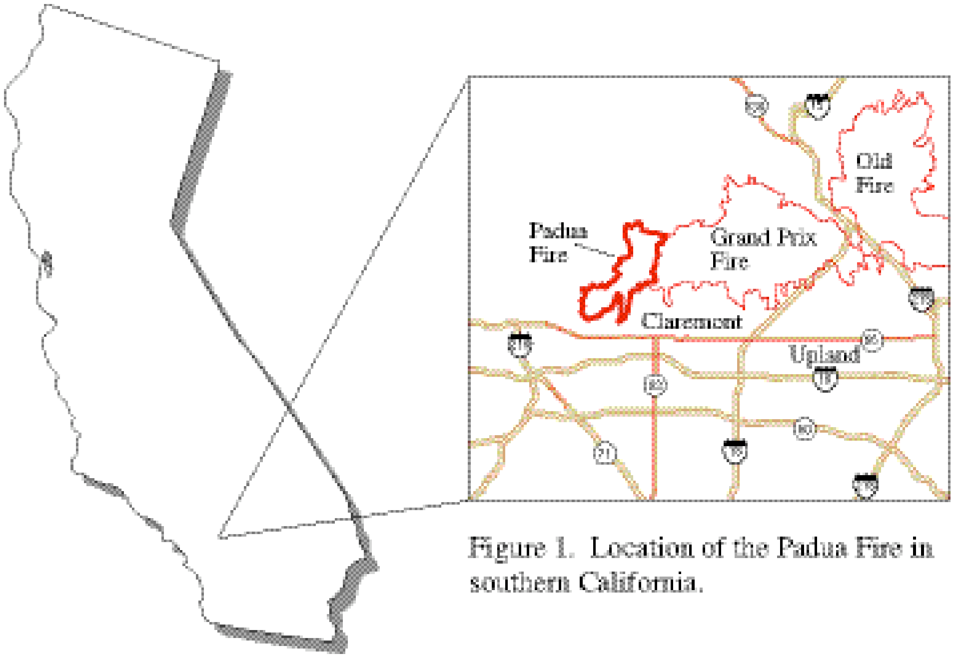


Figure 1. Location of the Padua Fire in southern California.

Fire-Related Debris-Flow Hazards

Wildfire can have profound effects on a watershed. Consumption of the rainfall-intercepting canopy and of the soil-mantling litter and duff, intensive drying of the soil, combustion of soil-binding organic matter, and the enhancement or formation of water-repellent soils can result in decreased rainfall infiltration capacity of the soil and subsequent significantly increased overland flow and runoff in channels. Removal of obstructions to flow (e.g., live and downed timber, plant stems, etc.) by wildfire can enhance the erosive power of overland flow, resulting in accelerated removal of material from hillslopes. Increased runoff can also erode significant volumes of material from channels. The net result of rainfall on burned basins is often the transport and deposition of large volumes of sediment, both within and down-channel from the burned area.

Debris flows are among the most hazardous consequences of rainfall on burned hillslopes. Debris flows pose a hazard distinct from other sediment-laden flows because of their unique destructive power. They can occur with little warning, can exert great impulsive loads on objects in their paths, and even small debris flows can strip vegetation, block drainage ways, damage structures, and endanger human life. For example, record-breaking winter storms in 1969 triggered debris flows from steep basins burned the previous summer above the city of Glendora, California (Scott, 1971). More than one million cubic meters of rock, mud, and debris came racing downhill, and at least 175 homes were either completely destroyed or damaged by these events. Damage from debris flows and associated flooding totaled $2,500,000 in 1969 dollars in the Glendora area.

Studies of debris-flow processes throughout the western U.S. and in southern California, Cannon (2000, 2001) demonstrated that the great majority of fire-related debris flows initiate through a process of progressive bulking of storm runoff with sediment eroded from both hillslopes and channels. Although some infiltration-triggered landsliding can occasionally occur in burned basins, generally in response to prolonged rainfall events, these failures generally contribute a small proportion to the total volume of material transported from the basin (Cannon and others, 2001; Scott, 1971). This finding points to the relative importance of runoff-dominated, rather than infiltration-dominated, processes of debris-flow initiation in recently burned basins, and indicates that methodologies developed to map landslide potential for unburned basins are generally not appropriate for recently burned areas. As an alternative, this finding suggests that the relations traditionally defined between peak discharges of floods and basin characteristics may be useful in predicting the magnitude of potential debris-flow response from burned basins.

APPROACH AND METHODS

In a study of the erosional response of recently burned basins throughout the western U.S, including southern California, Cannon (2000, 2001) found that not all basins produce debris flows; most burned watersheds respond to even heavy rainfall events by sediment-laden flooding. However, debris flows are potentially the most destructive end of the post-fire runoff response spectrum. Analysis of data collected from 398 burned basins from 15 fires throughout the inter-mountain west revealed that the probability of a given basin to produce debris flows can be readily identified by a combination of geologic, soil, basin morphology, burn severity, and rainfall conditions in the form:

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

where

$$x = -29.693 + 10.697(\%Burn) - 9.875(Sorting) + 0.208(I) + 5.729(\%Organics) - 0.957(Permeability) + 9.351(Drainage) + 2.864(\%GE30\%) - 8.335(\%Burn*\%Organics) + 4.669(Sorting*Drainage) - 0.174(\%GE30\%*I),$$

and P is the probability of debris-flow activity, *%Burn* is the percent of the burned area in each basin burned at high and moderate severities, *Sorting* is the sorting of the grain-size distribution of the burned soil, *%Organics* is the percent of soil organic matter, *Permeability* is the soil permeability, *Drainage* is the soil drainage, *%GE30%* is the percent of the basin with slopes greater than or equal to 30%, and I is the average storm rainfall intensity (in mm/hr) (Cannon and others, 2004).

Because debris-flow kinematics are significantly distinct from those of streamflow (Iverson, 1997), Cannon and others (2004) took the approach of developing predictive relations that are specific to debris flow. Using data collected from debris-flow producing basins throughout the western U.S., including southern California (Bigio and Cannon, 2001), Cannon and others (2004) developed an empirical relation that can be used to obtain estimates of debris-flow peak magnitudes as a function of the area of the basin burned, storm rainfall conditions, and basin gradients of the form:

$$Qp = -171 + 0.552(AvgSlope) + 28.4(logAb) + 3.6(I),$$

where *Qp* is the predicated peak discharge (in m^3/s), *AvgSlope* is the average basin gradient (in percent), *logAb* is the log of the area burned (in m^2), and I is the average storm intensity (in mm/hr).

In this assessment, we use these recently developed models to predict which basins might produce fire-related debris flows, and how big these events might be. The results obtained in this assessment can be used to identify those watersheds that are most prone to the largest debris-flow events. Note that the models used for the generation of these maps are new and have not been thoroughly tested and reviewed. However, in light of the current emergency situation, this method presents a reasonable preliminary approach to evaluate hazards.

Mapping debris-flow probability and peak discharge

As the first step in this assessment, the perimeters of 50 basins burned by the Padua Fire were delineated. The outlets of basins of interest were located using a shaded relief image from a 30-m DEM overlain by a detailed stream network generated using Arc Hydro©. Basin outlets were positioned at breaks in slope between mountain fronts and valleys or, if present, at road crossings or above development. Using the ranges of data in the databases used to derive the statistical models, we focused on basins between 0.04 mi^2 (0.1 km^2) and 10 mi^2 (25 km^2) in area. Basins larger than 10 mi^2 (25 km^2) were sub-divided into tributary basins to the main channel. Although debris flows may be generated in the lower-order drainages of such basins, they are generally not of sufficient size or energy to travel the entire length of the basin.

For each basin, we then compiled values for each of the input variables for the two models. Basin area and measures of gradients were obtained from 30-m DEMs, and soil organic matter, permeability and drainage were obtained from the STATSGO database (Schwartz and Alexander, 1995). The basin areas burned at different severities were characterized from the burn severity map developed by the BAER (Burned Area Emergency Rehabilitation) Team. In this mapping, the northern half of the burned area is mapped as unburned to low severity. If more than one value for any one parameter is available in a basin, we calculated a single spatially-weighted average value for that parameter. The time available to conduct this emergency assessment did not allow for the collection and analysis of samples of burned surficial soils. Rather, we used

1:250,000-scale geologic mapping compiled by Bortugno and Spittler (1998) as a surrogate for soils (assuming grain-size varies with parent material), and substituted median values of known measures of sorting of the grain-size distribution of burned soils for each primary rock type present in each basin.

The probability of debris flow and estimates of debris-flow peak discharge for the 25-year, 10-year and 2-year recurrence, 1-hour duration storms are calculated using the logistic multivariate regression model for debris-flow probability and the multivariate statistical model for debris-flow peak discharge (Cannon and others, 2004). The storm rainfall values input into the models were obtained from the San Dimas Tanbark Flat Station, located at 34.2^{O}N latitude, 117.7^{O}W longitude, and at 2,785 feet elevation (Bonnin and others, 2003). Although there is some variability in storm-rainfall characteristics across the burned area, the present versions of the models allow for only a single storm input. We thus identified a representative average storm rainfall value from a gage located within the burned area. The rainfall values used in the analyses are shown in Table 1. The calculated debris-flow probability and peak discharges were proportioned into classes, and the class value for both probability and discharge were attributed to each basin. The basin class values are presented for each basin in map form as Map 1A and B, Map 2A and B, and Map 3A and B.

Table 1. Storm rainfall values used in assessments.

25-year, 1-hour storm (inches/mm)	10-year, 1-hour storm inches/mm	2-year, 1-hour storm inches/mm
1.46/ 37.1	1.20/30.5	0.79/20.1

Use and Limitations of the Maps

These maps provide estimates of the probability of debris-flow occurrence and of the ranges of debris-flow peak discharges that can potentially issue from the outlets of basins burned by the Padua Fire in response to the 2-year, 10-year, and 25-year 1-hour storms. This information can be used to prioritize mitigation efforts, to aid in the design of mitigation structures, and to guide decisions for evacuation, shelter, and escape routes in the event that storms of similar magnitude to those evaluated here are forecast for the area.

The potential for debris-flow activity decreases with time and the concurrent revegetation and stabilization of hillslopes. A compilation of information on post-fire runoff events reported in the literature from throughout the western U.S. indicates that most debris-flow activity occurs within about 2 years following a fire (Bigio and Cannon, 2001). We thus conservatively expect that the maps presented here may be applicable for approximately 3 years after the fires for the storm conditions considered here. Further, the assessments presented here are specific to post-fire debris flows; significant hazards from flash flooding can remain for many years after a fire.

The methods used to derive the probability and peak discharge estimates are new and have not been thoroughly tested and reviewed. However, in light of the current emergency situation, these methods present a reasonable approach to preliminarily evaluate debris-flow hazards. A significant advantage to this approach is that it is based on analysis of data specifically from post wildfire debris-flow events, rather than on estimates of flood runoff with assumed sediment-bulking factors.

In this approach, we considered peak discharge as the measure of the magnitude of the potential debris-flow hazards; debris-flow hazards can also be characterized by measures of potential volumes emanating from basin outlets. Measures of volume are of particular use in evaluating the effectiveness of debris retention basins. We conducted analyses similar to those described above using measures of debris-flow volume as the dependent variable. However, it was not possible to develop a robust, statistically significant model with the available dataset. Hopefully, data collected in the following winters will allow for the definition of such a relationship.

And last, the parameters included in the models are considered to be possible first-order effects that can be rapidly evaluated immediately after a fire. Other conditions than those used in the models may certainly affect debris-flow occurrence and peak discharge from recently burned basins in southern California. For example, an abundance of dry-ravel material in a specific channel may certainly affect peak discharges, and the frequently occurring fire–flood sequence that characterizes southern California basins may similarly limit material availability (e.g. Spittler, 1995). Data necessary to evaluate these effects are not currently available to account them in this approach.

RESULTS

25-year, 1-hour storm of 1.46 inches (37.1 mm)

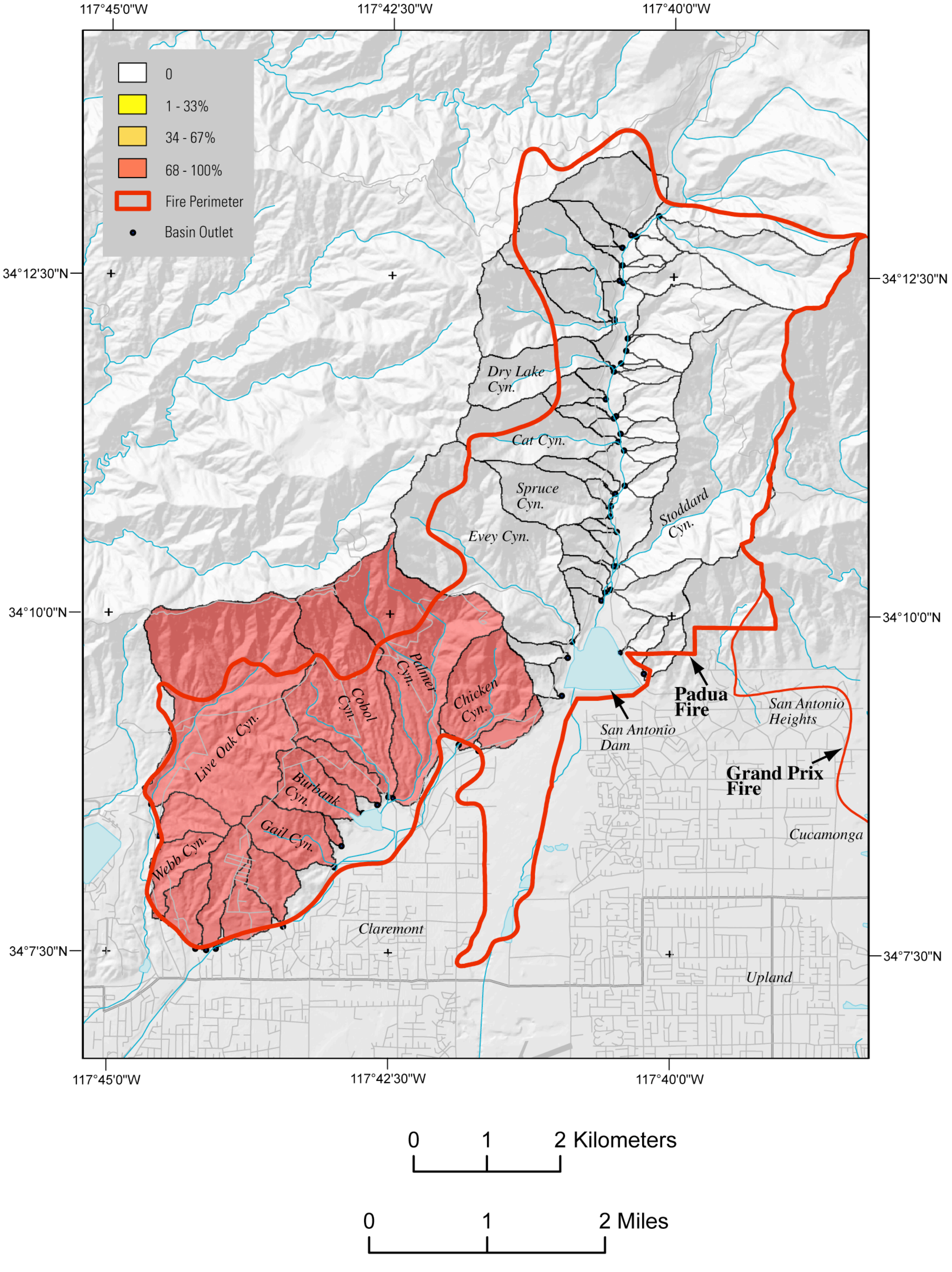
Of the 50 basins evaluated in this assessment, 15 were identified as having probabilities greater than 67% that debris flows will occur in response to the 25-year, 1-hour rainstorm (Map 1A). These include Live Oak Canyon and an adjacent unnamed basin to the south; Webb Canyon; four unnamed tributaries along the mountain front east of Webb Canyon; Gail Canyon and adjacent unnamed basin; Burbank Canyon and an adjacent unnamed basin; Cobol, Palmer, and Chicken Canyons; and an unnamed basin adjacent to Chicken Canyon. In response to a 25-year, 1-hour storm, debris-flow peak discharges between 3,000 and 6,096 ft^3/s (85 and 173 m^3/s) are estimated for these basins (Map 1B). The highest peak discharge is estimated for Live Oak Canyon.

Because of the low to unburned classification of burn severity for the northern-most extent of the fire, 35 basins show a negligible probability of debris-flow production in response to this storm (Map 1A).

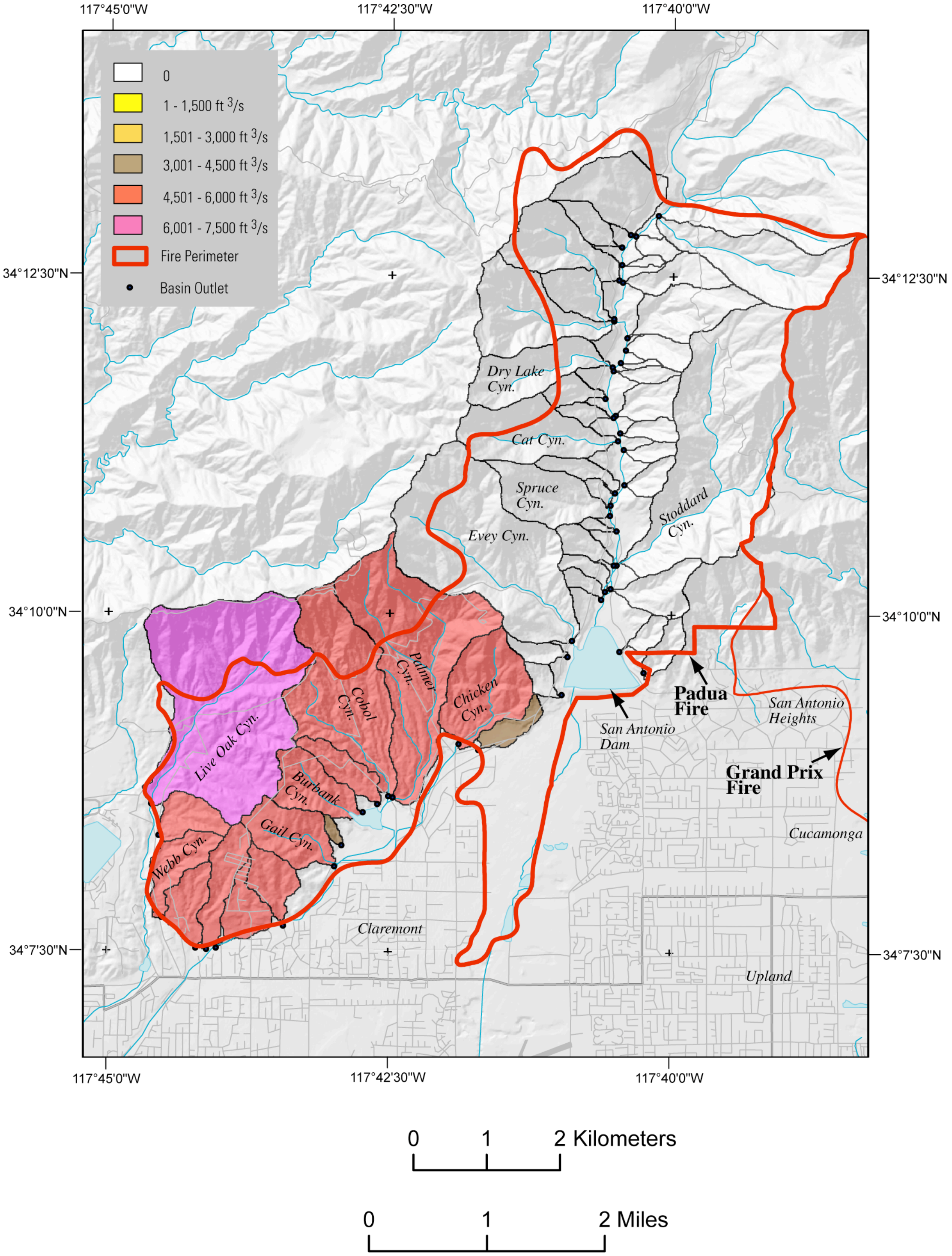
10-year, 1-hour storm of 1.20 inches (30.5 mm)

In response to a 10-year, 1-hour storm, a probability of debris-flow occurrence greater than 67 percent is identified for the following basins within the Padua Fire (Map 2A): Live Oak Canyon and an adjacent unnamed basin to the south; Webb Canyon; four unnamed tributaries along the mountain front east of Webb Canyon; Gail Canyon and adjacent unnamed basin; Burbank Canyon and an adjacent unnamed basin; Cobol, Palmer, and Chicken Canyons; and an unnamed basin adjacent to Chicken Canyon. Debris flows with peak discharges between 3,001 and 6,000 ft^3/s (85 and 170 m^3/s) are estimated for these basins, with Live Oak, Burbank, Cobol, and Palmer Canyons showing the highest values (Map 2B).

Because of the low to unburned classification of burn severity for the northern-most extent of the fire, 35 basins show a negligible probability of debris-flow production in response to this storm (Map 2A).



Map 1A. Probability of debris-flow occurrence from basins burned by the Padua Fire in response to the 25-year, 1-hour storm of 1.46 inches (37.1 mm).



Map 1B. Estimates of debris-flow peak discharge from basins burned by the Padua Fire in response to the 25-year, 1-hour storm of 1.46 inches (37.1 mm).

2-year, 1-hour storm of 0.79 inches (20.1 mm)

The same 15 basins identified above also show a greater than 67 pecent probability of debris-flow occurrence in response to the 2-year, 1-hour storm (Map 3A). Debris-flow peak discharges between 1,501 and 4,500 ft^3/s (42 and 127 m^3/s) are estimated for these basins, with Live Oak, Gail, Burbank, Cobol and Palmer Canyons showing the highest values (Map 3B).

Because of the low to unburned classification of burn severity for the northern-most extent of the fire, 35 basins show a negligible probability of debris-flow production in response to this storm (Map 3A).

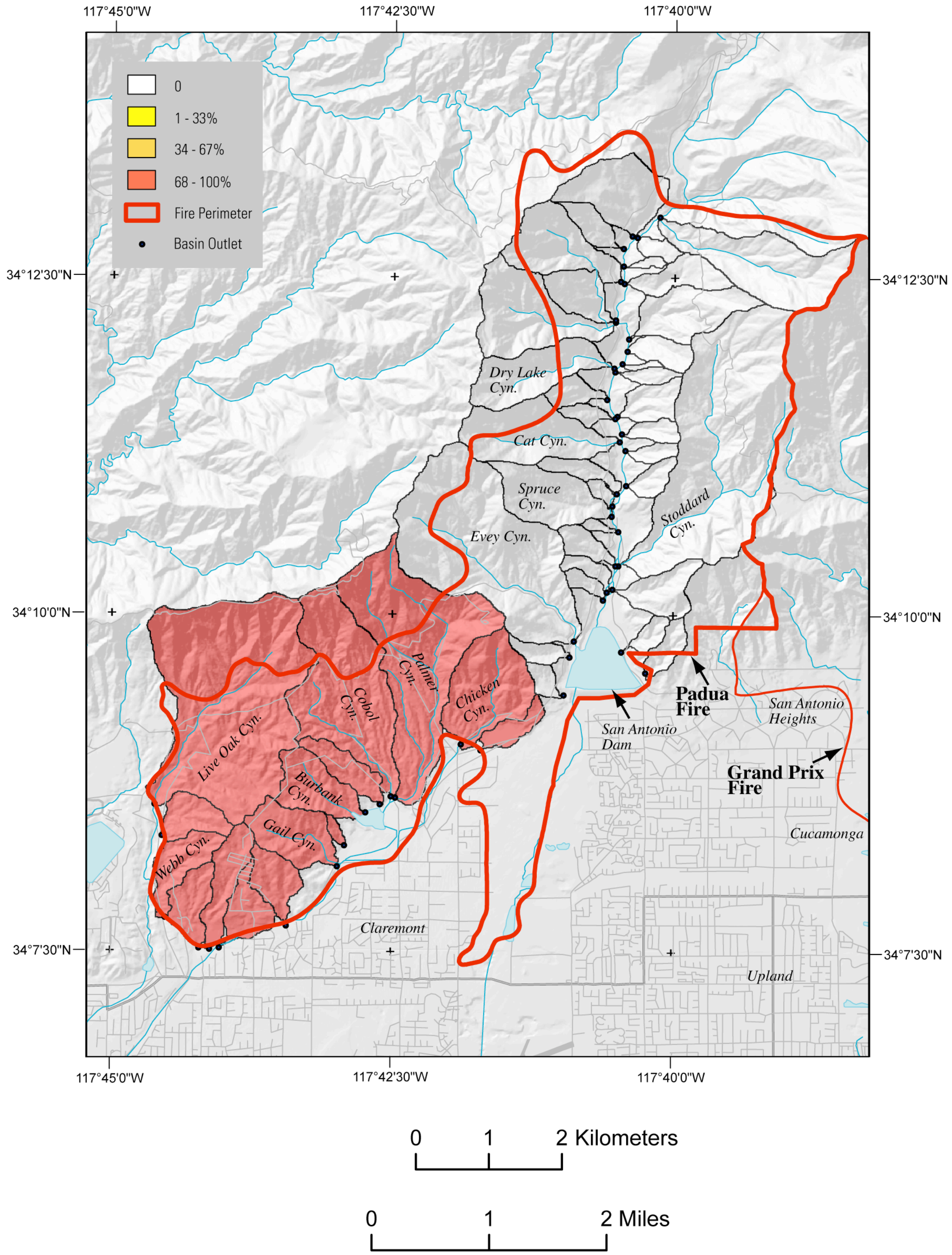
CONCLUSIONS

The basins identified as having probabilities of debris-flow occurrence greater than 67 percent are extremely dangerous for anyone living, working, or recreating within or downstream from them during rainfall events similar to, or greater than, the storms used in this evaluation. Of the storms evaluated here, the hazard level is greatest for the 25-year storm, although the probability of this storm occurring is only about 4 percent in any given year. The probability of debris-flow occurrence is not any lower for the 10- and 2-year storms, and the estimated peak discharges of greater than 1,501 ft^3/s (42 m^3/s) associated with these storms can be quite destructive.

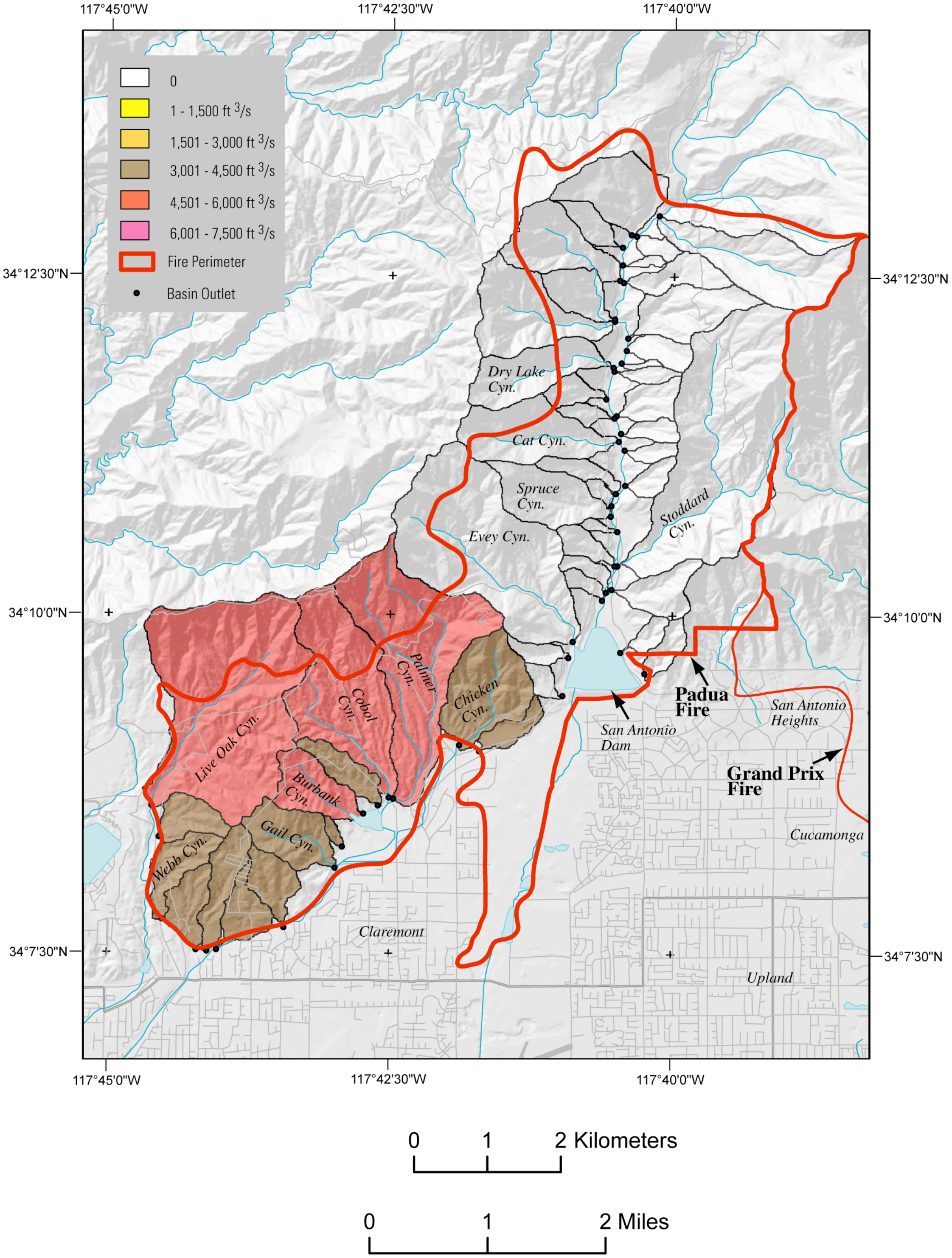
In addition to the potential dangers within these basins, areas downstream from the basin outlets are also at risk. In some of these areas homes were destroyed by the fire, and workers and residents may be busy cleaning and rebuilding sites. These people are at high risk for impact by debris flow during rainfall events such as those used in this assessment. In addition, in the event of the passage of a debris flow, there is a great possibility of culverts plugging or being overwhelmed, and of roads washing out. Such events can strand motorists for long periods of time. In some cases, drainages cross roads on blind curves where motorists could abruptly encounter debris-flow material on the road.

RECOMMENDATIONS

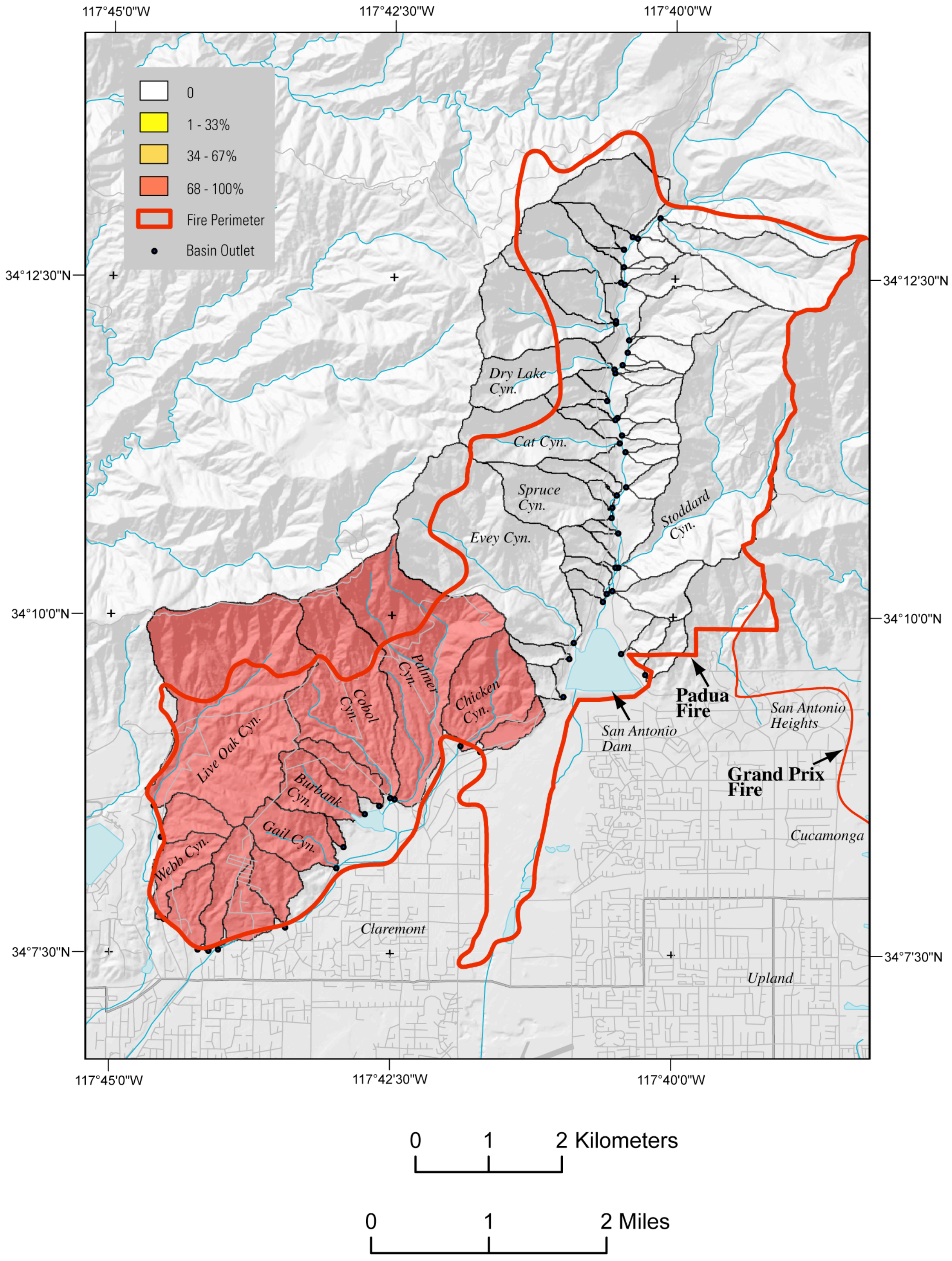
It is imperative to insure that people occupying businesses, homes, and recreational facilities downstream of the basins identified as the most hazardous are informed of the potential dangers from debris flows and flooding. Warning must be given even for those basins with mitigation structures at their mouths in the event that the structures are not adequate to contain potential debris-flow material. We further recommend site-specific debris-flow hazard assessments be performed above structures and facilities that could be impacted by flows from basins smaller than those evaluated here. In addition, this assessment is specific to post-fire debris-flow activity; further assessment of potential hazards posed by flash floods is necessary. And last, we highly recommend the establishment of an early-warning system for both flash floods and debris flows. Such a system should consist of an extensive reporting rain gage and stream gage network coupled with National Weather Service weather forecasts. Any early-warning system should be coordinated with existing county and flood-district facilities.



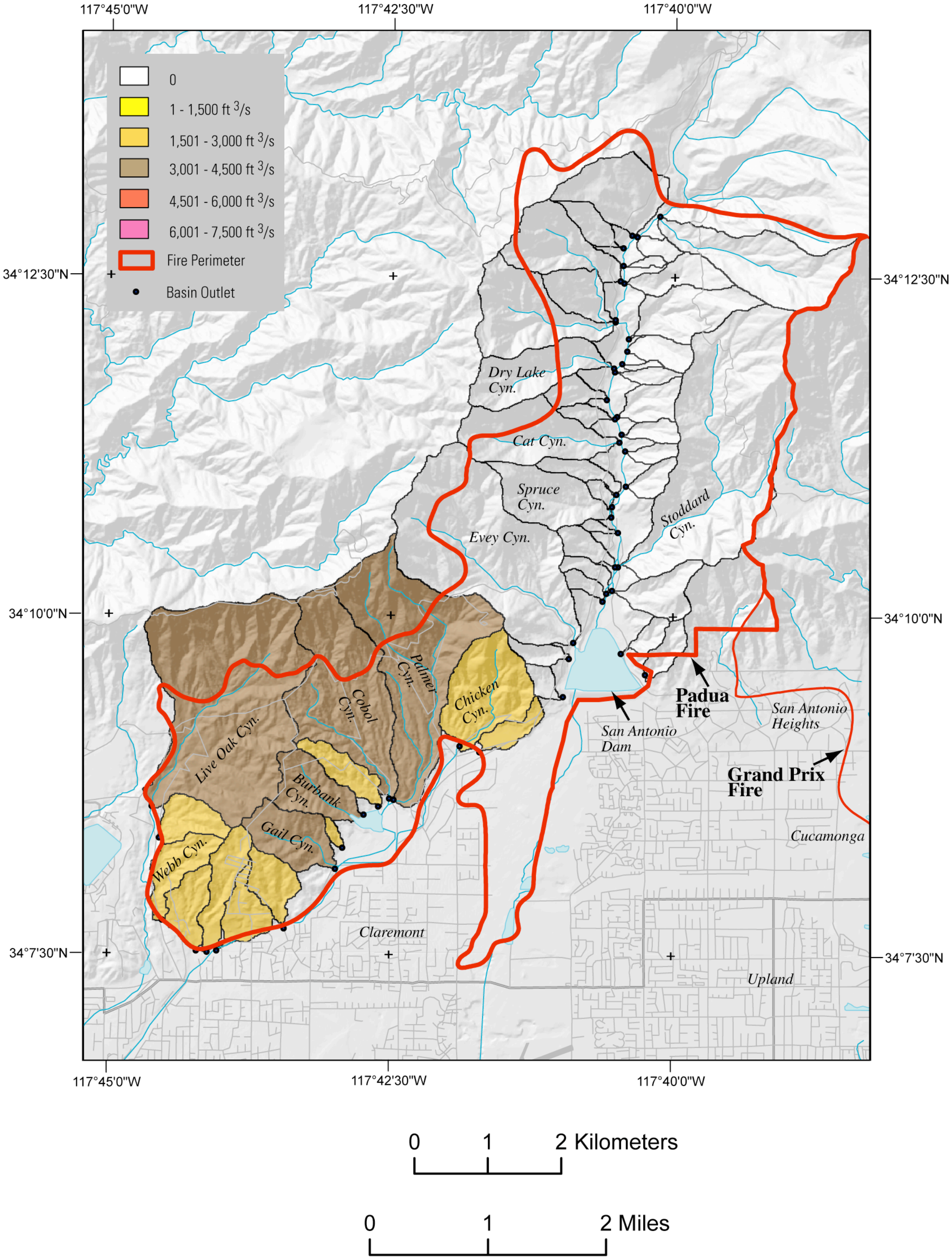
Map 2A. Probability of debris-flow occurrence from basins burned by the Padua Fire in response to the 10-year, 1-hour storm of 1.20 inches (30.5 mm).



Map 2B. Estimates of debris-flow peak discharge from basins burned by the Padua Fire in response to the 10-year, 1-hour storm of 1.20 inches (30.5 mm).



Map 3A. Probability of debris-flow occurrence from basins burned by the Padua Fire in response to the 2-year, 1-hour storm of 0.79 inches (20.1 mm).



Map 3B. Estimates of debris-flow peak discharge from basins burned by the Padua Fire in response to the 2-year, 1-hour storm of 0.79 inches (20.1 mm).

REFERENCES

Bigio, E.R., and Cannon, S.H., 2001, Compilation of post-wildfire data from the western United States: U.S. Geological Survey Open-File Report 02-443. http://landslides.usgs.gov/html_files/landslides/frdebris/Database.html

Bonnin, G.M., Todd, D., Lin, B., Parzybok, T., Yekta, M., and Riley, D., 2003, Precipitation Frequency Atlas of the United States: NOAA Atlas 14, Volume 1, Version 2, NOAA, National Weather Service, Silver Spring, Maryland. http://hdsc.nws.noaa.gov

Bortugno, E.J. and Spittler, T.E., 1998, Geologic map of the San Bernardino Quadrangle, 1:250,000: California Division of Mines and Geology, Regional Geologic Map Series, San Bernardino Quadrangle, Map No 3A.

Cannon, S.H., 2000, Debris-flow response of southern California watersheds recently burned by wildfire, *in* Wieczorek, G.F., and Naeser, N.D, eds., Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, Proceedings of the Second International Conference on Debris-Flow Hazards Mitigation, Taipei, Taiwan, 16-18 August 2000: A.A. Balkema, Rotterdam, p. 45-52.

Cannon, S.H., 2001, Debris-flow generation from recently burned watersheds: Environmental & Engineering Geoscience, v. 7, p. 321-341.

Cannon, S.H., Kirkham, R.M. and Parise, M., 2001, Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado: Geomorphology, v. 39, p. 171-188.

Cannon, S.H., Gartner, J.E., Rupert, M.G., and Michael, J.A., 2004, Emergency assessment of debris-flow hazards from basins burned by the Cedar and Paradise Fires of 2003, southern California: U.S. Geological Survey Open-File Report 04-1011. http://pubs.usgs.gov/of/2003/ofr-04-1011/

Iverson, R.M., 1997, The physics of debris flow, Reviews in Geophysics, v. 35, p. 245-296.

Scott, K.M., 1971, Origin and sedimentology of 1969 debris flows near Glendora, California: U.S. Geological Survey Professional Paper 750-C, p. C242-C247.

Schwartz, G.E, and Alexander, R.B., 1995, State Soil Geographic (STATSGO) database for the conterminous United States: U.S. Geological Survey Open-File Report 95-449, http://water.usgs.gov/lookup/getspatial?ussoils.

Spittler, T.E., 1995, Fire and debris flow potential of winter storms, *in* Keely, J.E., and Scott, T., eds., Brushfires in California Wildlands—Ecology and Resource Management: International Association of Wildland Fire, Fairfield, WA.