The Increasing Wildfire and Post-Fire Debris-Flow Threat in Western USA, and Implications for Consequences of Climate Change

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Susan H. Cannon and Jerry DeGraff

Abstract In southern California and the intermountain west of the USA, debris flows generated from recently-burned basins pose significant hazards. Increases in the frequency and size of wildfires throughout the western USA can be attributed to increases in the number of fire ignitions, fire suppression practices, and climatic influences. Increased urbanization throughout the western USA, combined with the increased wildfire magnitude and frequency, carries with it the increased threat of subsequent debris-flow occurrence. Differences between rainfall thresholds and empirical debris-flow susceptibility models for southern California and the intermountain west indicate a strong influence of climatic and geologic settings on post-fire debris-flow potential. The linkages between wildfires, debris-flow occurrence, and global warming suggests that the experiences in the western United States are highly likely to be duplicated in many other parts of the world, and necessitate hazard assessment tools that are specific to local climates and physiographies.

Keywords Debris flow • Hazards • Risk • Climate change • Western USA • Southern California • Intermountain west USA

9.1 Introduction

An association between debris-flow occurrence and recent wildfire in mountain watersheds was recognized in southern California and northern Utah in the 1930 s and 1940s (Eaton, 1935; Bailey et al., 1947). Southern California (USA) is an area where this relationship between wildfires and debris flows is particularly well understood (Wells, 1987). There are several reasons for the commonly referred to "fire and flood cycle" in this area (Kotok and Kraebel, 1935). Southern California is within the Mediterranean climate chaparral biome. Consequently, it experiences wildfires nearly every year with most of them taking place immediately before the winter rainy season (Wells, 1987). Much of the burned area is on steep, brush-covered slopes drained by equally steep, short channels which facilitate debris flow occurrence.

The study of debris flows and wildfire received much of its continuing emphasis because of the dramatic increase in population and urbanization in southern California beginning during World War II and continuing to present. This placed many more

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people and ever greater amounts of property and infrastructure at risk from both wildfires and any subsequent debris-flow activity. However, due to the combination of population growth and increased wildfire occurrence and size throughout the western USA, the concern for risk from both wildfires and subsequent debris flows is no longer limited to southern California.

The purpose of this paper is to examine the relations between population growth, increased wildfire magnitudes and frequencies, climatic variability and debris-flow generation, to describe some of the tools presently available to assess the associated debris-flow hazards, and to consider the potential implications of climate change on these relations. Population growth has placed many more people, property and infrastructure at risk throughout the western USA. Coincident with population growth, wildfire occurrence and size is increasing in the western United States. Although this may reflect an increased probability of anthropogenically-caused wildfire (e.g. arson, downed power lines, car fires, etc.), we also describe how, in some settings, past fire suppression policies that have lead to greater natural fuel availability. Climatic variation may also have a role in increasing forest vulnerability to more frequent and bigger wildfires. Regardless of the specific importance of these factors, greater wildfire frequencies result in increased likelihood of precipitation-induced debris-flow events in recently burned areas.

To reduce the risk to the public, it is crucial to more effectively identify where post-wildfire debris flows might occur and the rainfall conditions that may trigger these events. These predictions are necessary to effectively allocate limited financial resources for warning and protective measures over large potentially affected areas. Tools to predict when within a storm debris flows might occur, the probability that a given drainage basin will produce a debris flow, and the potential volume of the event in southern California and the intermountain west, USA, are described.

Recognition that climate oscillations on interannual and decadal time scales influence wildfire occurrence and size has implications for debris flow risk. Debris flows will be more likely during time when climatic variation promotes greater likelihood for large stand-replacing wildfires. This effect suggests that debris flow risk might also be influenced by global warming. Less clear is whether global warming will affect the number or strength of storms that carry the potential for triggering debris flows.

9.2 Wildfire and Debris Flow Coincident Hazards

Wildfire represents a distinct natural hazard with many immediate and disastrous consequences. By the 1920 s and 1930 s, it appears that the dual disaster of post-wildfire flooding was being recognized in southern California (Wells, 1987). Eaton (1935) was one of the earliest southern California researchers to correctly recognize that some of what being described as flooding was actually the occurrence of debris flows, as described in his account of the January 1, 1934 event that affected the Los Angeles Basin towns of Montrose and La Crescenta. Wells (1987) notes the failure by later researchers to correctly identify debris flows even while accurately describing that phenomenon. By the 1970 s, researchers began to more fully recognize the hazards associated with precipitation-induced debris flows from recently burned areas (Scott, 1971; Wells, 1981, 1987). As such, agencies and scientists involved in post-wildfire emergency response now incorporate methods for assessing debris-flow potential into their evaluations (DeGraff and Lewis, 1989; DeGraff et al., 2007).

The local population understandably feels the worst is over if a wildfire is prevented from burning over their homes and communities. This was especially true in southern California in October 2003. More than 4,220 homes were destroyed by wildfires that year, and nearly all of them were in southern California (Radeloff et al., 2005). However, that wasn’t the end of the saga. Debris flows were triggered from many of the basins that had been burned by the Old and Grand Prix Fires in response to a late December 2003 storm event. Debris flows from two basins were responsible for the deaths of 16 people and costs for clean up and infrastructure repair were reported in the billions of US dollars (P. Mead personal communication, 2004). The often short time period between fire containment and storms that trigger debris flows adds a significant challenge to agencies and scientists responsible for protecting the public from these types of events. In addition to the lack of expectation, a second deceptive aspect of post-wildfire debris flows is that they can cause damage several kilometers from the actual fire boundary. While it is the effect of the wildfire on the vegetation and soil within the burned watershed that enables a debris flow to occur with the right triggering storm event, they can travel significant distances from their origin. A third characteristic that makes debris flows a significant concern is their speed in covering those distances. The debris flow impacting Camp St. Sophia, which was responsible for the greatest number of deaths, was estimated to be moving at about 4 m/s at the time of arrival (DeGraff et al., 2007) (Fig. 9.1).

A debris flow is composed of a slurry of finer-grained particles with large rock fragments including large boulders and woody debris entrained within it (Costa, 1984). Because debris flows are more viscous than flood waters, it maintains a relative coherent mass (Costa, 1984). The leading edge of the debris flow is typically a bouldery snout followed by a more viscous body that transitions to a very muddy water flow as it passed down a channel. Debris flow damage occurs by drag, buoyancy, lateral impact or burial (Campbell, 1985). Damage resulting from drag takes place as it passes by building foundations or bridge abutments. A frictional and differential pressure is exerted that can displace the structure. Buoyance damage results from the debris flow entraining an object like a vehicle or lifting a bridge off its foundation and rafting it to another location. Lateral impact primarily is damage inflicted by the large boulders or woody debris battering into structures or other obstructions within the debris flow path. Burial is common in low-gradient, wider reaches of the channel or in the runout area of the debris flow. Objects and structures within the runout area where the debris flow comes to rest may be partially or completely buried (Fig. 9.2). Levee deposits along the lateral margins of the debris-flow path more commonly cause partial burial.

While southern California may be widely recognized as a location where wildfires and debris flows commonly occur, many other parts of the western United States are subject to this combination of hazards. On September 1-2, 1994, debris flows were triggered in the recently burned watersheds on Storm King Mountain, Colorado in response to a torrential downpour (Cannon et al., 2001). Flows issued from fifteen channels onto or near Interstate Highway 70 trapping or engulfing thirty vehicles. Two people traveling with these vehicles were swept into the adjacent Colorado River

Fig. 9.1 Debris-flow damage at Camp St. Sophia in southern California. Fourteen people were killed at this site when the building they were taking shelter in (of which the rectangular concrete foundation in photo center remains) was swept away by the debris flow

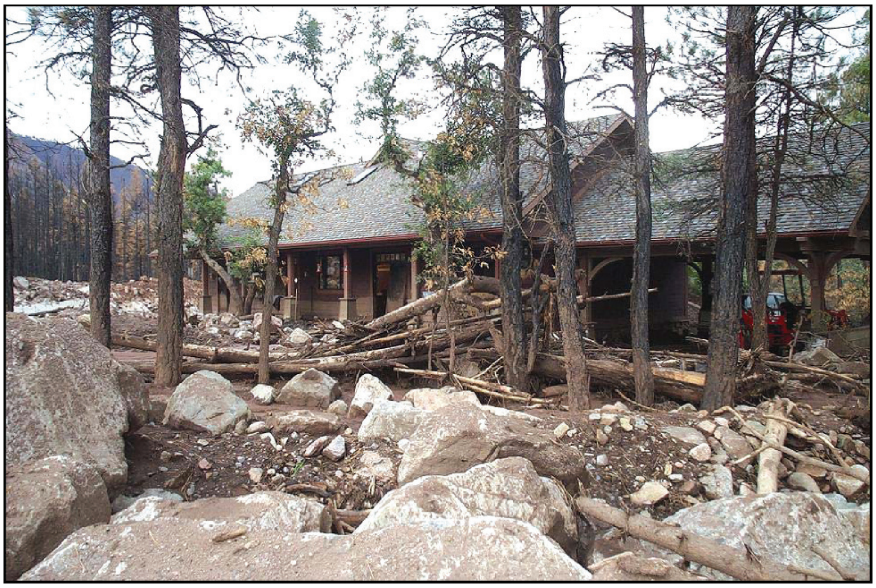

Fig. 9.2 House damaged by debris flow generated from 2002 Missionary Ridge Fire in southwest Colorado (USA)

resulting in their sustaining serious injury. Between 2000 and 2004, twenty-six debris flows were generated from seven wildfire areas in northern Utah (Giraud and McDonald, 2007). Major damage to five houses and minor damage to 27 others inflicted losses amounting to $500,000. Many of the basins burned by the Missionary Ridge and Coal Seam Fires in 2002 in Colorado responded to a series of summer thunderstorms by generating damaging debris flows (Cannon et al., 2003) (Fig. 9.2). In the Sierra Nevada of California, burned watersheds upslope from El Portal, a gateway community to Yosemite National Park, generated several debris flows in March 1991. Major damage was avoided partly because debris flow protective measures had been installed (DeGraff, 1994).

9.3 Increasing Threats

9.3.1 Expanded Urbanization

Among the geographic regions of the United States, the Federal government controls a much higher proportion of land within the western United States. It includes land designated as national parks, national forest, set aside as military reserves and land managed by the Bureau of Land Management. For example, these Federally-managed lands represent just a little more than 67% of the State of Utah. Consequently, the booming population growth occurs on the border of these undeveloped or wildland areas. Within in the last decade the term *wildland-urban interface*, has been coined to describe this urban and suburban development in or near wildland vegetation (Fig. 9.3). It is recognized as a focal point for a number of environmental issues, including increasing property losses to wildfires (Radeloff et al., 2005).

In addition to southern California, other parts of the western United States experienced population growth for a number of diverse reasons ranging from a burgeoning elderly population attracted to the warm, sunny Southwest to a better quality of life that coupled wide open spaces with increased recreational and employment opportunities. Between 1900 and 1990, the population of the southwestern United States (California, Nevada, Utah, Arizona, New Mexico and Colorado) increased by about 1,500%, while during the same period, the population in the entire United States only grew by 225% (Chourre and Wright, 2005). This has resulted in development patterns similar to southern California arising along the Wasatch Front in Utah, around Reno and Las Vegas, Nevada, the Colorado Front Range and the

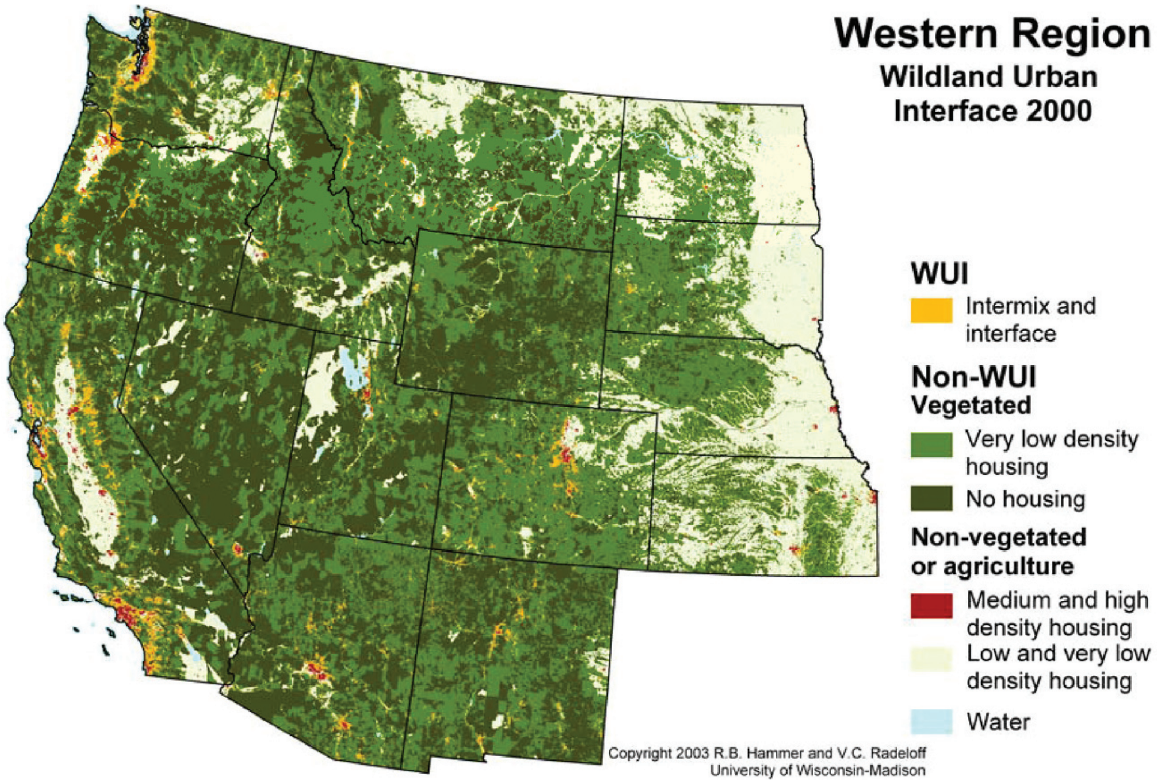

Fig. 9.3 Map of 2000 Wildland-Urban Interface in western U.S. (From Radeloff et al 2005)

Phoenix, Arizona and Albuquerque, New Mexico metropolitan areas (Fig. 9.4).

9.3.2 Increased Wildfire Frequency and Magnitude

The increase in wildfire occurrence is likely related to population. Radeloff et al. (2005) note human-caused fire ignitions are most common in the wildland-urban interface. As a recent example, they point out that human-caused ignitions were responsible for 43% of the fires during the record-setting 2000 wildfire season. There are many more opportunities for fire ignition with increased population during the dry, hot periods when vegetation is most vulnerable. Sparks from engines and activities such as welding, carelessness with fire from cigarettes to barbecues and fire setting by true arsonists to children experimenting with matches or fireworks are all more frequent occurrences with greater population. However, increased fire ignitions do not consistently account for the observed increase in number or size of destructive wildfires. For example, Keeley et al. (1999) contend that in the shrubland of southern California, any increase in fire starts has been largely offset by effective fire suppression.

The expansion of the wildland-urban interface and its attendant increase in population can affect the size of wildfires. Fighting wildfires tactically involves containing the fire to prevent it from growing larger and then controlling it until the wildfire is extinguished from a lack of fuel or application of retardant or water. Firelines are built by hand and machine to remove a swath of vegetation around the fire to deny it access to an additional fuels (Fig. 9.5). Fireline effectiveness during containment is increased by starting backfires to widen them. In a formerly rural area of scattered individual structures or small clusters of homes, it was possible to establish firelines across a broad front with little property loss. Urbanization limits the location of firelines and leaves far more property at risk. Keeley et al. (1999) note that the

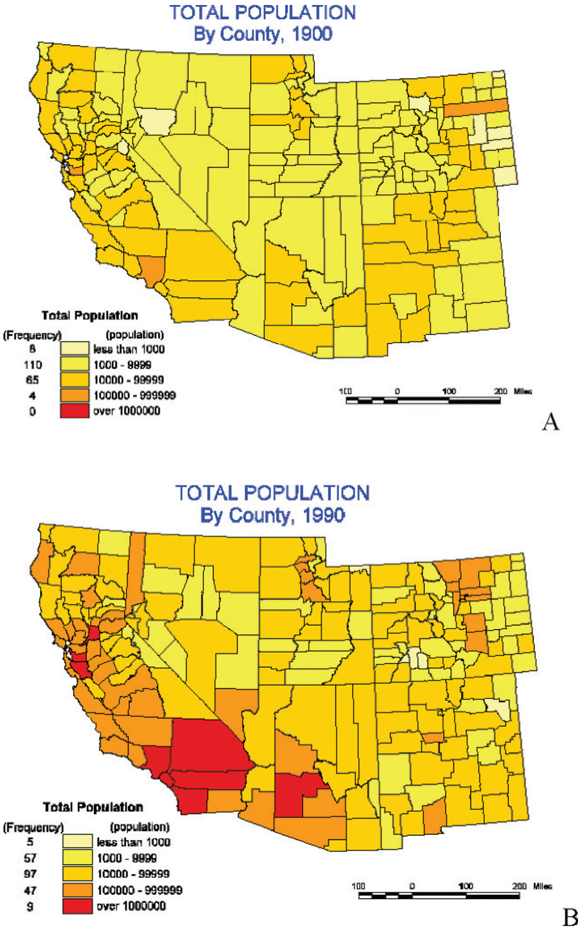

Fig. 9.4 Population change in the western USA between 1900 (**A**) and 1990 USA (**B**) (from Chourre and Wright, 2005)

Fig. 9.5 Fire line used for fire control of the 2007 Day Fire in the Topatopa Mountains of southern California. Dust rises from post-fire rehabilitation activity by large excavators

expansion of the urban-wildland interface makes it more and more difficult to put measures in place that would limit California shrubland wildfire from becoming larger and increasingly destructive.

Increased wildfire occurrence and size has another human component as well as a natural one. Over the last 80 years, suppression of wildfires was the common practice on national forests and other Western wildlands under both Federal and State control. This included fires triggered by both natural and human causes. The role of fire as a natural component of forest ecology was fully understood in only the last few decades. While efforts are being made to reintroduce fires as a frequent and natural aspect of these forest ecosystems, it is made difficult by the build up of fuels, (e.g. fallen woody material), resulting from previous suppression activities and grazing (Minnich, 1989; Allen et al., 1996; Grissino-Meyer et al., 2004). When fires occur in areas with heavy fuel loads, they are much more conducive to large and intense wildfires. This effect varies in importance among different wildland ecosystems within the western United States. While Grissino-Meyer et al. (2004) demonstrated that changes in forest species and density attributed to fire suppression result in increased fire frequencies and extents in southwestern Colorado, build up of high fuel loads, and long return intervals for large, intense fires, is expected in the Lodgepole Pine forests of northwestern Montana (Kauffman, 2004). Allen et al. (1996) found that the introduction of grazing animals in southwest USA Ponderosa Pine forests removed the fine fuels that carried frequent, low-intensity fires which served to prevent accumulations of significant fuel loads, and thus resulted in a changed the fire regime. However, Keeley and Fotheringham (2000) used historical records to demonstrate that the natural fire regime of southern California chaparral ecosystems in the past is little different from today. It remains dominated by wildfires driven by intense Santa Ana windstorms. Therefore, fuels treatments that might reduce fuel loads in northern Montana forests would be less likely to have the same beneficial results in southern California chaparral ecosystems.

The natural component responsible for periodically greater wildfire activity is climate. A number of studies have demonstrated how variations in climate resulting from atmosphere-ocean interactions influence fire occurrence and severity. In the southwestern

United States, large areas are burned after dry springs associated with the La Nĩna or high phase of the El Niño-Southern Oscillation (ENSO) phenomena in the Pacific Ocean. This association was evident from fire scar and tree growth chronologies covering the period of 1700–1905 and extended to 1985 by fire statistics (Swetnam and Betancourt, 1990). Their research showed large fires associated with deficient spring precipitation and reduced tree growth tied to the high phase of the ENSO. Fires over a large area were found to be synchronous in a manner which implies a greater control by seasonal climatic influence rather than just fire weather.

Similarly, the occurrence of large wildfires in northern California and Oregon reflect the influence of the ENSO and the Pacific Decadal Oscillation (PDO). Trouet et al. (2008) were able to link these synoptic-scale circulation patterns to interannual variations in specific fire weather indices. These indices are associated with fires becoming large or showing erratic behavior. Synoptic-scale circulation conditions that induce low atmospheric stability and humidity moisture levels produce high indices associated with widespread wildfires.

Westerling et al. (2006) see climate as the principle force behind wildfire risk at the interannual to decadal scales. Their conclusions are that climate variability at the interannual scale influences how flammable the forest fuels are when an ignition occurs. This would include both dead and live vegetation within the forest. These results are consistent with the findings of Trouet et al. (2008). Climate acting on a decadal scale alters the structure of vegetation communities (Westerling et al., 2006). Fuel continuity and drought tolerance of dominant species are identified as significant components affecting fire regime responses.

On these same interannual timescales affecting fire occurrence and severity, there is a connection to fire-related geomorphological events Pierce et al. (2004). Dating of fire-related sediment deposits on alluvial fans suggests that shifts in fire regimes also changed fire-related geomorphological events. In the western Ponderosa forests and subalpine forests of Yellowstone National Park, their data suggests that warmer periods experienced severe droughts, stand-replacing wildfires and large debris-flow events. Therefore, the increased threat of more and larger wildfires carries within it the increased threat of subsequent debris-flow occurrence.

The increased risk of wildfire-related debris flow highlights the need for methods to quantify the potential hazards posed by debris flows produced from burned watersheds. Science-based information on post wildfire debris-flow hazards is necessary to mitigate the impacts of fire on people and their property, and on natural resources. To reduce risk, it is crucial to more effectively identify the rainfall conditions that may trigger debris flows, where they might be generated, and how big they might be. Identification of potential debris-flow hazards from burned drainage basins is necessary to develop effective and appropriate mitigation strategies and decisions regarding emergency warnings, evacuation timing, and routes. Application of predictive models before the occurrence of wildfires can help identify potentially hazardous drainage basins and thus direct planning and use strategies for forests and areas slated for future development.

Tools for Assessing Debris-Flow Hazards from Recently Burned Areas

9.3.3 Rainfall Conditions and Intensity-Duration Thresholds

Debris flows generated during rain storms on recently burned areas have destroyed lives and property throughout the Western USA. Definition of the rainfall conditions that triggered these events, and of the rainfall intensity-duration threshold conditions for their occurrence, is a critical first step in a hazard assessment. Field evidence indicates that unlike landslide-triggered debris flows, these events have no identifiable initiation source and can occur with little or no antecedent moisture (Cannon et al., 2008). In addition, the great majority in the flows is derived from channel erosion and incision, rather than from an initial landslide event (Santi et al., 2008). Given these physical differences, rainfall and threshold conditions will be different from those that trigger landslide-triggered debris flows in a given location. Using rain gage and response data from five fires in Colorado and southern California, Cannon et al. (2008) documented the rainfall conditions that have triggered post-fire debris flows and developed empirical rainfall intensity-duration

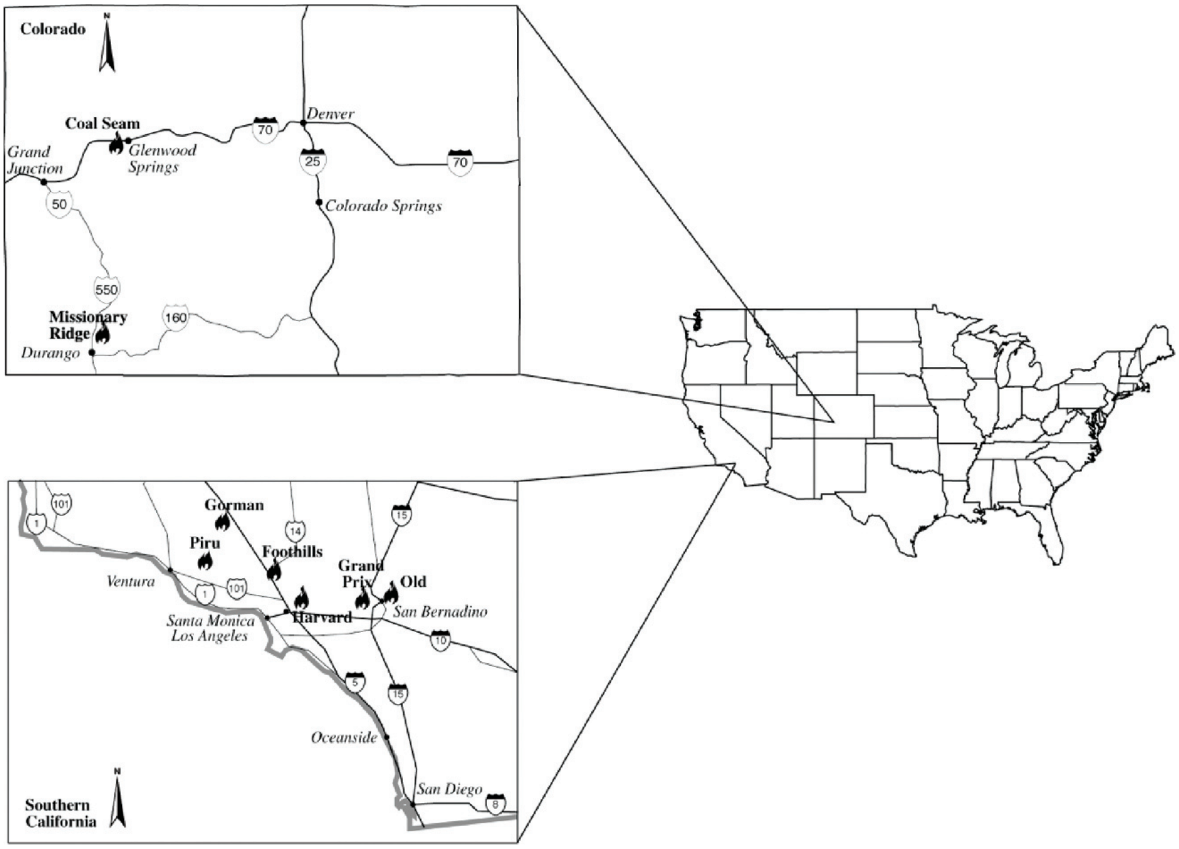

Fig. 9.6 Maps showing locations of fires in the study by Cannon et al. (2008)

thresholds for the occurrence of debris flows and floods following wildfires in these settings (Fig. 9.6).

Debris flows were produced from 25 recently burned basins in Colorado in response to 13 short-duration, high-intensity convective storms. Debris flows were reported after as little as six to 10 min of storm rainfall. About 80% of the storms that generated debris flows lasted less than three hours, with most of the rain falling in less than one hour. The debris-flow triggering storms ranged in average intensity between 1.0 and 32.0 mm/h, and had recurrence intervals of two years or less. Threshold rainfall conditions for floods and debris flows sufficiently large to pose threats to life and property from recently burned areas in south-central, and southwestern, Colorado are defined by:

$$I = 6.5D^{-0.7} \tag{9.1}$$

and

$$I = 9.5D^{-0.7}, \tag{9.2}$$

where I = rainfall intensity (in mm/hr) and D = duration (in hours). These thresholds define storm conditions with 2-year, or less, recurrence intervals. The threshold for southwestern Colorado is slightly higher than that for south-central, reflecting the larger and lower gradient drainage basins in the southwest.

Debris flows were generated from 68 recently burned areas in southern California in response to long-duration frontal storms (Cannon et al., 2008). The flows occurred after as little as two hours, and up to 16 h, of low intensity (2–10 mm/h) rainfall. The storms lasted between 5.5 and 33 h, with average intensities between 1.3 and 20.4 mm/h, and had recurrence intervals of two years or less. Threshold rainfall conditions for life- and property-threatening floods and debris flows during the first winter season following fires in Ventura County, and in the San

Bernardino, San Gabriel and San Jacinto Mountains of southern California represent recurrence intervals of less than or equal to two years and are defined by:

$$I = 12.5D^{-0.4}, \tag{9.3}$$

and

$$I = 7.2D^{-0.4}. \tag{9.4}$$

Threshold conditions change with vegetative recovery and sediment removal following a wildfire. A threshold defined for flood and debris-flow conditions following a year of recovery for the San Bernardino, San Gabriel and San Jacinto Mountains of:

$$I = 14.0D^{-0.5} \tag{9.5}$$

is approximately 25 mm/h higher than that developed for the first year following fires (Cannon et al., 2008).

The thresholds defined by Cannon et al. (2008) are significantly lower than most identified for unburned settings (Fig 9.7). This difference can be attributed to the differences between extremely rapid, runoff-dominated processes acting in burned areas and longer-term, infiltration-dominated processes on unburned hillslopes.

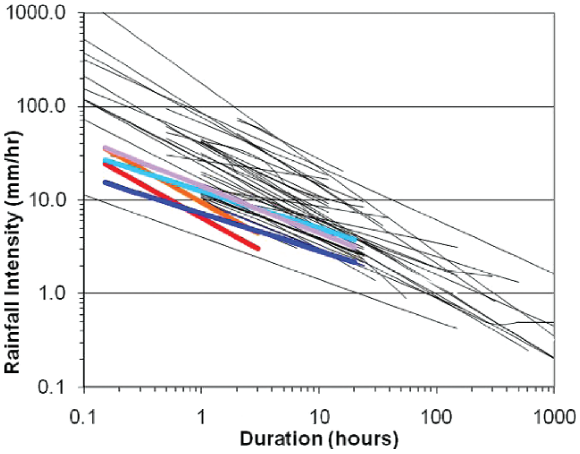

Fig. 9.7 Rainfall intensity-duration thresholds in Cannon et al. (2008) compared with a compilation of worldwide, regional, and local thresholds by Guzzietti et al. (in press); (http://rainfallthresholds.irpi.cnr.it/) – black lines. Old and Grand Prix Fire – *dark blue line*; Coal Seam Fire – *red line*; Missionary Ridge Fire – *orange line*; Piru Fire – *light blue line*; second winter following fire – *violet line*

This work illustrates three important points regarding the rainfall conditions that trigger debris flows for recently burned areas. Both convective thunderstorms and longer-duration synoptic storms can trigger debris flows from susceptible recently burned areas, and the conditions that result in debris flows are frequently occurring, or low-recurrence interval (<2 to 2 year) events. In addition, the conditions that trigger debris flows from recently burned areas vary considerably both within and between different climatic settings, indicating the necessity of separate thresholds for distinct geologic and climatic settings.

Based on the assumption that rainfall characteristics are the primary drivers of a post-wildfire runoff response, the thresholds presented here can provide guidance for rudimentary warning systems and planning for emergency response in similar settings. However, rainfall thresholds alone are not able to provide information on specific areas that are likely to experience post-fire debris flows or the size of potential events.

9.3.4 Debris-Flow Probability and Volume Models

A set of empirical models have recently been developed to estimate the probability of post-wildfire debris-flow activity and the volume of the response (Gartner et al., 2008) for both basins within the inter-mountain west and southern California.

A pair of models that calculate, for a given rainfall event, the probability of debris-flow production from individual drainage basins were developed using logistic regression analyses of a database from 388 basins that were burned by 15 recent fires located throughout the U.S. Intermountain West, and a separate database of information for 37 basins in 13 recent fires in southern California (unpublished data). The database used to develop the models consists of a set of potential explanatory variables that characterize runoff processes in burned basins (e.g. Moody et al., 2008; Beven, 2000). These variables include different measures of basin gradient, basin aspect, burn severity distribution within the basin, soil properties, and storm rainfall conditions in basins that were characterized either as having produced debris flows, sediment-laden floods, or having a negligible response. The statistical analysis consisted of building the model with the strongest predictive capability from the potential explanatory variables. The models describe debris-flow probability in the form

$$P = e^x / l + e^x, \tag{9.6}$$

Where P is the probability of debris flow. For the intermountain west,

$$x = -0.7 + 0.03(\%A_{30}) - 1.6(R) + 0.06(\%B_{H+M}) + 0.2(C) - 0.4(LL) + 0.07(I), \tag{9.7}$$

where $\%A_{30}$ is the percentage of the basin area with gradients greater or equal to 30%, R is basin ruggedness (calculated as the change in basin elevation divided by the square root of the basin area (Melton, 1965)), $\%B_{H+M}$ is the percentage of the basin area burned at a combination of high and moderate severity, C is the soil clay content (in percent), LL is the soil liquid limit, and I is average storm rainfall intensity (in mm/h). A model sensitivity (the percentage of basins known to have produced debris flows that are predicted by the model to have a probability of occurrence greater than 50%) of 44% was calculated for this model. Comparison of the p-values of the independent variables indicate that basin ruggedness and the percentage of the basin burned at high and moderate severity have the largest effect in the model.

For southern California,

$$x = -20.8 + 1.6(InE) + 0.1(S) - 0.7(InL) + 0.04(\%B_H) - 0.2(C) + 7.24(O) + 2.5(InI_3), \tag{9.8}$$

where E is the basin relief (in m), S is the average basin gradient (in percent), L is basin length (in m), $\%B_H$ is the percentage of the basin area burned at high severity, C is the soil clay content (in percent), O is the percent soil organic matter (by weight), and I_3 is the peak three hour rainfall intensity (in mm/hr). Model sensitivity is 76% and, in contrast with the intermountain west model, the peak three hour rainfall has the largest effect.

The differences between the controlling variables in the intermountain west and southern California models point to the effects of local climatic and physiographic setting on post-fire debris-flow susceptibility. To adequately characterize the hazards, it is necessary to develop models that are specific to each setting.

Models for estimating the volume of material that may issue from a basin mouth, for a given rainfall event, in the U.S. Intermountain west and southern California were developed by Gartner et al. (2008) using a series of multiple linear regression analyses on a database from 50 basins burned by eight fires located throughout the western U.S., and a separate database consisting of information from 25 basins burned by seven recent fires in southern California. In addition to measures of the volume of material either eroded from the channel network or deposited in a debris basin, the databases include the same independent variables as do the probability databases. The statistical analysis consisted of building the model with the strongest predictive capability from each of the two databases. The strongest models for both the western U.S. and southern California are virtually identical, and can be represented as:

$$In\ V = 7.0 + 0.6(InA_{30}) - 0.6(B_{H+M})^{1/2} + 0.2(T)^{1/2} + 0.3, \tag{9.9}$$

where V is debris flow volume (in m^3), A_{30} is the area of the basin with slopes greater than or equal to 30% (in km^2), B_{H+M} is the area of the basin burned at high and moderate severity (in km^2), T is the total storm rainfall (in mm), and 0.3 is a bias correction that changes the predicted estimate from a median to a mean value (Helsel and Hirsch, 2002). The R^2 and standard error of the residuals for this model are 0.83 and 0.90 (Gartner et al., 2008).

9.3.5 Application of Models for Hazard Assessments

These models can be quickly implemented on a GIS platform to generate debris-flow hazard maps either before, or immediately following, wildfires. Application of the probability model for southern California and the volume model are illustrated using information from the 2008 Poomacha Fire in southern California. This fire burned nearly 50,000 acres in northern San Diego County in October of 2007. One hundred thirty eight homes and 78 outbuildings were lost in this fire.

Figure 9.8A shows a map of the probability of debris flow occurrence for the Poomacha Fire that was generated by calculating a probability for each basin based on the distribution of burn severity, gradient and soils within the basin and the probability model in response to 57.15 mm of rainfall in 3 h (a 10-year recurrence storm). Calculated values are then parsed into classes. Similar maps of the volume of material that can issue from basin outlets are generated using a similar procedure (Fig. 9.8B). The probability and volume rankings can be combined to give a relative measure of hazards for each basin (Fig. 9.8C). This combination serves to identify the spectrum of possible responses, from those basins that are most likely to produce the largest debris-flow events, to basins with a moderate probability of producing moderately-sized events, to basins with a low probability of producing small events. These maps provide information necessary to prioritize areas for pre-fire forest restoration efforts and post-fire erosion mitigation in southern California.

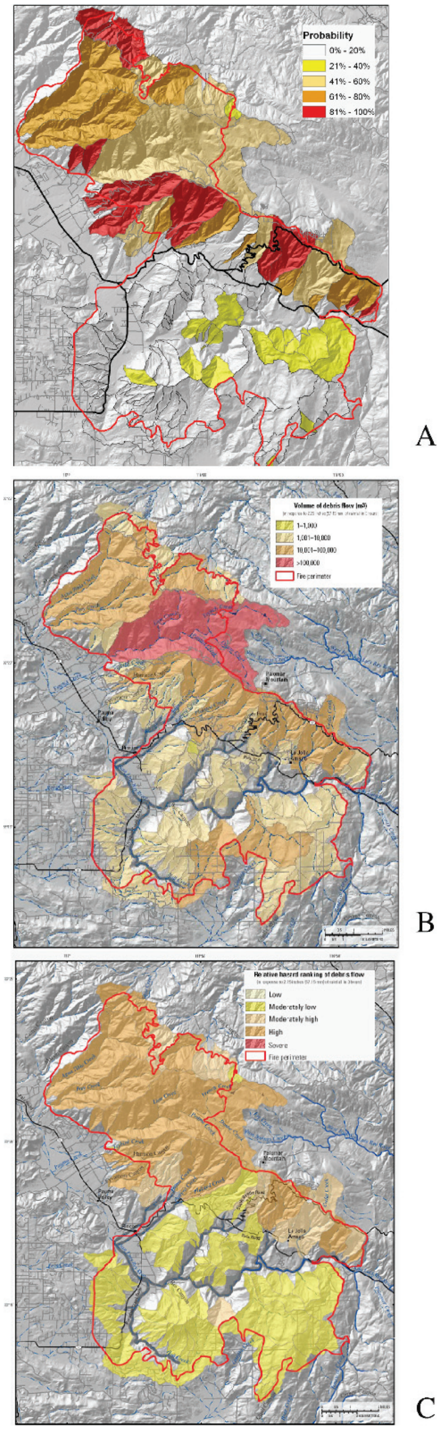

Fig. 9.8 Maps of debris flow (**A**) probability, (**B**) volume and (**C**) combined relative hazards for 2007 Poomacha Fire in southern California, USA in response to 57.15 mm of rainfall in 3 h

9.4 Implications in Response to Climate Change

Westerling et al. (2006) demonstrated that large wildfire activity during the period 1970–2003 in the western United States increased suddenly and markedly in the mid-1980s. While this effect is widespread, they found that the greatest increases of higher large-wildfire frequency, longer wildfire durations and longer wildfire seasons were in mid-elevation, northern Rocky Mountain forests. This is an important point because past land use practices, in general, and wildfire suppression efforts, in particular, have been advanced as the cause of increased wildfire occurrence and size. While Westerling et al. (2006) do not discount an effect from land use practices, they conclude that it is an overlay on the more significant control exerted by climate. Because the northern Rocky Mountains have experienced far less land use effect than other areas in the western United States, it makes clear the overall influence of climate on wildfire size and frequency.

Statistical associations between wildfire and hydroclimatology, particularly for northern Rocky Mountain forests, were found to be climate-driven by reduced winter precipitation and an early spring snowmelt (Westerling et al., 2006). Data from 1,166 large (defined as greater than 400 ha) forest wildfires between 1970 and 2003 permitted a detailed fire-climate analysis. A notable shift in the 1980s was found. Earlier wildfire observations defined a regime of a few large wildfires lasting about one week. This has altered to much more frequent large wildfires lasting about five weeks. This shift in the typical wildfire pattern coincides with a shift to unusually warm springs, longer summer dry seasons and drier vegetation. These conditions are linked to reduced winter precipitation and an earlier spring snowmelt during this same period (Westerling et al., 2006). Because the hydrology of the western United States is dependant on the winter snowpack, any reduction in accumulation and persistence into the spring means drier conditions earlier in the season for the forests (Running, 2006).

Whether this is a short-term trend or a long-term one has significant implications for both large wildfire and debris-flow occurrence. While the underlying mechanisms for this hydroclimatic shift associated with increased large wildfires in the 1980s can be argued, Westerling et al. (2006) point out that nearly every climate-model projects warmer springs and summers occurring over the region in upcoming

Fig. 9.9 Smoke plumes from extensive fires burning in southern California in the fall of 2007 (**A**), and Greece (**B**) in the late summer of 2007 illustrating potential application of the fire-flood-debris flow paradigm from USA to other settings throughout the world (images from NASA)

decades. This means future conditions will favor the occurrence of large wildfires throughout the western United States.

Backlund et al. (2008) come to a similar conclusion. Fire-debris chronologies on alluvial fans and fire scars in tree rings record warmer and drier periods over the last million years being associated with more frequent and severe wildfires in the western United States. Based on modeling of global climate change, they suggest that large, stand-replacing wildfires will generally increase in frequency over the next few decades.

In addition to an increase in frequency and magnitude of fires, Wentz et al. (2007) found that increased warming can result in increased precipitation (on a global scale). Given that short-recurrence, garden-variety storms are generally sufficient to generate debris flows from burned areas, even small increases in precipitation will magnify the potential for debris flows from these areas.

The link between increased wildfires with their positive influence on debris-flow occurrence and global warming suggests that the experiences in the western United States are highly likely to be duplicated in many other parts of the world. Even if this were not the case, the continued population growth and urbanization within the Mediterranean climate chaparral biome around the world would still represent a significant increase in debris-flow risk to human populations. The multiple large fires in Greece in late summer of 2007 are only the latest in series of significant wildfires events within this extensive biome (Fig. 9.9).

9.5 Conclusions

In southern California and the intermountain west of the USA, debris flows generated from steep, short, recently-burned basins pose significant hazards. Increases in the frequency and size of wildfires throughout the western USA can be attributed increases in the number of fire ignitions, fire suppression, and climatic influences. Increased urbanization throughout the western USA, combined with the increased threat of more and larger wildfires, carries within it the increased risk from debris-flow occurrence. Preventing increased debris flow risk requires effective efforts to reduce the vulnerability of elements at risk (people, property, etc.). In the post-wildfire environment, time, money and physical constraints make imposition of mitigating measures at all possible locations an impossible task. Only by focusing these resources on the critical locations can effective risk reduction be achieved. This makes rapid identification of those critical locations a vital concern. Empirical models linked to a GIS environment are proving to be one of the best scientific means for this identification process.

Differences between rainfall thresholds and empirical debris-flow susceptibility models for southern California and the intermountain west indicate the strong influence of climatic setting on post-fire debris-flow potential. The link between increased wildfires with their positive influence on debris-flow occurrence and global warming suggests that the experiences in the western United States are highly likely to be duplicated in many other parts of the world, and the necessity of hazard assessment tools for additional climatic settings.

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