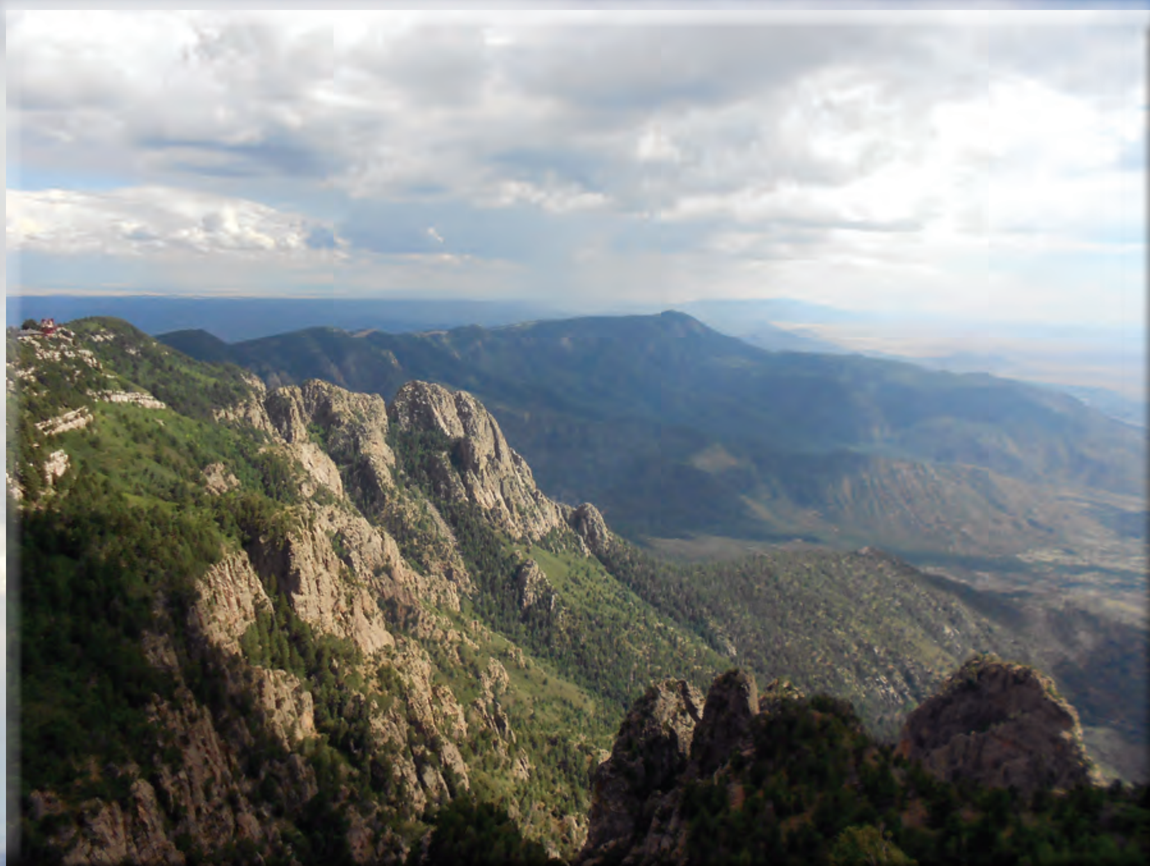
Prepared in cooperation with the Bernalillo County Natural Resources Services

Potential Postwildfire Debris-Flow Hazards—A Prewildfire Evaluation for the Sandia and Manzano Mountains and Surrounding Areas, Central New Mexico



Scientific Investigations Report 2014–5161

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

Cover photograph. View of Sandia Mountains looking south from Sandia Crest. Photograph by Peter Voshefski.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0002642	million gallons (Mgal)
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)

Potential Postwildfire Debris-Flow Hazards—A Prewildfire Evaluation for the Sandia and Manzano Mountains and Surrounding Areas, Central New Mexico

By Anne C. Tillery[1], Jessica R. Haas[2], Lara W. Miller[3], Joe H. Scott[4], and Matthew P. Thompson[2]

Abstract

Wildfire can drastically increase the probability of debris flows, a potentially hazardous and destructive form of mass wasting, in landscapes that have otherwise been stable throughout recent history. Although there is no way to know the exact location, extent, and severity of wildfire, or the subsequent rainfall intensity and duration before it happens, probabilities of fire and debris-flow occurrence for different locations can be estimated with geospatial analysis and modeling efforts. The purpose of this report is to provide information on which watersheds might constitute the most serious, potential, debris-flow hazards in the event of a large-scale wildfire and subsequent rainfall in the Sandia and Manzano Mountains. Potential probabilities and estimated volumes of postwildfire debris flows in the unburned Sandia and Manzano Mountains and surrounding areas were estimated using empirical debris-flow models developed by the U.S. Geological Survey in combination with fire behavior and burn probability models developed by the U.S. Department of Agriculture Forest Service.

The locations of the greatest debris-flow hazards correlate with the areas of steepest slopes and simulated crown-fire behavior. The four subbasins with the highest computed debris-flow probabilities (greater than 98 percent) were all in the Manzano Mountains, two flowing east and two flowing west. Volumes in sixteen subbasins were greater than 50,000 square meters and most of these were in the central Manzanos and the western facing slopes of the Sandias.

Five subbasins on the west-facing slopes of the Sandia Mountains, four of which have downstream reaches that lead into the outskirts of the City of Albuquerque, are among subbasins in the 98th percentile of integrated relative debris-flow hazard rankings. The bulk of the remaining subbasins in the 98th percentile of integrated relative debris-flow hazard rankings are located along the highest and steepest slopes of the Manzano Mountains. One of the subbasins is several miles upstream from the community of Tajique and another is several miles upstream from the community of Manzano, both on the eastern slopes of the Manzano Mountains.

This prewildfire assessment approach is valuable to resource managers because the analysis of the debris-flow threat is made before a wildfire occurs, which facilitates prewildfire management, planning, and mitigation. In northern New Mexico, widespread watershed restoration efforts are being carried out to safeguard vital watersheds against the threat of catastrophic wildfire. This study was initiated to help select ideal locations for the restoration efforts that could have the best return on investment.

Introduction

Wildfire is a natural process in forest ecosystems, and occurs with varying frequencies and severities depending on landscape characteristics, climatic conditions, and the historical fire regime. Although attention often is focused on the potential damages from wildfire in the wildland-urban interface, wildfire also presents a threat to critical infrastructure including flood water conveyances and water conveyances critical to municipal water supplies. Further, burned landscapes are at risk of damage from postwildfire erosion, such as that caused by debris flows and flash floods, which can be the most catastrophic of the postwildfire threats to an area.

Debris flows are high-density slurries of water, rock fragments, soil, woody debris, and mud that can have enormous destructive power particularly when they are fast moving. Debris flows are a common geomorphic process in response to intense rainfall in some unburned watersheds that have steep slopes, ample erodible materials, and minimal infiltration (Elliott and others, 2012). Wildfire can drastically increase the probability of debris flows in landscapes that have otherwise been stable throughout recent history. A primary watershed effect of wildfire is rapid and dramatic decrease in infiltration

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because of widespread removal of vegetation and development of hydrophobic soils (Cannon and Gartner, 2005). Although there is no way to know the location, extent, and severity of wildfire, or the subsequent rainfall intensity and duration before it happens, probabilities of fire and debris-flow occurrence for different locations can be estimated with geospatial analysis and modeling efforts. These models can be useful planning tools for better understanding and mitigating the risks of potential postwildfire debris flows.

Debris flows have been documented after many fires in the western United States (Cannon and others, 2001a and b; Cannon and others, 2010; DeGraff and others, 2011; Kean and others, 2011). In addition, debris flows following wildfire can be generated in response to low-recurrence interval/high intensity rainfall. Recently burned landscapes may be at risk of such postwildfire hydrologic hazards for several to many years following the fire (Cannon and Gartner, 2005). The U.S. Geological Survey (USGS) has developed a model (Cannon and others, 2010) to estimate postwildfire debris-flow probability and volume. This information can be used to determine watersheds of concern or areas most at risk for loss of life and property.

A second, key spatial variable for risk assessment and prioritization efforts is wildfire likelihood (Scott and others, 2013), typically measured as annual burn probability. Numerous studies have linked wildfire occurrence and extent to increasing spring and summer temperatures (Westerling and others, 2006; Swetnam and Betancourt, 1990; Balling and others, 1992; Pierce and others, 2004). The warmest and driest 2-year period since record-keeping began in New Mexico in the late 1800s was during 2011–12 (Charles H. Jones, National Weather Service, written commun., 2014) and the wildfire seasons during those years included two of the largest fires in the State's history. The seasonal drought outlook (National Weather Service, 2014) indicates that drought is likely to persist or intensify throughout the southwestern states at least through June 2014. The threat of severe wildfires is likely to persist in New Mexico with continuing hot and dry weather patterns, hence the need for prewildfire assessment and mitigation efforts.

Localized variation in the probability of burning is affected by factors such as topography and fuel, or vegetation characteristics, as well as fire weather and ignition patterns. Spatial information on wildfire probability makes it possible to distinguish across basins and subbasins with potentially different likelihoods of experiencing wildfire, which can be an important distinction for efficient prioritization of mitigation efforts. Information on wildfire probability is therefore critical for prewildfire risk assessment. Combining the debris-flow models with models for fire behavior and burn probability developed by the U.S. Department of Agriculture Forest Service (USFS) (Finney, 2006; Finney and others, 2011) allows for characterization of potential threats of postwildfire debris flows in watersheds that have not experienced wildfires in recent years.

A prewildfire evaluation to determine potential for postwildfire debris flows in the Sandia Mountains in central New Mexico was started in 2013 by the USGS in cooperation with Bernalillo County Natural Resources Services as a part of the Rio Grande Water Fund. The Manzano Mountains were later added to the study area for this evaluation because of their proximity to the Sandia Mountains and the ease in expanding the study area to include them. The USFS and The Nature Conservancy provided support for this effort, principally through fire simulation modeling.

The Rio Grande Water Fund is a groundbreaking project that engages private and public partners in protecting vital watersheds in northern New Mexico with a primary goal to generate sustainable funding for a 10–30-year program of large-scale forest and watershed restoration treatments, including thinning overgrown forests, restoring streams, and rehabilitating areas that experience flooding and other damaging effects after wildfires (The Nature Conservancy, 2014). This study was initiated to provide information on which subbasins might constitute the most serious, potential debris-flow hazards in the event of a large-scale wildfire and subsequent rainfall in the Sandia and Manzano Mountains and surrounding areas.

Purpose and Scope

The purpose of this report is to present estimates for the likelihood and potential magnitude of postwildfire debris flows for the unburned areas of the Sandia and Manzano Mountains and surrounding areas. The study area includes all mountainous regions in the Sandia and Manzano Mountains and extends to the break in slope at the base of the mountains on all sides. The overarching modeling effort involved the coupling of multiple models for estimating spatial variation in burn probability, burn severity, and debris-flow hazard and is described in detail in appendix 1. The USFS large-fire simulation system referred to as FSim (Finney and others, 2011) was used to estimate burn probability and the USFS fire-behavior model FlamMap (Finney, 2006) was used to estimate crown-fire activity and to infer burn severity likely to occur in the study area. The USGS postwildfire debris-flow models (Cannon and others, 2010) were used to make estimates of the probabilities of debris flows and of volumes of material that could be transported through subbasins based on topography, soil characteristics, and simulated burn intensities.

This prewildfire assessment approach is valuable to resource managers because the analysis of the debris-flow threat is made before a wildfire occurs, which facilitates prewildfire management, planning, and mitigation. Widespread watershed restoration efforts are being undertaken to safeguard vital watersheds against the threat of catastrophic wildfire in northern New Mexico (The Nature Conservancy, 2014). This study was initiated to help select ideal locations for the restoration efforts that are the most appropriate and provide the best benefits.

Description of Study Area

The study area includes the Sandia and Manzano Mountains and surrounding areas east and south of the City of Albuquerque, in central New Mexico (fig. 1). The Sandia Mountains (hereafter referred to as the "Sandias") includes 914 square kilometers (km^2) (353 square miles [mi^2]) of forest and wilderness land within the Cibola National Forest and Sandia Indian Reservation and encompasses parts of Bernalillo and Sandoval Counties. The Manzano Mountains (hereafter referred to as the "Manzanos") includes 57.6 km^2 (22.2 mi^2) of designated wilderness land including parts of the Cibola National Forest, military facilities, and Isleta Indian Reservation, and encompass parts of Bernalillo, Torrance, and Valencia Counties. Because of their proximity to the City of Albuquerque, areas in the Sandias and Manzanos have been developed over many decades into wildland-urban interface areas where homes, businesses, roads, and water-supply systems are adjacent to fuel-rich forests with additional development in the area progressing rapidly. The population on the eastern slopes of the Sandias, referred to locally as the "East Mountains," increased by 43 percent from 1990 through 2000 though it has since slowed down (SWCA Environmental Consultants and others, 2006). Many of the watersheds on the western slopes of the Sandias drain directly through the City of Albuquerque. Watersheds and communities of the Sandias, Manzanos, and surrounding areas are vulnerable to several potential threats including wildfire and postwildfire hydrologic hazards.

Elevation in the study area ranges from about 1,621 meters (m) (5,318 feet [ft]) at the base of the west slope of the Sandias north of the City of Albuquerque to 3,252.9 m (10,672 ft) at the summit of Sandia Peak. The Sandias consist of a granite core that is overlain on the eastern slopes by eastern dipping, Pennsylvanian-aged sedimentary beds (Hawley and Haase, 1992). Mean annual precipitation ranges from about 22.8 centimeters (cm) (9 inches [in.]) near the Rio Grande at the base of the mountains to about 68 cm (27 in.) at Sandia Peak (Bonnin and others, 2004).

Forested areas generally are denser and cover more area on the eastern slopes of the mountainous areas than the western slopes, due in part to the steeper (and in some cases very sheer) western slopes that preclude development of dense woodlands. Typical of mountainous terrain, the vegetation types tend to follow elevation gradients. Vegetation in the lowest elevation areas (below approximately 2,000 m (6,562 ft) on the eastern side of the study area consists of primarily short grass prairie, whereas the western low land is dominated by Chihuahua semidesert grassland. At the mid elevations (2,000 to 2,200 m [6,562 to 7,218 ft]), these vegetation zones start to give way to pinyon pine (*pinus edulis*) and juniper (*juniperus monosperma*) woodlands on the eastern and western flanks of the mountains. At the mid-high elevations (approximately 2,200 to 2,400 m [7,218 to 7,874 ft]), ponderosa pine (*pinus ponderosa*) forests dominate, with gamble oaks (*Quercus gambelii*). Eventually, at the highest elevations (more than 3,000 m [9,842 ft]) the ponderosa forest gives way to a spruce (*picea*) and fir (*abies*) mixture, primarily present on the eastern slopes (Julyan and Stuever, 2005).

The Manzanos are similar to the Sandias in terms of north-south orientation and vegetation; however, the Manzanos are much longer, extending nearly 65 kilometers (km; 40 miles [mi]) and slightly lower in elevation reaching only 3,178 m (10,426 ft). There are several small communities on the eastern slopes of the Manzanos but the range generally is less densely populated than the Sandias. The Manzanos are separated from the Sandias by Interstate-40 on figure 1. I-40 follows the east-west trending Tijeras Canyon which is structurally controlled by a fault.

The Sandias have not experienced any large wildfires in recent years. The latest fire of substantial size was in 2011, and burned only 42 acres (Short, 2014). The Monitoring Trends in Burn Severity (MTBS) dataset (U.S. Geological Survey, 2013) maps all fires greater than 1,000 acres and dates back to 1984 (Eidenshink and others, 2007). This dataset indicates no fires within the Sandias during the period from 1984 to 2011. The lack of large fires on this landscape has resulted in a condition where abundant dry fuel remains on the ground. In the event of an ignition, this fuel source can contribute to increased fire intensity, wildfire size, or both. Such a high-intensity fire would leave the areas in the Sandias vulnerable to postwildfire hydrologic hazards such as debris flows. Although vegetation cover is less dense and fuel loads are lower on the western side of the Sandias, postwildfire hazards are still a concern because of the proximity to the City of Albuquerque. The Manzano Mountains have experienced several large wildfires over the past 10 years but there are large tracks of unburned forested lands remaining. A study to determine likely locations and sizes of postwildfire debris flows would facilitate prewildfire hazardous fuels mitigation, such as forest thinning, prescribed burning, and infrastructure stabilization by resource managers.

Methods and Approach

The hazard assessment presented in this report was created by combining the results of three different wildfire hazard assessment models. Postwildfire debris flows are the primary focus of this assessment. The postwildfire debris flows are modeled as probabilities and expected volumes in response to a design storm according to the postwildfire debris-flow models developed by the USGS (Cannon and others, 2010). The debris-flow assessments rely upon a measure of burn severity, which was estimated using the USFS FlamMap fire-behavior model (Finney, 2006). Prefire assessment requires an estimation of where fires will occur or a burn probability for each location. Burn probabilities were estimated using the USFS FSim burn probability model (Finney and others, 2011). The analysis carried out with each of these three models is discussed in detail in appendix 1.

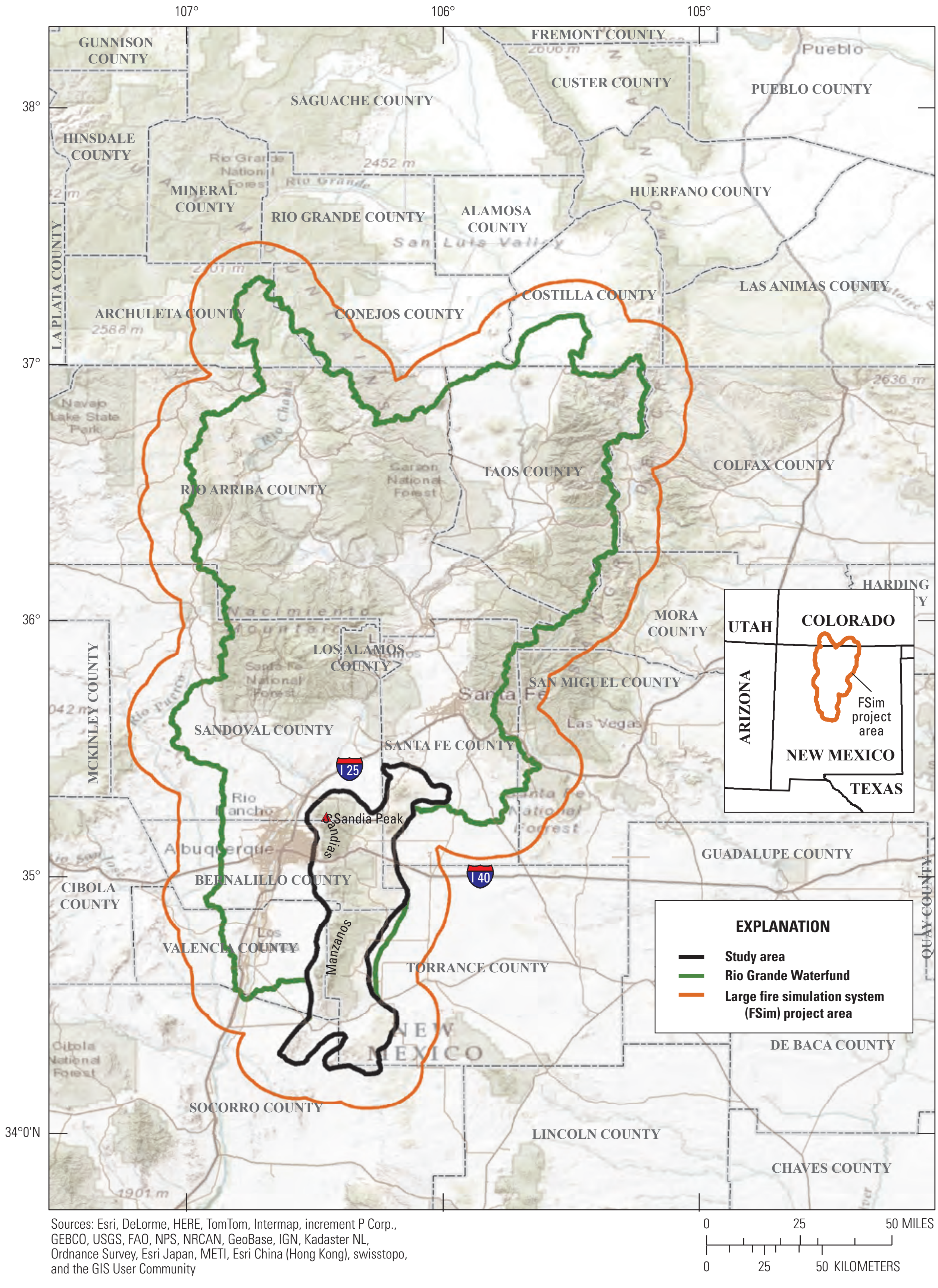

Figure 1. Location of study area.

The final, integrated debris-flow hazard index for each basin analyzed was created by combining the postwildfire debris-flow hazards (probability and volume) with an average annual burn probability value for each basin. The probability and volume of the postwildfire debris flows were calculated assuming that a rainfall event of a specified intensity (43 mm/30 minutes) occurs after the wildfire. The rainfall event chosen is the intensity of a 5-year, 30-minute rainfall event (Bonnin and others, 2004). The postwildfire debris-flow probability and volume calculations also required an estimate of the subbasin percentage and total area of moderate and high severity fire; these factors were estimated using FlamMap.

The use of the FlamMap fire-behavior model in this analysis should produce a more realistic representation of the geographic distributions of burn severity across the landscape than studies that used vegetation distributions alone (Elliot and others, 2012), because the FlamMap simulation will incorporate the effects of slope and fuel moisture that vegetation distributions alone cannot capture. The incorporation of the FSim burn-probability simulation results will bring in the important aspect of where fires are most likely to occur in these currently (2014) unburned landscapes. Other efforts that have used FSim to focus on capturing spatial heterogeneity of fire likelihood and behavior have been limited in the sophistication regarding potential watershed effects (for example, Scott and others, 2012; Thompson and others, 2013); therefore, the modeling efforts presented in this report present a step forward in combining spatial wildfire modeling with debris-flow modeling to inform assessment and mitigation efforts. A version of the model interactions for this study is shown using a flow chart in figure 2.

Modeling Extent

The landscape size needed to appropriately model burn probabilities is larger than those commonly used for debris-flow assessments, because of the nature of probabilistic fire-spread models. Fires that ignite in remote areas outside the study area, but spread into the study area, as well as those that ignite within the study area, needed to be accounted for; therefore, the FSim project area includes the entire Rio Grande Water Fund boundary as well as the Sandia and Manzano Mountains (fig. 1). The FSim project area includes a buffer of 15 km beyond the Rio Grande Water Fund boundary to allow for fires to burn onto the study area. The FSim project area is 30,500 km^2 in size (fig. 3, located at *http://pubs.usgs.gov/sir/2014/5161/downloads/sir2014-5161_fig03.pdf*).

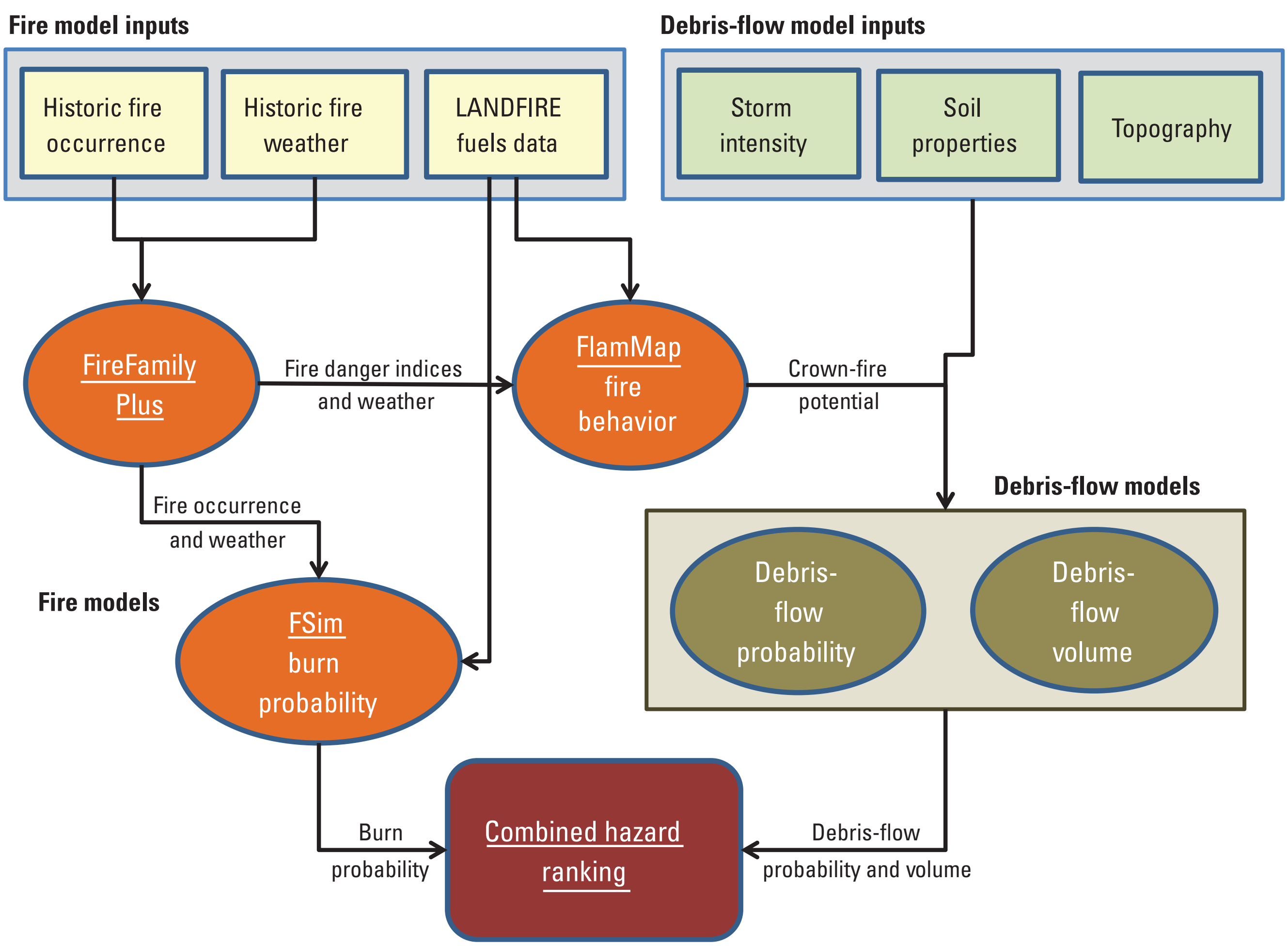

Figure 2. Model interactions.

The debris-flow modeling extent was selected on the basis of three criteria: terrain, simulated burn severity, and precipitation patterns. The postwildfire, debris-flow models are designed for application in mountainous areas; therefore, the boundaries of the model were designed not to extend beyond the break in slope at the base of the Sandias and Manzanos on all sides. On the west face of the Sandias, the break in slope was clearly distinct, whereas on the eastern slopes, some amount of interpretation was necessary. Finally, NOAA Atlas 14 (Bonnin and others, 2004) isohyets were considered because they are indicative of areas with similar rainfall patterns; rainfall is a strong driver of debris flow probability in the postwildfire, debris-flow model.

Modeling Results

FlamMap Fire Behavior Simulation Results

The primary vegetation types covering the area modeled are low shrub and grasslands. The simulated fire activity in these types of vegetation is surface fire, rather than crown fire. The results of the FlamMap simulation (fig. 4) show passive and active crown-fire activity only in locations where there are vegetation patterns that can support crown fires, such as timber. Crown-fire activity was predicted only for 12 percent of the study area, and occurred in timber lands (fig. 4). Timber fuel models (appendix 1) covered approximately 15 percent of the study area. Within these areas, crown-fire activity was predicted for more than 75 percent of the forested fuels. Seventy-five percent crown-fire activity is comparable to the actual moderate and high burn severities in forested areas seen in the Big Spring and Trigo fires, which were used for calibration of the model (appendix 1). In the area burned by the Big Spring fire, 75 percent of the area classified as a timber fuel model (appendix 1) burned severely (MTBS categories 3 and 4). For the Trigo fire, 61 percent of the areas classified as a timber fuel model (appendix 1) burned severely (MTBS categories 3 and 4).

Burn Probability Modeling Results

The FSim annual burn probabilities vary across the entire landscape from 0.00004 to 0.01, with a mean burn probability of 0.0023 (fig. 5, located at *http://pubs.usgs.gov/sir/2014/5161/downloads/sir2014-5161_fig05.pdf*). The FSim model outputs result in an average of 4.3 large fires (greater than 250 acres) per season, and an average of 28,500 acres burned per season. The burn probabilities are greatest in the valley bottoms, where fuel models with rapid rates of spread lead to large fire sizes. For the entire FSim project area, the burn probabilities are highest southeast of Los Alamos. In the Sandias and Manzanos, burn probabilities generally are highest in the eastern part of the study area, in the grass and shrub fuel models, which have higher rates of spread than forested fuel models.

Outside of the grasslands, there are two distinct areas of high burn probabilities on the western slopes of the Sandias and Manzanos. The most predominant area is north of I-40, and east of Albuquerque and the North Valley. This area has not experienced any large fires (greater than 250 acres) since 1992; however, given the current climate and fuels configuration of the area, this island is now more likely to experience large wildfires than other areas in close proximity. The remaining area of high burn probability is west of Torreon, in the high elevation shrub vegetation. The study area has experienced three fires larger than 1,000 acres since 1984 in the mid-elevation timber: the Big Springs, Trigo, and Ojo Peak fires (fig. 3). It is important to note that the mid-elevation timber fuel areas have a lower burn probability relative to the adjacent shrubs and grass vegetation. Because of the difficulty of suppressing fires in remote timbered areas, fires that do get established in areas with these characteristics tend to last a long time and therefore have the potential to burn large areas of land.

Debris-Flow Probability and Volume Estimates

Because the debris-flow model solves for debris-flow hazards as a function of steep terrain, and burn severity in part, the locations of the greatest debris-flow hazards in the study area correlate with the areas with steepest slopes and simulated fire behavior of passive or active crown fire (figs. 4 and 6, located at *http://pubs.usgs.gov/sir/2014/5161/downloads/sir2014-5161_fig06.pdf*). To aid in discussion of model results, the major drainages within the modeled area were delineated into 972 subbasins, each 11 km^2 or less. The subbasin areas delineated range in size from 0.18 to 11 km^2 and average 1.8 km^2. The maximum size of 11 km^2 was used because that is the largest sized basin that is represented with reasonable confidence in the original debris-flow database used to generate the debris-flow model (Gartner and others, 2005). The total area encompassed by the 972 subbasins is 2,620 km^2.

Analysis of debris-flow probabilities for this study area were calculated in response to a 5-year, 30-minute rainfall event of 43 millimeters (mm; 1.71 in.), and a 10-year, 30-minute rainfall event of 52 mm (2.04 in.). The rainfall is assumed to have occurred within the first 3 years of the fire. High debris-flow probabilities reflect the combined effects of drainage basins being nearly completely burned at high and moderate severities and having steep slopes.

The results for a 5-year recurrence interval, 30-minute rainfall event were chosen for the map presentation because these results exhibited the best differentiation among the drainage basins and best highlighted the highest probability response drainage basins. Across the entire study area, the probabilities of debris flows in response to the 5-year recurrence interval, 30-minute rainfall event range from less than 5 to greater than 95 percent. Debris-flow probabilities average 24 percent with 75 subbasins, or 8 percent of all basins, having debris-flow probabilities greater than 80 percent.

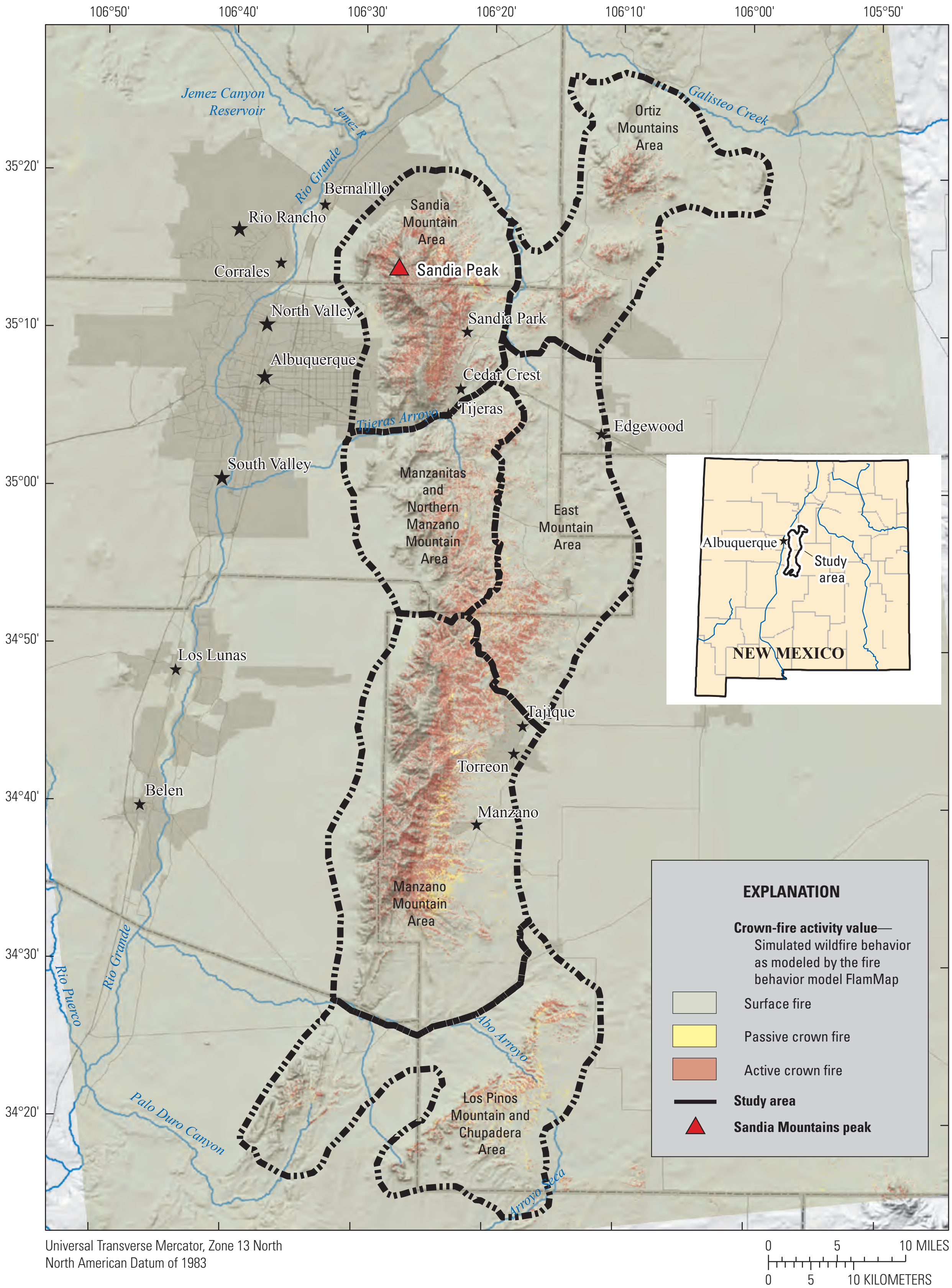

Figure 4. FlamMap simulation results.

The probability of debris flows are strongly related to rainfall intensity. When comparing results between the 5- and 10-year recurrence interval rainfall events, the subbasin total debris-flow probabilities increase by an average of 100 percent across the study area. The number of subbasins with debris-flow probabilities greater than 80 percent is 179 percent higher or 21.5 percent of all subbasins when looking at the 10-year recurrence interval rainfall event as compared to the 5-year event. The 10-year recurrence interval model results were not depicted in a plate because the hazards are uniformly higher than the 5-year event hazards and are therefore not useful in terms of hazard prioritization compared to the 5-year recurrence interval plates. A breakdown of the debris-flow probabilities by subbasin in response to the 5- and 10-year recurrence interval, 30-minute rainfall events is summarized in table 1 and figure 7.

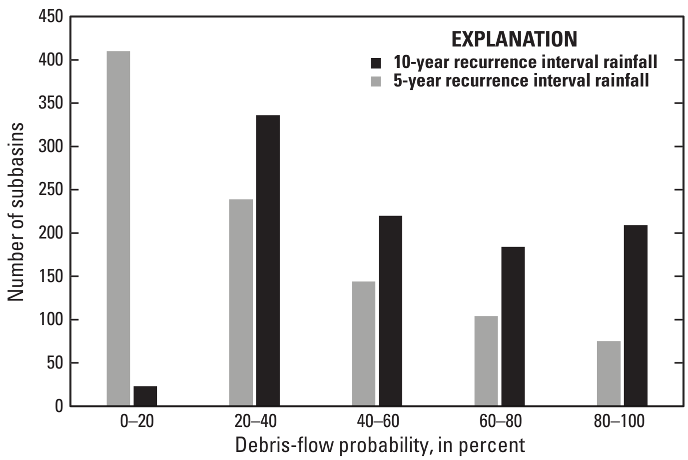

Figure 7. Comparison of debris-flow probability subbasin totals for 5- and 10-year recurrence interval, 30-minute rainfall events

Estimated debris-flow volumes range from less than 30 to greater than 100,000 cubic meters (m^3) and average more than 3,000 m^3. Stream reaches draining the delineated subbasins are shown on figure 6 as “drainages within study areas that can be affected by the combined effects of debris flows from upstream drainages and side tributaries.”

Hazard Assessment

The 972 basins have been grouped together into six geographic areas to facilitate ease of discussion. From north to south, the six geographic areas are the Ortiz Mountains area, the Sandia Mountains area, the East Mountain area, the Manzanitas and Northern Manzano Mountain area, the Mazano Mountain area, and the Los Pinos Mountain and Chupadera area (fig. 6).

Ortiz Mountains Area

The Ortiz Mountains area (fig. 6) is the most northern section of the study area. The Ortiz Mountains area encompasses the Ortiz Mountains closest to Galisteo Creek and the smaller San Pedro and South Mountains, both of which are south of the Ortiz Mountains. Basin areas delineated in the Ortiz Mountains area total 363 km^2 or 13.85 percent of the total basin areas delineated in the study area. Outside of the isolated peaks, the area has fairly gentle topography and low burn severity (fig 4). This geographic area has a total of 131 delineated basins.

The debris-flow probabilities (fig. 6) in response to the modeled 5-year, 30-minute rainfall event in the Ortiz Mountains area range from less than 5 percent to greater than 90 percent and average about 26 percent. The estimated debris-flow

Table 1. Summary of debris-flow probability values by subbasin in response to 5- and 10-year recurrence interval, 30-minute rainfall events.

Debris-flow probability, in percent	5-year recurrence, 30-minute duration rainfall 1.71 inches (43 millimeters)		10-year recurrence, 30-minute duration rainfall 2.04 inches (52 millimeters)		Percent increase in probability from 5-year event to 10-year event
	Number of subbasins	Percent of subbasins	Number of subbasins	Percent of subbasins	
80–100	75	8	209	21.5	179
60–80	104	10	184	19	77
40–60	144	15	220	23	53
20–40	239	25	336	34.5	41
0–20	410	42	23	2	-94

volumes (fig. 6) in this area range from less than 30 m^3 to nearly 60,000 m^3 and average about 6,400 m^3. The Ortiz Mountains area only contains five subbasins that have debris-flow probabilities greater than 80 percent and, as with the rest of the study area, the greatest hazards are on the steepest slopes of the mountainous areas. The Ortiz gold mine (not shown) is located on the east-facing slopes of the Ortiz Mountains about 2 miles from the summit within one of these five subbasins.

Sandia Mountains Area

The Sandia Mountains area (fig. 6) is just east of the Albuquerque metropolitan area. The Sandia Mountains area stretches from the northern extent of the Sandias south to Tijeras Arroyo. The southernmost, west-facing basins drain into the Albuquerque metropolitan area. The eastern slopes are moderately populated with widely distributed rural housing and small communities. Basin areas delineated in the Sandia Mountains area total 395.7 km^2 or 15.1 percent of the total basin areas delineated in the study area. The topography of this area is characterized by a mostly north-south trending mountain range, which has steep and heavily dissected slopes on the west-facing flank and somewhat shallower slopes on the east-facing flank. The simulated burn severity based on crown-fire activity (fig. 4) is high in patchy areas around the mid slopes of the mountains on all sides but particularly on the eastern slopes where the forested areas are denser and extend farther down the slopes. This geographic area has a total of 162 delineated basins.

The debris-flow probabilities (fig. 6) in response to the modeled 5-year, 30-minute rainfall event in the Sandia Mountains area range from less than 5 percent to greater than 90 percent and average about 42 percent. There are 18 subbasins in this area that have debris-flow probabilities greater than 80 percent, most of which are on west-facing slopes and upstream from the Albuquerque metropolitan area. Four small subbasins with debris-flow probabilities greater than 80 percent are upstream tributaries to Las Huertas Creek along Highway 165 upstream from a section of the community of Placitas. Two subbasins with debris-flow probabilities between 60 and 80 percent terminate along Highway 14 within the community of Cedar Crest. The estimated debris-flow volumes (fig. 6) in this area range from less than 30 m^3 to more than 70,000 m^3 and average around 10,000 m^3.

Manzanitas and Northern Manzano Mountain Area

The Manzanitas and Northern Manzano Mountain area (fig. 6) is the area just south of the Sandia Mountain area and Tijeras Arroyo. Basin areas delineated in the Manzanitas and Northern Manzano Mountain area total 290 km^2 or 11.1 percent of the total basin areas delineated in the study area. The topography of this area is characterized by a moderately high zone on the east side that is dissected by numerous complex drainages on the western side. Areas of high simulated burn severity based on crown-fire activity (fig. 4) are minimal and occur almost exclusively on the eastern slopes where, like in the Sandias, the forested areas are denser and extend farther down the slopes. This geographic area has a total of 136 delineated basins.

The debris-flow probabilities (fig. 6) in response to the modeled 5-year, 30-minute rainfall event in the Manzanitas and Northern Manzano Mountain area range from less than 10 percent to greater than 90 percent and average around 45 percent. There are 10 subbasins in this area that have debris-flow probabilities greater than 80 percent, all of which are located on tributaries to major trunk channels in the area. In the northern part of this geographic area, some of the high debris-flow probability subbasins are upstream from military facilities associated with the Kirtland Air Force Base. The estimated debris-flow volumes (fig. 6) in this area range from 35 m^3 to nearly 50,000 m^3 and average around 6,800 m^3.

East Mountain Area

The East Mountain area (fig. 6) covers the area south of the Ortiz Mountains area and east of the Sandia and Manzanitas and Northern Manzano Mountains areas. It is characterized by the gentlest slopes of all the geographic areas with only a small patch of simulated high burn severity based on crown-fire activity (fig. 4) in the southwest corner near the Manzanos. These factors lead to the area having lower debris-flow probabilities than the other areas. This geographic area has a total of 131 delineated basins. Basin areas delineated in the East Mountain area total 388 km^2 or 14.8 percent of the total basin areas delineated in the study area.

The debris-flow probabilities (fig. 6) in response to the modeled 5-year, 30-minute rainfall event in the East Mountain area range from just over 8 percent to greater than 60 percent and average around 15 percent. There are no subbasins in this area that have debris-flow probabilities greater than 80 percent and only two subbasins with debris-flow probabilities between 60 and 80 percent. The estimated debris-flow volumes (fig. 6) in this area range from 27 m^3 to greater than 10,000 m^3 and average around 1,100 m^3.

Manzano Mountain Area

The Manzano Mountain area (fig. 6) encompasses the main body of the Manzano Mountains. The topography of the Manzano Mountain area is characterized by steep slopes draining the eastern and western flanks of the north-south trending mountain range. This area includes a fairly high concentration of simulated high burn severity based on crown-fire activity (fig. 4) and, as with the Sandias, it is located mostly on the eastern slopes. The Manzano Mountain area is the largest of the geographic areas with a total of 247 delineated basins. Basin areas delineated in the Manzano Mountain area total 383 km^2 or 26.05 percent of the total basin areas delineated in the study area.

The debris-flow probabilities (fig. 6) in response to the modeled 5-year, 30-minute rainfall event in the Manzano Mountain area range from just under 8 percent to nearly 100 percent and average around 40 percent. There are 40 subbasins in this area that have debris-flow probabilities greater than 80 percent, which generally are associated with the steepest drainages along the crest of the mountain range occurring on the eastern and western sides. Fortunately, there is very little development as of yet on the western slopes of the southern Manzanos that would be impacted by the many basins with debris-flow probabilities greater than 80 percent that drain those slopes; however, on the eastern slopes of the Manzanos the communities of Tajique, Torreon, and Manzano are all located within 2 to 5 miles downstream from subbasins with debris-flow probabilities greater than 80 percent. The estimated debris-flow volumes (fig. 6) in this area range from 27 m^3 to nearly 35,000 m^3 and average around 4,800 m^3.

Los Pinos Mountain and Chupadera Area

The Los Pinos Mountain and Chupadera area (fig. 6) consists of the smaller mountains and mesas in the southern parts of the study area and is separated from the bulk of the Manzano Mountains by Abo Arroyo. The topography of the Los Pinos Mountain and Chupadera area is characterized more by mesas and plateaus than steep mountain slopes. The simulated burn severity based on crown-fire activity (fig 4) in most of this area is low with the exception of small high-severity patches along the highest ridges. This area has a total of 165 delineated basins. Basin areas delineated in the Los Pinos Mountain and Chupadera area total 500 km^2 or 19.1 percent of the total basin areas delineated in the study area.

The debris-flow probabilities (fig. 6) in response to the modeled 5-year, 30-minute rainfall event in the Los Pinos Mountain and Chupadera area range from nearly 11 percent to greater than 85 percent and average around 30 percent. There are only 2 subbasins in this area that have debris-flow probabilities greater than 80 percent, and 11 subbasins with debris-flow probabilities from 60 to 80 percent. The development in these areas ranges from sparse to nonexistent. The estimated debris-flow volumes (fig. 6) in this area range from 27 m^3 to 100,000 m^3 and average around 10,000 m^3.

Integrated Relative Debris-Flow Hazard Rankings

Debris-flow hazards from a given subbasin can also be represented by an Integrated Relative Debris-Flow Hazard Index that is based on a combination of debris-flow probability, estimated volume of debris flow, and average burn probability for each basin. For example, the most hazardous subbasins will have the highest probabilities of experiencing a fire in some part of the subbasin, the highest probabilities of debris-flow occurrence, and the largest estimated volumes of debris-flow material. Slightly less hazardous would be subbasins that show a combination of high probabilities of burning but only low probabilities of moderate-sized debris flow or perhaps subbasins with moderate probabilities of very large debris flows but only low probabilities of burning.

To compute an integrated debris-flow hazard for each basin, it was necessary to generate a single burn probability value for each basin. To generate the individual basin burn probability values, the results of the FSim burn probability simulation were averaged for each basin analyzed using the continuous parameterization method to create an average burn probability index (see appendix 1). Although the basin-average burn probability index values do not actually quantify the likelihood of an entire given basin burning in 1 year, they provide a measure of burn likeliness that is useful for prioritizing hazards by basins. This technique allowed for a synoptic view of conditions throughout the entire study area, which could be used to identify specific subbasins that might pose a higher risk of experiencing a wildfire somewhere within the subbasin area.

The results of the basin-average burn-probability indices are shown in figure 8, located at *http://pubs.usgs.gov/sir/2014/5161/downloads/sir2014-5161_fig08.pdf*. These results can be compared directly to the FSim burn probability output as shown in figure 5. By averaging over the entire basin, the within-basin spatial information provided by the burn probability values is lost; however, the comparisons of figure 8 with figure 5 show that the basin averaged values are not unreasonable compared to the spatially distributed values.

Computation of the integrated relative debris-flow hazard index for each subbasin was a two-step process. For each subbasin, the estimated debris-flow probability was first multiplied by the average burn probability index to produce a debris-flow likelihood index. In the second step, the debris-flow likelihood index for each subbasin was then multiplied by the estimated debris-flow volume for that subbasin to produce an integrated debris-flow hazard index.

The integrated debris-flow hazard index values were then ranked from 1 to 972, with 1 representing the highest and 972 representing the lowest integrated debris-flow hazard index value. This integrated debris-flow hazard index ranking identifies a possible range of responses from basins with the highest probabilities of producing debris flows with the largest volumes in areas that are most likely to experience fires to basins with the lowest probabilities of producing debris flows with the smallest volumes in areas that are the least likely to experience fires.

The wildfire and debris-flow modeling results for the 972 subbasins in the study area are shown in figure 9 using a scatterplot of conditional (based on the 5-year recurrence interval, 30-minute rainfall event) debris-flow volumes with debris-flow likelihood indices (postwildfire debris-flow probability multiplied by annual burn probability) for all subbasins. The 972 subbasins are divided into three categories based on their integrated relative debris-flow hazard rankings: top 2 percent, top 10 percent, and lowest 90 percent of subbasins.

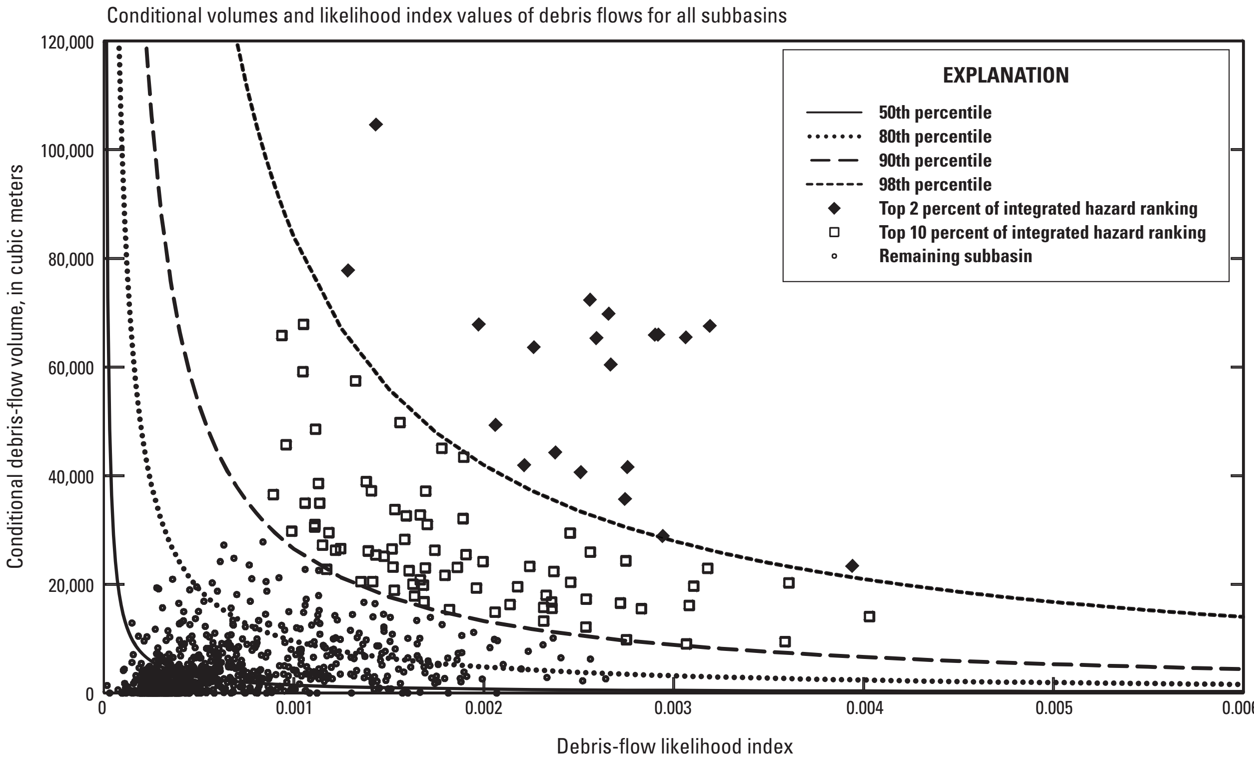

Figure 9. Scatterplot of conditional debris-flow volume with debris-flow likelihood index for all modeled subbasins.

Reference lines for common percentile breakdowns also are shown on the scatterplot of conditional volumes with annual probabilities of debris flows for all modeled subbasins.

Most of the subbasins with the highest integrated debris-flow hazard index rankings are in the steepest parts of the Sandias and Manzanos and contain substantial areas of high, simulated burn severity and therefore high basin-average, annual burn probability indices. Subbasins in the Ortiz Mountains and the Los Pinos Mountain and Chupadera areas have generally low integrated debris-flow hazard indices with a few scattered, high integrated debris-flow hazard index subbasins. Subbasins in the East Mountain geographic area have exclusively moderate to low integrated debris-flow hazard indices.

Nineteen subbasins are contained in the upper 2 percent of integrated debris-flow hazard indices rankings. These subbasins include five subbasins on the west-facing slopes of the Sandias, four of which have downstream reaches that lead into the outskirts of the City of Albuquerque (see inset on figure 8). Of the remaining 14 subbasins in the upper 2 percent of integrated debris-flow hazard indices rankings, 12 are located along the highest and steepest slopes of the Manzano Mountains, largely on the western slope; however, one of these subbasins is approximately 5 miles upstream from the community of Tajique and another is several miles upstream from the community of Manzano, both on the eastern slopes of the Manzanos. The Ortiz Mountains and Cupadera geographic area also each have one basin in the top 2 percent of integrated debris-flow hazard index rankings including the subbasin in which the Ortiz gold mine is located in the Ortiz Mountains geographic area.

The top 5 percent of integrated debris-flow hazard index rankings includes 28 subbasins in addition to the 19 from the top 2 percent. Four of these subbasins also are on the west-facing slopes of the Sandias, with downstream reaches that eventually lead into the City of Albuquerque. Other subbasins in the top 5 percent have basin outlets within the communities of Sandia Park and Cedar Grove on the eastern slopes of the Sandias. Two communities on the eastern slopes of the Manzanos could be threatened by debris flows in subbasins that have integrated debris-flow hazard indices in the upper 5th percentile. One high, integrated debris-flow hazard index subbasin outlets within the community of Manzano, one outlets several miles upstream from the community of Torreon, and a third is approximately 5 miles upstream from the community of Tajique.

Limitations of Hazard Assessment

The use of models for forecasting uncertain events necessarily comes with limitations and potential errors, particularly when multiple models are combined. With respect to both wildfire and debris-flow modeling, a limited empirical basis for model calibration purposes may not be capturing the full range of possible outcomes, highlighting a need for updating models as new observations are made. The assumption of uniform rainfall intensity across the study area and the use of a single Remote Automated Weather Station may not be capturing fine-scale variation in factors influencing wildfire and postwildfire debris-flow potential. Limitations and uncertainties specific to fire modeling tools include an incomplete understanding of how uncertainty and errors propagate through models and knowledge gaps relating to crown-fire potential and propagation, fire-atmosphere dynamics, and fire-fuel interactions (Scott and others, 2012). Further, the spatial aggregation of basin average burn probabilities for continuous parameterization purposes likely is masking finer scale variation because of topography and local fuel conditions. These factors may, in part, explain why the subbasin burn probabilities index is not a strong driver of the integrated relative debris-flow hazard rankings.

The probability of debris flow increases with increasing recurrence interval (larger, less frequent) design storm. Larger, less frequent storms (for example, a 50-year recurrence interval rainfall event) are likely to produce larger debris flows, whereas smaller, more frequent storms (for example, a 1-year recurrence rainfall) could also trigger debris flows, but they would likely be smaller. Higher probabilities of debris flows than those shown on figure 6 may exist within any part of the drainage basins. Because most rainstorms will not be large enough to affect the entire burn area, debris flows will not be produced from all drainage basins during a given storm.

It is important to note that the maps shown in figures 6 and 8 do not categorize those areas that can be affected by debris flows as the material moves downstream from the basin outlets (Cannon and others, 2010). The maps only categorize those areas from which debris will be moved.

The variables included in the debris-flow models and used in this assessment are considered to directly affect debris-flow generation in the intermountain Western United States. Conditions other than those used in the models (for example, the amount of sediment stored in a canyon) could also affect debris-flow production. Data necessary to evaluate such effects, however, are not readily available.

The continuous parameterization technique, while efficient for analytical purposes, may be masking localized variation in conditions affecting either wildfire potential or debris-flow potential. Fine-scale variability in surface characteristics that are not captured by the independent variables used in the model (such as local sediment supply or differences in infiltration rates) may dramatically affect debris flow generation and propagation.

The debris-flow model is considered valid for conditions that typically persist in a burned watershed for one to several years after a fire. The model does not account for variations in the timing of landscape recovery after a fire. The rate of recovery of individual landscapes will vary particularly with respect to post fire rainfall amount, timing, and intensity.

The debris-flow analysis is based on simulated postwildfire conditions and does not account for potential mitigating effects of prefire treatments such as forest thinning or prescribed burning. The analysis does serve to highlight, especially by the stream segment analysis, those parts of a basin with an increased debris-flow probability based on physical characteristics. The information provided by this study should be considered together with local expertise and information to guide mitigation and restoration planning.

This study was initiated to help select ideal locations for watershed restoration that could have the best return on investment. The study provides information on which watersheds might constitute the most serious, potential, debris-flow hazards in the event of a large-scale wildfire and subsequent rainfall in the Sandia and Manzano Mountain areas. The maps and geospatial data provided with this report may be used to prioritize areas where forest thinning or other protective measures may be needed prior to wildfires within these drainage basins, their outlets, or areas downstream from these drainage basins to help reduce potential burn severities. This assessment evaluates only postwildfire debris flows and does not consider hazards associated with flash floods; such hazards may remain for many years after a fire.

Future Considerations for Prewildfire Assessments of Postwildfire Hazards

This study has extended applications of several different models beyond what they were originally designed for. The debris-flow models used in this report were designed for postfire assessments; for this study, they were applied before any fire occurred. The FlamMap model was designed to model fire behavior; for this study, it was used to estimate burn severity. The FSim model was developed to present spatially specific burn probabilities; for this study, those values were averaged over basin areas and combined with outputs from the debris-flow and FlamMap models to compute an integrated debris-flow hazard for each basin. These extensions of the original model applications are not ideal but were used because of the need for prioritization of prefire hazards. Individually these models are difficult to verify and the errors associated with combining them in the manner used here will be difficult to verify as well. Although this methodology represents a step forward in how pre-event assessments of potential hazards are evaluated, the methodology is still in the early stages of development and will continue to evolve as more studies like this are completed.

Summary

Debris flows are high-density slurries of water, rock fragments, soil, and mud that can have enormous destructive power particularly when they are fast moving. Wildfire can drastically increase the probability of debris flows in landscapes that have otherwise been stable throughout recent history. A prewildfire study to determine the potential for postwildfire debris flows in the Sandia and Manzano Mountain areas in Central New Mexico was initiated in 2013 by the U.S Geological Survey in cooperation with the Bernalillo

County Natural Resources Services as a part of the Rio Grande Water Fund. The U.S. Forest Service and The Nature Conservancy provided support for this effort principally through fire simulation modeling. The study was conducted to provide information on which subwatersheds might constitute the most serious, potential, debris-flow hazards in the event of a large-scale wildfire and subsequent rainfall in the Sandia and Manzano Mountain areas. The U.S. Forest Service fire behavior model FlamMap was used to estimate the burn severity likely to occur in unburned areas of the Sandia and Manzano Mountains. The U.S. Forest Service large fire simulation system FSim was used to estimate the probability of fire spreading across all areas of the Sandia Mountains and beyond. The U.S. Geological Survey post-wildfire debris flow model was used to make estimates of the probabilities of debris flows and of volumes of material that could be removed from subbasins based on topography, soil characteristics, and simulated burn intensities.

The results of this study indicate that there is a wide range of postwildfire hazards present in the Sandia and Manzano Mountains areas. Those areas with the highest modeled hazards generally are steep areas, with ample fuel supplies. Some of the highest modeled hazards subbasins are upstream from the metropolitan area of Albuquerque and other smaller communities within the wildland-urban interface area.

Across the entire study area, the probabilities of debris flows in response to the 5-year-recurrence interval, 30-minute rainfall event range from less than 5 to greater than 95 percent and average 24 percent with 75 subbasins, or 8 percent of all basins, having debris-flow probabilities greater than 80 percent. When comparing debris-flow probability results between the 5-year and 10-year recurrence interval rainfall events, subbasin debris-flow probabilities increase 100 percent across the study area. The number of subbasins with debris-flow probabilities greater than 80 percent is 179 percent higher or 21.5 percent of all subbasins when looking at the 10-year recurrence interval rainfall event as compared to the 5-year event. Estimated debris-flow volumes in response to the 5-year recurrence interval, 30- minute intensity rainfall range from less than 30 to greater than 100,000 m^3 and average over 3,000 m^3.

The integrated relative debris-flow hazard rankings for each subbasin were generated by multiplying the individual values for debris-flow volume, debris-flow probability, and average burn probability for each subbasin. The integrated relative debris-flow hazard ranking analysis shows that most of the basins with the highest integrated relative debris-flow-hazard rankings are in the steepest portions of the Sandia and Manzano Mountains. Among subbasins in the upper 2 percentile of integrated relative debris-flow hazard rankings, are 5 subbasins on the west-facing slopes of the Sandia Mountains, 4 of which have downstream reaches that lead into the outskirts of the City of Albuquerque. The bulk of the remaining 14 subbasin in the upper 2 percent of integrated relative debris-flow hazard rankings are located along the highest and steepest slopes of the Manzano Mountains, largely on the western slope. However one is a subbasin several miles upstream of the community of Torreon and another is several miles upstream of the community of Manzano, both on the eastern slopes of the Manzanos.

The top 5 percent of integrated relative debris-flow hazard rankings includes 47 total subbasins. Four of these subbasins are also on the west-facing slopes of the Sandias with downstream reaches that eventually lead into the City of Albuquerque. Other subbasins in the top 5 percent have basin outlets within the communities of Sandia Park and Cedar Grove on the eastern slopes of the Sandias. On the eastern slopes of the Manzano Mountains, upper 5th percentile integrated relative debris-flow hazard subbasins outlet within the community of Manzano, and several miles upstream of the community of Tajique.

The maps in this report may be used to prioritize areas where forest thinning or other protective measures may be needed prior to wildfires within these drainage basins, their outlets, or areas downstream from these drainage basins to help reduce potential burn severities. This assessment evaluates only postwildfire debris flows and does not consider hazards associated with flash floods; such hazards may remain for many years after a fire.

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Appendix

Modeling Methods and Approach

In northern New Mexico, widespread watershed restoration efforts are being undertaken to safeguard vital watersheds against the threat of catastrophic wildfire. This study was initiated to help select ideal locations for the restoration efforts in places that could have the best return on investment. The hazard assessment presented in this report was created by combining the results of three different wildfire hazard-assessment models: a large fire simulation system model, a fire behavior model and a postwildfire debris-flow model.

Postwildfire debris flows are the primary focus of this assessment. The postwildfire debris flows are modeled as probabilities and expected volumes in response to a design storm according to the postwildfire debris-flow models developed by the U.S. Geological Survey (USGS) (Cannon and others, 2010). The debris-flow assessments rely on a measure of burn severity that was estimated using the U.S. Department of Agriculture, Forest Service USFS FlamMap fire-behavior model (Finney, 2006). Prefire assessment requires an estimation of where fires will occur or a burn probability for each location. The large fire simulation system known as FSim (Finney and others, 2011) is a burn probability model that has been used in numerous wildfire exposure and risk assessments at various scales (Thompson and others, 2011; Ager and others, 2012) and to address impacts to various resources (Haas and others, 2013; Thompson and others, 2013; and Scott and others, 2012). For this study, the USFS FSim burn probability model burn was used to estimate burn probabilities. A schematic for the model interactions in this study is shown in figure 1–1.

The final step in the project was to generate an overall hazard index for all basins in the study area by combining the modeled debris-flow hazards, which incorporate the fire-severity estimates, with the modeled burn probabilities for each basin. This appendix covers additional technical details of the modeling methods, model interactions, and model calibrations used in the study. The primary topics covered are the postwildfire debris-flow, FlamMap fire behavior, and FSim burn probability modeling efforts.

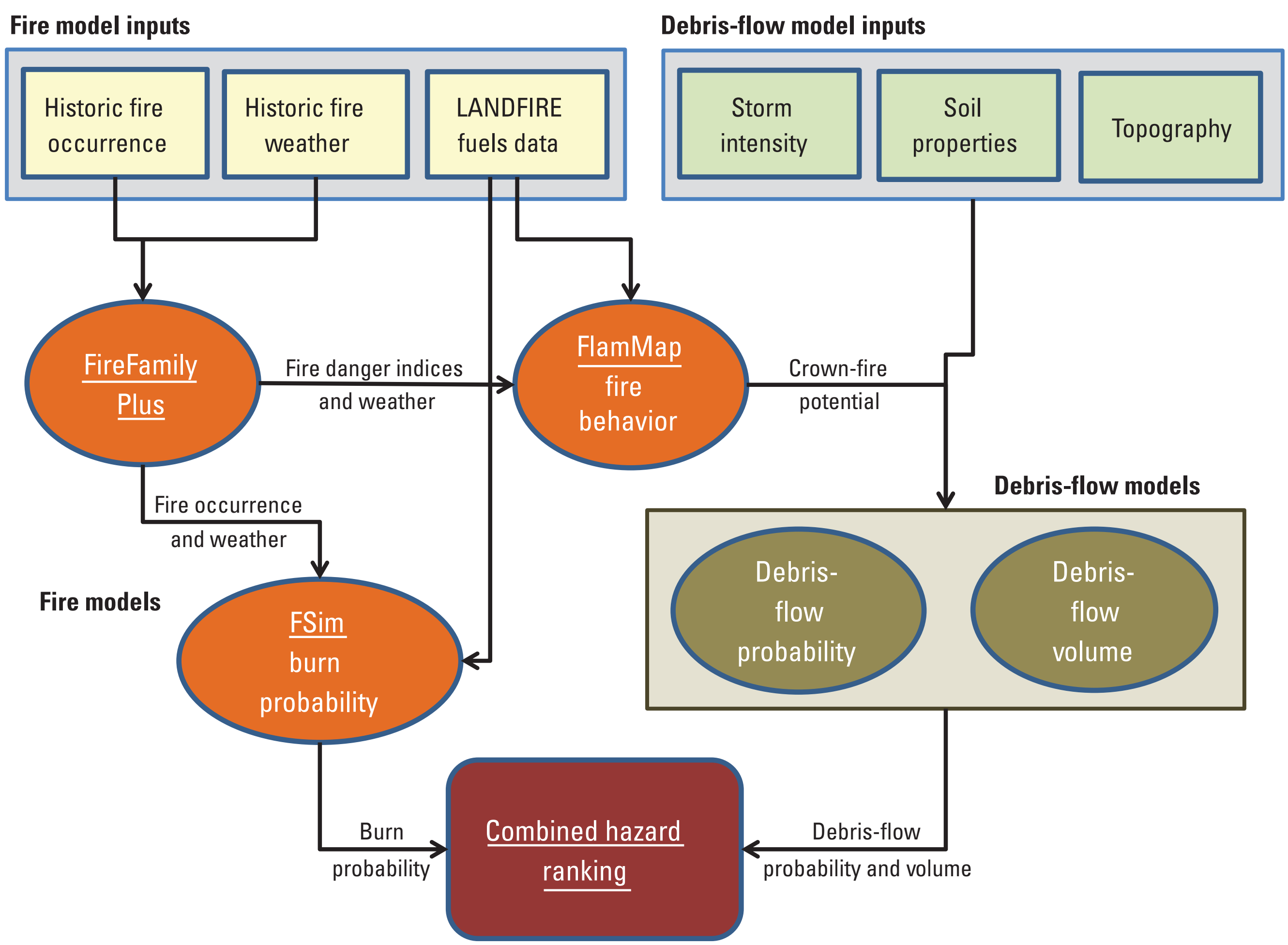

Figure 1–1. Model interactions.

Debris-Flow Hazard Modeling

A pair of empirical models was used to estimate the probability and volume of debris flows along the drainage network and for selected drainage basins in response to a given rainfall event in the study area. The model for predicting debris-flow probability was developed by Cannon and others (2010) using logistic multiple-regression analyses of data from 388 basins in 15 burned areas in the intermountain western United States. Conditions in each basin were quantified using readily obtained measures of basin gradient, soil properties, storm rainfall, and a simulated measure of areal burned extent. Statistical analyses were used to identify the variables that most strongly influenced debris-flow occurrence and to build the predictive model. Equation 1 is used to calculate debris-flow probability (Cannon and others, 2010):

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

where

- P is the probability of debris-flow occurrence in fractional form, and
- e^{x} is the exponential function where e represents the mathematical constant 2.718.

Equation 2 is used to calculate x:

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

where

- $\%SG30$ is the percent 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 (in meters) divided by the square root of the drainage basin area (in square meters) (Melton, 1965);
- $\%AB$ is the percentage of drainage basin area burned at moderate and high severity;
- I is average storm intensity (the total storm rainfall divided by the storm duration, in millimeters per hour);
- $\%C$ is the percent clay content of the soil (STATSGO, Schwartz and Alexander, 1995); and
- LL is the liquid limit of the soil (the percent of soil moisture by weight at which soil begins to behave as a liquid) (STATSGO, Schwartz and Alexander, 1995).

A second statistical model was used to estimate the volume of material that could issue from the basin mouth of a recently burned drainage basin in response to a given magnitude storm. This model was developed using multiple linear-regression analyses of data compiled from 56 debris-flow-producing basins burned by 8 fires (Cannon and others, 2010). Debris-flow volume measurements were derived from records of the amount of material removed from sediment-retention basins and from field measurements of the amount of material eroded from the main channels within a burned drainage. Statistical analyses were used to identify the variables that most strongly influenced debris-flow volume. The model provides estimates of the volume of material that may pass through a drainage-basin outlet in response to a single rainfall event. The model has the following form:

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

where

- V is the debris-flow volume (in cubic meters);
- Ln is the natural log function;
- $SG30$ is the area of drainage basin with slopes equal to or greater than 30 percent (in square kilometers);
- AB is the drainage basin area burned at moderate and high severity (in square kilometers);
- T is the total storm rainfall (in millimeters); and
- 0.3 is a bias correction factor that changes the predicted estimate from a median to a mean value (Cannon and others, 2009; Helsel and Hirsch, 2002).

Values for debris-flow probability and volume were obtained along drainage networks using the continuous parameterization technique (Verdin and Greenlee, 2003; Verdin and Worstell, 2008). With this technique, estimates of debris-flow probability and volume (Cannon and others, 2010) were obtained for every 10-meter pixel along the drainage network as a function of conditions in the drainage basin upstream from each pixel. The independent variable values can be represented as forming continuous surfaces over the burned area. Once the surfaces of the independent variables were developed, the probability and volume equations were solved using map algebra for each grid cell along the drainage network. This technique was developed as an alternative to basin-characterization approaches used previously (for example, Cannon and others, 2010), which require definition of outlets or pour points and their corresponding basins at the beginning of the analysis. The technique used here allows for a synoptic view of conditions throughout the entire study area, which can be used to identify specific 10-meter pixels or stream reaches that might pose a higher risk of debris flows; the technique also aids in sampling design and monitoring-site selection. The computations were carried out using an ArcGIS toolbox developed by the USGS (Andrew Bock, Barbara Ruddy, and Kristine Verdin, U.S. Geological Survey, written commun., 2013).

The base layer on which the continuous-parameterization layers are built is the 1/3-arc-second National Elevation Dataset (Gesch and others, 2002). This digital elevation model (DEM) was transformed into a projection system appropriate to central New Mexico (Universal Transverse Mercator [UTM], Zone 13) and processed using standard DEM-conditioning tools in ArcGIS (Esri, 2011) and RiverTools (Rivix, 2012). Once the overland flow structure was derived (in the form of a flow-direction matrix) using the DEM, the independent variables driving the probability and volume equations were evaluated for every grid cell within the extent of the DEM.

Because of orographic effects of the mountainous terrain and the size of the area modeled, rainfall totals and rainfall intensities will vary over the extent of the burned area. For this study, however, the maximum rainfall amounts for each storm were assumed to be uniform over the entire area modeled, providing the most conservative or highest estimate of the probability and volumes of potential debris flows.

FlamMap Fire-Behavior Modeling

Burn severity is a necessary input for the debris-flow model (Cannon and others, 2010). Burn severity is a measure of the relative changes in pre- and immediate postfire vegetation cover combined with relative measures of the distribution of water-repellent soils (Parsons and others, 2002; Keeley, 2009); therefore, a prewildfire assessment of potential post-wildfire debris-flow activity requires some estimate of potential burn severity. Burn severity can be estimated using fire intensity and crown-fire metrics output by fire-behavior modeling systems as a proxy for burn severity. These fire-behavior modeling systems can capture spatial variability in topography, vegetation, and fuel characteristics, which in turn, can influence the spatial pattern and extent of basin burn severity. For this prewildfire debris-flow assessment, the fire-behavior model FlamMap was used to estimate the burn severity likely to occur in the study area. FlamMap was created by the U.S. Department of Agriculture Forest Service, Missoula Fire Sciences Laboratory (Finney, 2006), and is designed to characterize spatial variability in potential fire behavior under a constant set of environmental conditions for an entire landscape. FlamMap uses spatial information on topography and fuels, fuel moisture, and weather data to calculate potential fire behavior including crown-fire activity as well as rate of spread, flame length, and fireline intensity across the landscape. FlamMap incorporates surface fire spread (Rothermel, 1972), crown-fire spread (Rothermel, 1991), and crown-fire initiation (Van Wagner, 1977) models. FlamMap models the potential fire behavior across an entire landscape at one instant in time.

The crown-fire activity fire-behavior output from FlamMap, which is a classification of fire type as either surface fire, passive crown fire, or active crown fire, was used to estimate the burn severity likely in unburned areas of the study area. Crown fire is the movement of fire into and through the forest canopy: active crown fire carries continuously through the forest canopy, whereas passive crown fire does not carry continuously but burns crown fuels intermittently (that is, when individual trees or groups of trees burn). Areas simulated as having crown-fire activity, either passive or active, were interpreted as areas likely to burn with moderate to high severity for the purpose of the debris-flow model. Crown-fire activity output was chosen for two reasons. First, crown-fire activity is considered representative of the actual burn-severity data calculated from remotely sensed imagery (Davis and others, 2010). Second, simulated fire activity in grassland fuel types always results in surface fire rather than crown fire, so burn severity is not expected to be severe; therefore, the results are not expected to overpredict severity (Davis and others, 2010).

Spatial fuel and topography information needed to run FlamMap was obtained from LANDFIRE (Ryan and Opperman, 2013; U.S. Geological Survey, 2013b). LANDFIRE is an interagency mapping program responsible for producing and maintaining a suite of comprehensive and consistent geospatial layers representing topographic, vegetation, fuels, and fire conditions across the United States. The LANDFIRE topographic layers include slope, aspect, and elevation (Ryan and others, 2013). The LANDFIRE fuels layers include canopy cover, stand height, canopy base height, canopy bulk density, fuel-loading model, and fire-behavior fuel model (Scott and Burgan, 2005). Specific methodology on the creation of the LANDFIRE topographic and fuels layers can be accessed at *http://landfire.gov/*.

Fire-Behavior Model Calibration

Calibration for the debris-flow assessment study area was based on an accuracy assessment of the modeled crown-fire activity output using prewildfire LANDFIRE fuel layers compared to the actual burn severity from two fires that occurred in 2008 in the Manzano Mountains: Trigo Fire and Big Spring Fire. These two fires were chosen for the local calibration and accuracy assessment because they represent fires in the vicinity with potential fuel conditions and resulting burn severity that may occur in the Sandias or elsewhere in the study area. Burn severity data from the Trigo and Big Spring Fires were downloaded from the USGS Monitoring Trends in Burn Severity (MTBS) project (U.S. Geological Survey, 2013a). The MTBS burn severity layers depict severity in five thematic categories: (1) unburned to low severity, (2) low severity, (3) moderate severity, (4) high severity, and (5) increased greenness or increased postfire vegetation response. The MTBS severity layers are created using Normalized Burn Ratios derived from pre- and post-fire remote imagery that are analyzed and classified into the above thematic categories using methodology developed by USFS and USGS. A full description of the methodology can be accessed at *http://www.mtbs.gov*. In the area burned by the Big Spring fire, 75 percent of the area classified as a timber fuel model burned severely (MTBS categories 3 and 4). For the Trigo fire, 61 percent of the areas classified as a timber fuel model burned severely (MTBS categories 3 and 4).

The comparison between the measured burn severities given by the MTBS analysis and the simulated burn severities output by FlamMap yields four basic categories of results. The actual (MTBS) and simulated (FlamMap) severities either are

(1) in agreement that the severity is high; (2) in agreement that the severity is low; (3) in disagreement, with actual severities showing high severity and simulated output showing low severity; or (4) in disagreement, with actual severities showing low severity and the simulated output showing high severity.

Canopy Base Height (CBH), the average height from the ground to the canopy bottom of a forest stand, measured in meters, can have a substantial impact on whether a fuel model will result in simulated surface-fire behavior (low severity) or crown-fire behavior (high severity) in a FlamMap simulation. The smaller the CBH, the more likely the area is to produce higher, simulated burn intensity. For example, in some areas of the Trigo and Big Springs Fires that had burn severities of moderate to high according to MTBS, but showed low severity (or surface fire) in the FlamMap simulation, the mean CBH was 2.1 meters (m), whereas, in other areas of those fires where MTBS and the FlamMap simulations were in agreement that the severity was high, the mean CBH was 0.7 m.

FlamMap incorporates the VanWagner (1977) crown-fire initiation model and the Rothermel (1991) crown fire spread model to compute the potential crown-fire activity of an area. In an analysis on the sensitivity of VanWagner's crown-fire initiation model, Scott (1998) reported that CBH and the surface fuel-model were the critical input factors affecting initiation of crown fires. In 2006, the LANDFIRE team reported (U.S. Geological Survey, 2006) that the values in the CBH layer were too high to simulate expected crown-fire results and recommended modifying this value using a calibration factor 0.6106.

For this study, a local calibration and accuracy assessment was completed. Crown-fire activity was modeled using CBH calibration factors ranging from 0.1 to 0.6 and compared with MTBS burn severity values. The goal of the calibration assessment was to find the CBH factor that allowed for the closest match between the FlamMap simulated crown-fire activity areas and the MTBS moderate and high burn severity areas. The overall accuracy of the FlamMap simulated crown-fire activity in predicting MTBS moderate and high burn severity with no change to the CBH layer was 57 and 35 percent for the Trigo and Big Spring Fires, respectively. Using a calibration factor of .03 for the CBH layer, the overall accuracy improved to 64 percent for the Trigo Fire and 62 percent for the Big Spring Fire. Although the accuracy is not the highest overall accuracy from the calibration runs, it is the point at which there is not a substantial increase in areas that MTBS was recorded as having burned at low severity, but FlamMap crown-fire activity was predicted to burn with high or moderate severity (MTBS low severity equals Crown-Fire Activity crown fire). To run the final model, 30-m raster layers representing the topography and 2013 fuel conditions were obtained from LANDFIRE with the CBH fuel-layer value reduced using the revised CBH value of CBH*0.3.

The fuel moisture and weather parameters necessary for running the FlamMap model were derived using FireFamily Plus software (U.S. Department of Agriculture, 2002). FireFamily Plus is a software system used for summarizing and analyzing historical, daily fire-weather observations and computing fire-danger indices. Weather parameters used by FireFamily Plus include 20-foot above-ground windspeed, wind direction, and foliar moisture content. Fuel moisture is recorded in terms of live herbaceous fuels, live woody fuels, and 1-, 10-, and 100-hour fuels. The 1-hour fuel class represents the finer fuel particles that change in moisture content quickly in response to a change in ambient temperature and relative humidity.

Weather and fuel moisture data used for the FireFamily Plus simulation were from the Oakflats Remote Automated Weather Station (RAWS) (Zachariasson and others, 2003), which is representative of the Sandia Mountains area. Weather and fuel moisture parameters from the Oakflats RAWS used in the FireFamily Plus model are shown in table 1–1 and can be considered as weather and fuel moisture conditions representative of conditions observed during the Trigo and Big Spring Fires. These weather and fuel moisture parameters also were used for FlamMap crown-fire activity calibration runs. The resulting crown-fire activity layer was used as the burn-severity input in the debris-flow model.

Table 1–1. Weather and fuel moisture information at Oakflats Remote Automated Weather (RAW) station as reported by Fire Family Plus and modified as noted.

[%, percent; mph, miles per hour]

RAW station parameters	Input values used
Weather parameters	
Wind direction[a]	Uphill
Foliar moisture[b]	80%
20-foot wind speed[c]	17 mph
Fuel moisture parameters	
1-hour fuel moisture	5%
10-hour fuel moisture	8%
100-hour fuel moisture	12%
Live herbaceous fuel moisture	30%
Live woody fuel moisture[b]	60%

[a]Wind direction modeled using uphill wind conditions to represent worst case scenario.

[b]Expected default data values were used since RAW station output was higher than expected for these metrics.

[c]Maximum wind speed for April through July.

Burn Probability Modeling

Prefire assessment requires an estimation of where fires will occur or a burn probability for each location. The occurrence and spread of large wildfires (greater than 250 acres) were modeled to determine burn probability using the FSim large fire simulation system (Finney and others, 2011). The focus on "large" wildfires is because these relatively rare events account for most of the area burned (Short, 2013). The FSim simulates thousands of hypothetical fire seasons by incorporating fire weather information into three primary modules: fire occurrence, fire behavior and growth, and fire containment. First, historical fire weather information was obtained for the area to be modeled with FSim. The National Fire Danger Rating System's (NFDRS) Energy Release Component (ERC) is calculated from this weather information for a given fuel model. The ERC is the estimated potential available energy released per unit area in the flaming zone of a fire and is expressed in British Thermal Units per square foot (Bradshaw and others, 1984). The day to day variations of the ERC are caused by changes in the moisture contents of the various fuel classes (that is, fuel size diameters), which are affected by temperature, precipitation, and humidity. Fuel models combine the fuel classes into a stylized fuel bed for use in fire-behavior modeling. The NFDRS fuel models were created specifically for calculating fire danger ratings. The NFDRS fuel model "G" is used in the ERC calculations for FSim because it contains all fuel classes and is strongly correlated with wildfire occurrence across different climate zones (Andrews, 2003). The NFDRS fuel model "G" is typified by dense conifer (*coniferae*) stands with heavy accumulation of litter and downed woody material. The ERC as it is calculated for fuel model "G" is known as ERC(G).

Through the use of a statistical time-series analysis weather module (Finney and others, 2011), a series of daily fire weather conditions, representing the daily ERC value for thousands of possible fire seasons, is generated. Wind speeds and directions are independently random for each simulation day and follow historic frequency patterns. The fire occurrence module within FSim uses the relation between the historical ERCs and historical fire occurrence to determine the following: (1) given a daily ERC value, the probability that at least one ignition will escape initial suppression efforts and become a large fire (that is, probability of escape), and (2) given that the probability of escape is met, how many ignitions will escape. The escape ignitions are probabilistically located on a landscape for the fire growth simulation module, according to historical ignition-density patterns. The fire growth module uses FlamMap and the Minimum Travel Time (Finney, 2002) logic to grow the fires and determine fire intensity based on the fire weather and information regarding topography and fuels. The fires increase daily under the wind and fuel moistures determined by the weather module until the fire is either extinguished because of a number of consecutive days with ERC(G) values below the 80th percentile or contained due to suppression (Finney and others, 2011). The fire suppression algorithm determines the probability of containment due to suppression on any given day, and is a function of fire weather, fire duration, and fuel types. The FSim calculates annual burn probabilities by dividing the number of times a given pixel burns by the number of fire seasons simulated.

Burn Probability Model Calibration

Historical wildfire-occurrence data for the FSim modeling extent were obtained from the Fire Program Analysis fire-occurrence database for 1992–2011 (Short, 2013). This information was used to calibrate the FSim model. Over the past 20 years, the study area contained on average approximately 4.8 ignitions each year, which resulted in fires larger than 250 acres. Under the Complete Spatial Randomness hypothesis, the number of events, or points, in a planar region follows a Poisson distribution and each point is independent of each other (Diggle, 2003). In other words, the points are not clustered or dispersed, they are located randomly about the region. An average nearest neighbor spatial statistics test (Ebdon, 1985) among the large-fire ignitions showed that the large-fire ignitions had a less than 1 percent chance of occurring under conditions of Complete Spatial Randomness, and showed strong evidence of a clustered point densities pattern. These results prompted the use of an Ignition Density Grid (IDG), which allows the ignitions in FSim to be located randomly on the ground in accordance to the density specified by the IDG (Finney and others, 2011). An IDG was calculated based on the historical fire occurrence data within a 60-kilometer (km) buffer of the FSim project areas, using kernel smoothing (Berman and Diggle, 1989), with a kernel width of 50,000 m and a quartic kernel function as implemented in spkernel2d function (Rowlingson and Diggle, 2013) in R, an open source language and a general environment for statistical computing (R Core Team, 2012). The IDG and the ignition locations of the recent large fires within the FSim project area, and those used in the IDG are shown in figure 3 (located at *http://pubs.usgs.gov/sir/2014/5161/downloads/sir2014-5161_fig03.pdf*).

The landscape file data layers needed for FSim's fire growth module, FlamMap, were obtained from the LANDFIRE v1.2.0 (fig. 1–2, located at *http://pubs.usgs.gov/sir/2014/5161/downloads/sir2014-5161_fig1_2.pdf*) (*www.landfire.gov*). The CBH was decreased by 69 percent for the timber fuel models, using a calibration factor of 0.316, to maintain consistency with the FlamMap inputs as arrived at through the FlamMap calibration process (see "Fire-Behavior Model Calibration" section). The landscape file inputs were resampled from the native resolution of 30 m to 90 m, using the nearest neighbor technique (Lillesand and others, 2004, p. 750) wherein each cell in the 90-m raster is given the value of the nearest 30-m cell (as measured from cell center to cell center). The new 90-m resolution is needed for computational practicality, and the nearest neighbor technique is used to maintain rare and scattered fuel types that other resampling techniques would reduce or even eliminate. For example, linear roads and water features, which impede fire growth, would be lost using a majority resample.

To generate the relation between historic fire occurrence and weather needed by FSim, historical time series data of ERC values representative of the FSim project area are needed for the time period covered by the national fire occurrence database, 1992–2011 (Short, 2013). The national fire occurrence database was developed to reconcile differences between multiple wildfire recording agencies, such as various Federal, State, and local entities. The resulting dataset contains more than 1.6 million records for the 20-year period, with each record spatially located to a precision of at least the Public Land Survey Section, and further attributed with the discovery date and the final fire size. The weather information commonly is extracted from a representative RAWS (Zachariasson and others, 2003). The Oakflats (station number 290702) RAWS was used in the FlamMap runs for the burn severity model calibration; however, this weather station only has information dating back to 1993, and there are many missing dates from this time period. Other RAWS within the FSim project area have the same issue; therefore, the historical gridded ERC dataset (Abataglou, 2011) was used. This dataset is spatially and temporally complete from 1979 to 2011, at a 4-km grid for the contiguous United States. The necessary 20-year period was extracted from this dataset for the 4-km pixel that contained the geographic location of the Oakflats RAWS. Percentile weather and corresponding ERC streams were formatted for input into a FireFamily Plus fire risk file, for use with FlamMap. Winds were calculated from the Oakflats RAWS, because only a representative of the monthly frequency of wind speeds and directions detected in the FSim project area are needed.

A total of 30,000 fire seasons were simulated using FSim, with the suppression algorithm enabled, at a resolution of 90 m. The rate of spread was decreased for the grass fuel models GR1 and GR2, by a factor of 0.4, and for the shrub fuel models SH1 and SH2 by a factor of 0.2. The rates of spread for these fuel models tend to be extremely fast, and can lead to an unrealistically high frequency of extremely large fires in the grass and shrub fuel models. Because these fuel models tend to be relatively easier to suppress than timber fuel models, and tend to occur closer to human development reducing response times, a decrease in the rate of spread allows the FSim to suppress these fires in a more realistic time period. A large fire cutoff of 400,000 acres was used, which is almost three times the size of the largest fire observed in the area in the recent past. This large cutoff size allows for fires to burn in the area that, to date, are unprecedented in terms of size.

Continuous Parameterization of Burn Probability Results

The results of the burn probability modeling were averaged along drainage networks using the continuous parameterization technique (Verdin and Greelee, 2003; Verdin and Worstell, 2008) to create a basin average burn probability index. Using this technique, burn probability values were obtained for every 10-m pixel along the drainage network as an average of burn-probability values in the drainage basin upstream from that pixel. This technique allowed for a synoptic view of conditions throughout the entire study area, which could be used to identify specific subbasins that might pose a higher risk of experiencing a fire. The technique also aided in combining the burn-probability hazard with the debris-flow hazards for an integrated debris-flow hazard index for each subbasin.

A comparison of modeled burn probability with basin-average burn probability indices for an area around the Sandia Mountains is shown in figure 1–3. The modeled burn probability map shows that the probability of burning an entire basin in a single season is unlikely; however, downstream impacts to a watershed can be substantial when only the upper parts of a watershed are burned, particularly if those areas are severely burned. Although the basin-average burn probability values do not quantify the likelihood of an entire basin burning in 1 year, the values provide a measure of burn hazard that is useful for prioritizing hazards by basins.

Discussion of Hazard Modeling

This study was initiated because of a need to ensure that widespread watershed restoration efforts taken to safeguard vital watersheds against the threat of catastrophic wildfire are carried out in places that could have the best return on investment. The study uses a methodology that combines three models in a manner that is not ideal but is necessary for addressing a prefire hazard assessment of postfire hazards. The debris-flow model was developed using burn severity but there is no model that directly outputs an estimation of burn severity; therefore, fire behavior was used as simulated by FlamMap as a proxy for burn severity.

Three different sized grid cells were used in the different models throughout this study. All gridded inputs for the debris-flow models were in 10-m cell sizes with the exception of the FlamMap crown-fire potential. The gridded LANDFIRE fuels data and FlamMap crown-fire outputs are in 30-m cell sizes. The FlamMap output was resampled to a 10-m cell size using the continuous parameterization method. There is no loss of information going from a larger (30 m) to a smaller (10 m) cell size. Because of the nature of probabilistic fire spread models, the landscape size needed to appropriately run FSIM is larger than those commonly modeled in a debris-flow assessment; therefore, FSIM was run over a large landscape, using a 90-m cell size to allow for computation efficiency. The landscape file inputs for FSIM were resampled from the native resolution of 30 m to 90 m, using the nearest neighbor methods. Although the nearest neighbor methods maintain rare fuel types, there is still some loss in data resolution when resampling from a smaller to a larger grid size.

This study has employed applications of several different models beyond what they were originally designed to do. The debris-flow models used in this report were designed for postwildfire assessments; for this study, they were applied before any fire occurred. The FlamMap model was designed to model fire behavior; for this study, it was used to estimate

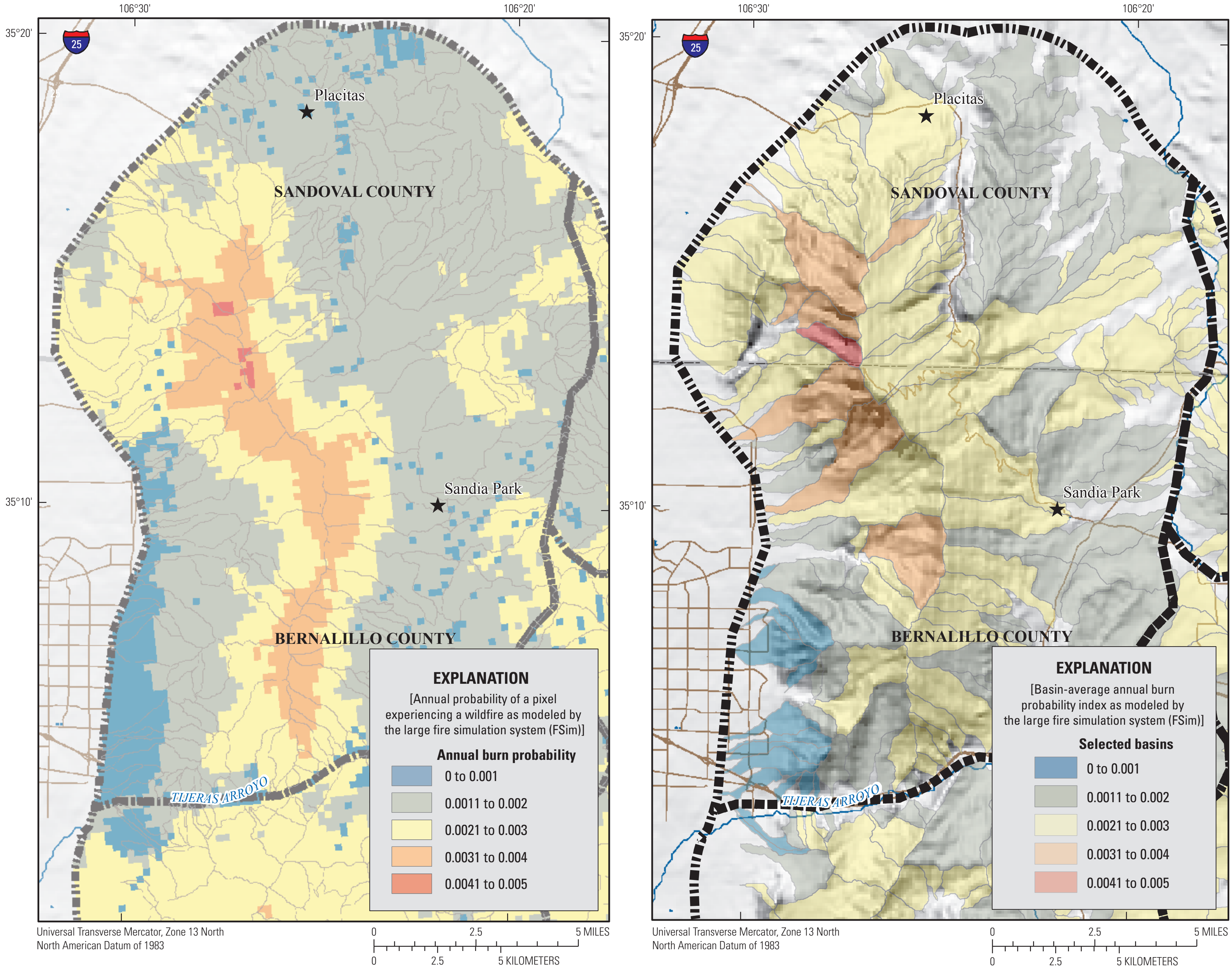

Figure 1–3. Comparison of unadjusted burn probability to basin-average burn probability indices.

burn severity. The FSIM model was developed to present spatial specific burn probabilities; for this study, it was averaged over basin areas and combined with postfire hazards. These extensions of the original model applications were used because of the need for prioritization of prefire hazards. Individually, these models are difficult to verify and the errors associated with combining them in the manner used here will be difficult to verify as well. Although this methodology represents a step forward in how pre-event assessments of potential hazards are evaluated, the methodology is still in the early stages of development and will continue to evolve as more studies like this are completed.

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Back photograph. Hairy Golden Asters (*Heterotheca villosa*) bloom in the Manzano Mountain Wilderness against a background including a portion of the Trigo Fire burn scar. Photograph by Peter Voshefski.

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