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Uncertainties in Predicting Debris Flow Hazards Following Wildfire

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ABSTRACT

Wildfire increases the probability of debris flows posing hazardous conditions where values-at-risk exist downstream of burned areas. Conditions and processes leading to postfire debris flows usually follow a general sequence defined here as the postfire debris flow hazard cascade: biophysical setting, fire processes, fire effects, rainfall, debris flow, and values-at-risk. Prediction of postfire debris flow hazards is a problem of identifying and understanding the spatial and temporal interactions within this cascade. Models exist that can predict each or several components of the cascade but no single model or prediction approach exists with capacity to link the entire sequence. Assessment of the uncertainty inherent with each of these approaches is limited and compounds if these predictive approaches are integrated or otherwise linked. We summarize present knowledge of the processes involved in this postfire debris flow hazard cascade and identify uncertainties in terms of knowledge gaps, contradictions in current process understanding, stochastic system variables, and limits to data to support hazard prediction. Understanding these uncertainties can improve delineation of areas threatened by postfire debris flows, can guide future research, and, when addressed, contribute to development of comprehensive and robust modeling and prediction systems that may ultimately reduce threats to values-at-risk.

19.1. INTRODUCTION

Debris flows are rapidly moving masses of water, fine sediments, rocks, and often woody material [*Iverson*, 1997] that constitute an extreme form of postfire erosion. Their probability is heightened following moderate- to high-severity wildfire on steep slopes in forested and shrub-dominated environments, such as sage and chaparral. These extreme events are natural processes that scour low-order channels, work as a major driver of landscape evolution [*Kirchner et al.*, 2001; *Pierce et al.*, 2004] and impact aquatic ecosystems. Depending on the location and timing of the debris flows relative to other disturbances, sediments and woody debris transported by debris flows into stream systems may periodically enhance or restore the complexity of aquatic habitats, or threaten the stability of fish populations [*Gresswell*, 1999; *Rieman et al.*, 2003].

Debris flows also pose hazardous conditions where values-at-risk exist downstream of burned areas and can threaten human life and property. While comprehensive losses are not well documented, multiple accounts report loss of life, damaged and destroyed infrastructure [*USGS*, 2015a], and impaired drinking water supplies [*Bladon et al.*, 2014; *Smith et al.*, 2011]. Losses are likely to increase given the expectation of more frequent large and severe fires [*Bachelet et al.*, Chapter 17, this volume; *Carvalho et al.*, 2010; *Holz and Veblen*, 2011; *LePage,* Chapter 18, this volume]

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COMPONENT	PRE-CONDITIONS AND PROCESSES
Biophysical setting	Steep, convergent, and vegetated hillslopes
Fire processes	Biomass consumption and soil heating
Fire effects	Vegetation disturbance and soil change
Rainfall	Timing, intensity, and duration
Runoff	Accumulation, convergence, and entrainment
Debris flow	Initiation, volume, flow path, and deposition
Values-at-risk	Location, susceptibility, value, and mitigation
Hazard	Probable loss

Figure 19.1 The postfire debris flow hazard cascade with the sequence of preconditions and processes leading to hazardous conditions. The down arrows reinforce the linear nature of this conceptual model where the generation of hazardous conditions is contingent upon the preceding component steps. This hazard cascade offers logic for future development of a comprehensive postfire debris flow hazard prediction framework.

and growing population and infrastructure development at the wildland-urban interface [*Calkin et al.*, 2011a; *Theobald and Romme*, 2007].

Not all burned areas subjected to heavy rainfall produce debris flows, suggesting that some combination of burn conditions, landform, and rainfall characteristics influence susceptibility to debris flows following fire [*Cannon and Gartner*, 2005]. Prediction of postfire debris flow hazards is a problem of identifying and understanding the spatial and temporal sequence of interactions of multiple preconditions and processes. We refer to this sequence as the postfire debris flow hazard cascade (Fig. 19.1). First, the biophysical setting must include flammable vegetation on a steep, concave hillslope. Second, a moderate- to high-severity fire must occur (fire processes) that removes of a significant amount of the vegetation and changes soil properties (fire effects). Next, rainfall of sufficient intensity and duration to produce overland flow (surface runoff) must follow the fire. Runoff must accumulate and converge, entraining sediments, and flowing with sufficient force to down-cut and initiate a debris flow. The flowing mass of debris must intersect values-at-risk with sufficient volume and force to cause damage and loss. Without threat to valued resources, there is no hazard.

The level of understanding of processes and process interactions varies among the hazard cascade components rendering differing levels of uncertainty in efforts to predict fire-related debris flow hazards. For example, the physics of debris flows and general debris flow behavior have been thoroughly studied [*Iverson*, 1997; *Jakob and Hungr*, 2005] while process-based understanding of fire behavior is emerging [*Finney et al.*, 2013] and process-based linkages between fire behavior and fire effects are poorly understood [*Hyde et al.*, 2013]. Further, the stochastic nature of environmental processes (e.g., fire ignitions and rainfall distribution) introduces additional uncertainty throughout the hazard cascade.

Models exist that can predict each or several components of the hazard cascade but no single model or prediction approach exists with capacity to link the entire sequence of preconditions and processes. The behavior of a fire can be modeled at one point in time given a single set of fuels and weather conditions, from which fire spread and intensity can be estimated [*Finney*, 2006]. Effective prediction of fire spread under active fire conditions can be accomplished using short-term weather predictions and a suite of weather scenarios based on historic weather patterns [*Finney et al.*, 2011b].This ensemble modeling approach accounts for the uncertainty of fire behavior under shifting weather patterns and has been incorporated into decision support systems [*Calkin et al.*, 2011b]. Burn probabilities and fire size distributions have been modeled across very large landscapes over extended time frames [*Finney et al.*, 2011a] and used to support prioritization of fuel treatments [*Ager et al.*, 2014].

Models of vegetation change from fire combined with crosswalks or rule sets link vegetation changes to alterations in ecosystem processes [*Black and Opperman*, 2005]. Empirical rainfall intensity-duration thresholds provide decision support for assessing the probability of postfire floods and debris flows throughout the western United States [e.g., *Cannon et al.*, 2008]. Probabilistic models have been developed to determine the binary occurrence of postfire debris flows based on fire severity, landform, soils, and other factors [e.g. *Gartner et al.*, 2015; *Hyde et al.*, 2015]. Several of the above-mentioned approaches have been combined, integrating prediction of fire intensity and spread and the estimation of vegetation consumption for use in probabilistic debris flow occurrence models [*Haas et al.*, Chapter 20, this volume].

General debris models estimate entrainment of materials during debris flow development, accumulated debris volume, and debris flow run-out and deposition [*Ghilardi et al.*, 2001; *Luna et al.*, 2012; *Luna et al.*, 2014]. A model developed to map the transport and impact of aqueous contaminants in streams and rivers [*Leidos Corp.*, 2014; *Samuels et al.*, 2006] is being modified to support fire management decisions including threats in the event of misapplications of fire retardant chemicals and from sediments transported from burned areas [*Hyde*, 2009]. Finally, a tool to support benefit-cost analysis for postfire emergency response treatments combines spatially explicit assessment of potential debris flow source with values-at-risk downstream with estimates of probable debris flow and flooding occurrence with probable loss [*Calkin et al.*, 2007].

Some of these approaches to predicting components of the postfire debris flow cascade have been subject to verification. However, there is limited if any assessment of the uncertainty inherent with each of these approaches, much less consideration of compounding uncertainties if these predictive approaches are integrated or otherwise linked. The many sources of uncertainty make accurate prediction of postfire debris flow occurrence complex. Further, these uncertainties have not been comprehensively identified or discussed. This information is needed to improve delineation of areas threatened by postfire debris flows and thus facilitate protection of human life and property, ecosystems, and ecosystem services.

In this chapter, we first summarize present knowledge of the processes involved in this postfire debris flow hazard cascade and then identify uncertainties in terms of knowledge gaps, contradictions in current process understanding, and stochastic system variables. We also discuss uncertainty in the data used to support current modeling approaches. The identified knowledge gaps can guide future research and, when addressed, contribute to development of comprehensive and robust modeling and prediction systems that may ultimately reduce threats to values-at-risk. We address two phases of postfire debris flow hazards: direct impacts from a debris flow mass and impaired water quality from sediments deposited into streams by debris flows. This discussion also considers two planning and analysis domains: hazard assessment following fire and prefire planning to predict both future fire and resulting postfire debris flows.

19.2. BIOPHYSICAL SETTING

The biophysical setting for postfire debris flows includes a combination of forested or shrub-covered landscapes, steep slopes (>25%), convex terrain, erodible soils, and stored debris. The probability of debris flows is much increased in watersheds that experience moderate or high-severity fire [*Cannon et al.*, 2010; *Gartner et al.*, 2008], suggesting the landscape must be prone to crown fires during which the majority of the forest canopy is consumed. Factors controlling crown fires include the spatial variability of forest structure or, more specifically, whether surface fire can ascend up "ladder fuels" into the upper canopy, a common condition in a multiage stand, and whether stands are of sufficient density. However, the physical conditions of the stand are not enough to predict crown fire; certain weather conditions, including high winds, are generally necessary for crown fire to be sustained. Where crown fires occur without surface fires, erosion risk is reduced, as undisturbed vegetation stabilizes the soil surface and severe surface erosion generally does not occur where vegetation is intact [*Jenkins et al.*, 2011; *Prosser and Williams*, 1998; *Wondzell and King*, 2003].

Under stable conditions, erodible materials (including soil, rock fragments, woody debris and other organic material) accumulate slowly over time on hillslopes and within hillslope hollows and channels [*Santi et al.*, 2008]. The amount of stored material available to be entrained and incorporated into a debris flow depends on the rock type, the local weathering conditions, and the time since the last fire [*Jenkins et al.*, 2011]. The last factor is in part determined by the fire return interval, which varies by region and vegetation type and can range from less than 10 to hundreds of years [*Oliveira et al.*, 2012; *Westerling et al.*, 2011]. Several soil properties also control the probability that debris flows will occur, such as clay content and organic matter, among others that increase or decrease occurrence probability [*Cannon et al.*, 2010].

Topography exerts two strong effects through curvature and slope. Curvature affects debris flow initiation as concave and therefore convergent contributing areas typically focus sediment-laden flows into existing swales [*Cannon*, 2001; *Hyde et al.*, 2014], although debris flows have been observed to originate on planar or flat slopes in very steep areas as well [*Neary et al.*, 2012]. Slope is particularly important in relation to the size of contributing areas, with steeper slopes generally requiring smaller upstream areas generating surface runoff to initiate debris flows than where slopes are less steep [*Stock and Dietrich*, 2006; *Hyde et al.*, 2014]. Further discussion of interactions between slope, curvature, and debris flow probability follows below in the section on initiation and mobilization.

Sources of uncertainty related to physical setting include the susceptibility of the vegetation structure to fire, time since last fire and therefore level of fuel accumulation, properties of the unburned soils, and limited understanding of the interactions of hillslope geometry (steepness and curvature) relative to fire effects. Mapping of forest stand conditions is reasonably thorough for all forested lands within the United States [*USGS*, 2009] and throughout Europe and Australia. However, given vegetation growth patterns, local conditions vary and the existence of forest structure mapping for other fire-prone regions throughout the world is uncertain. Mapping of soil properties poses similar uncertainty. Current soil maps in the United States were meant for broadscale regional comparisons [*Lathrop et al.*, 1995], not to capture the smaller-scale variability of critical properties of soils within the upper hillslope regions where debris flows initiate. European soil databases are more detailed and can more reliably provide soil property information to parameterize hazard prediction models.

19.3. FIRE PROCESSES

Fire processes and how fire behaves on the landscapes control the spatial variability and magnitude of fire effects. Fire propagates or spreads by a physical process that spawns a series of ignitions across the landscape. This physical process of surface fire spread has been widely modeled as propagating by thermal radiation where heat energy is transferred by electromagnetic waves [e.g., *Rothermel*, 1972]. However, recent work has shown that radiation is inadequate to ignite fine fuels, and that direct flame contact and more specifically ignition by buoyant gases are the more likely mechanism [*Finney et al.*, 2010; *Finney et al.*; 2015]. In addition, the mechanisms of crown fire spread (the spread of fire in the vegetation canopy usually leading to full canopy loss) are not well understood. Further, in current models, there is a degree of uncertainty in the rate of spread, fire intensity, and flame length calculations, factors that influence fire extent and degree of surface vegetation loss and soil heating, resulting in part from a number of questionable modeling assumptions. For example, fire spread models assume homogeneity of fuels when fuels are commonly not homogenous, use a discrete set of fuel models to map the landscape when a nearly infinite array of combinations of fuels is possible, and use a constant wind speed and direction when wind speed and directions typically vary across small distances and time steps.

Regardless of the mechanism for fire spread and these uncertainties, current models have been empirically tuned so that they predict physical properties of the fire (such as intensity, heat release, and rate of spread) well enough for the models to be useful during wildfire incidents and for landscape assessment [*Alexander and Cruz*, 2011; *Finney et al.*, 2011b]. While fire physics are not well understood [*Finney et al.*, 2010], a suite of models allows for reasonable prediction of the number of fires, their size, and intensity [*Finney et al.*, 2011a]. Because these models can be run over long time frames, simulating tens of thousands of possible fire seasons, a probability distribution for flame lengths (which depend on wind, fuel moisture, and direction of the fire) at each cell of a rasterized landscape can be generated. Translating these flame lengths into fire effects and impacts on highly valued resources is more difficult, and currently depends on expert opinion [*Thompson et al.*, 2010] introducing uncertainty related to decisions regarding ecological effects as well as valuation. In the postfire landscape, the extent of the fire and its behavior are already known, reducing overall uncertainty of fire behavior and fire effects. However, in the planning context, the extent and behavior of future fires are highly uncertain since fires will occur in response to stochastic and therefore very unpredictable patterns of ignition and weather conditions [*Riley and Thompson*, Chapter 13, this volume].

19.4. FIRE EFFECTS

The processes of fire behavior are distinct from fire effects, the resulting changes to biomass and soils [*Hyde et al.*, 2013; *Reinhardt and Dickinson*, 2010]. Fire consumes live and decaying vegetation or biomass above ground, and in some cases below ground, such as soil organic matter and roots (Fig. 19.2). The canopy, subcanopy, shrub, and herb layer, litter, and duff may be partially or completely killed depending on fire behavior and fuel moisture. Under severe fire conditions, forest canopy and ground cover are fully consumed, with only the trunks and larger branches of trees and shrubs remaining. Under less severe conditions, residual amounts of partially consumed vegetation, litter and duff form irregular patchworks or burn mosaics. The degree of vegetation disturbance and soil impacts is expressed as fire severity and soil-burn severity, respectively [*Keeley,* 2009].

Fire impact on soils and thus belowground fire effects are to a large degree determined by prefire soil characteristics and conditions, the soil temperature reached, and the duration of soil heating [*Keeley*, 2009; *Mataix-Solera et al.*, 2011; *Stoof et al.*, 2010]. Effects of fire on soil physical properties can range from increases in bulk density to decreases in soil organic matter, aggregate stability, infiltration capacity, and soil-water retention [*Certini*, 2005; *Ebel,* 2012; *Mataix-Solera et al.*, 2011; *Stoof et al.*, 2010]. Fire can also induce or enhance soil-water repellency, both due to soil heating [*DeBano*, 2000] and due to drier topsoils because of vegetation removal [*Stoof et al.*, 2011]. However, fire can also reduce or not change soil-water repellent properties [*Shakesby and Doerr*, 2006]. While soil physical changes only occur in fires where soil heating is pronounced, surface cover changes due to deposition of ash and char also occur in "cooler" fires. Like soil-burn severity, postfire ash and char cover form a mosaic reflecting prefire fuel

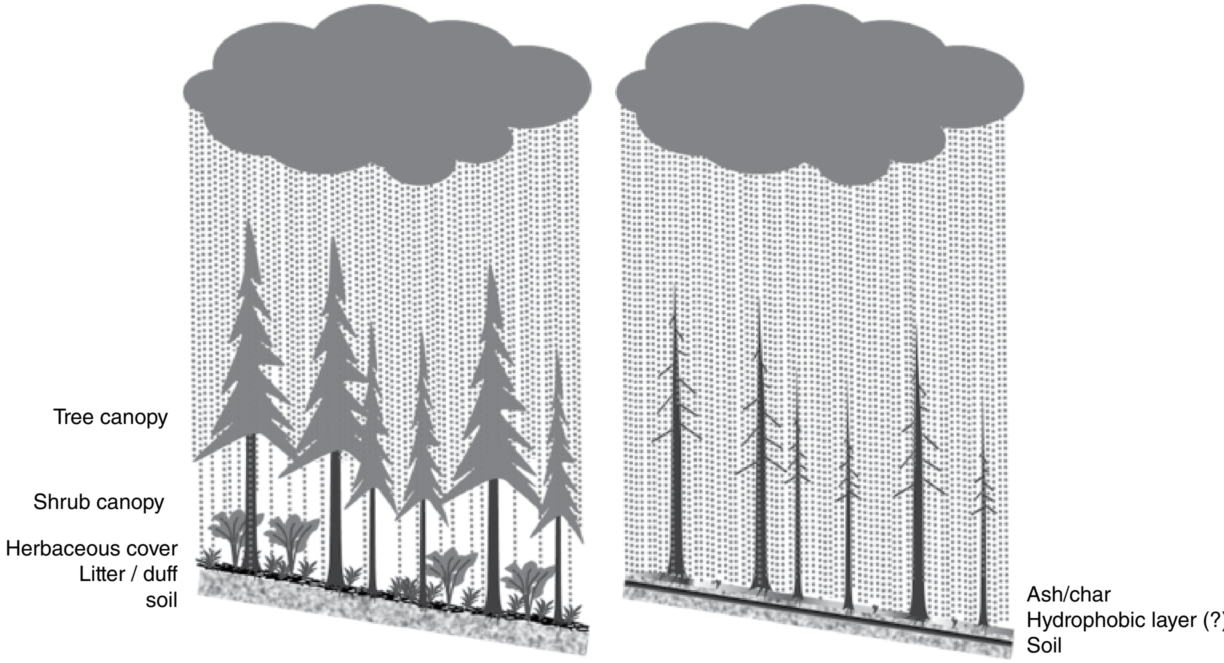

Figure 19.2 Conceptualization of forest hillslope structure before and after high-severity wildfire where all biomass is consumed, emphasizing the role of vegetation disturbance in postfire erosion processes and debris flow generation. Loss of vegetative cover including canopy, litter, and duff increases effective rainfall. Though coniferous trees are illustrated, the processes are similar in deciduous forests and shrublands. The presence of a soil hydrophobic layer is uncertain as fire may increase, decrease, or destroy water-repellent conditions [*Shakesby and Doerr*, 2006].While vegetation disturbance is recognized as exerting significant influence over postfire erosion and debris flow processes, research has substantially focused on the role of soil changes [*Moody et al.,* 2013; *Shakesby,* 2011] with limited study of effects of vegetation disturbance, leaving significant knowledge gaps.

loads and vegetation patterns [*Bodí et al.*, 2014]. After fire, ash and char are quickly redistributed across the landscape by wind and water.

The degree of vegetation disturbance by fire influences the hydrogeomorphic response and the occurrence of gully rejuvenation and debris flows following fire [*Hyde et al.*, 2007; *Hyde*, 2013]. Changes to vegetation by fire exert similar or greater control over postfire erosion response than fire effects on soils [*Doerr et al.*, 2009; *Hyde*, 2013; *Larsen et al.*, 2009]. As vegetation cover returns, the soil surface restabilizes. Vegetation recovery can begin within days after a fire, and can take from a few years to many decades for complete recovery, depending on weather and climate conditions and the regeneration potential of remaining and/or colonizing vegetation and seed stocks.

Fire effects–related uncertainties relevant in the debris flow hazard cascade can be grouped into four broad topics, related to the characterization and prediction of (1) spatial patterns and variability of landscape-scale soil heating and vegetation disturbance, (2) fire-induced changes to hydrological response, (3) spatial and temporal patterns of vegetation recovery, and (4) challenges to quantifying and mapping fire effects. Prediction of debris flow occurrence requires knowledge of the extent and duration of soil heating and related changes in soil structure in order to understand changes in erodibility and soil-water repellency. Yet, most fire behavior research is focused on the upward heat component, with little focus on the downward heat fluxes. Understanding of the relationship between upward and downward heat components is currently incomplete [*Stoof et al.*, 2013a], but essential for prefire assessment of landscape vulnerability to fire-induced soil changes. As not all fires cause soil changes, and fire effects with hydrological impact are not limited only to soil physical changes, it is important to assess the hydrological and erosion effects of soil changes in the context of the effects of vegetation removal and soil-water repellency. Also, ash is a factor to take into account, certainly above ground but also below ground. Ash can mitigate surface runoff by absorbing rainfall [*Bodí et al.*, 2014; *Cerdà and Doerr*, 2008; *Woods and Balfour*, 2008], but little is known about factors controlling ash production, composition, and downward movement into soils. Below ground, pore-clogging by ash has often been cited as cause of the reduction in infiltration observed after fire [*Bodí et al.*, 2014; *Etiegni and Campbell*, 1991; *Woods and Balfour*, 2010], though evidence for this is lacking. On the contrary, recent work by *Stoof et al.* [2016] indicates that the mere presence of ash in pores does not automatically lead to pore-clogging to the point that infiltration is hampered and ponding occurs. In short, fire-induced changes to soil produce a major source of uncertainty in prediction of debris flows in both the immediate postfire and landscape assessment contexts.

With the high spatial variability of fire effects in the postfire landscape, postfire hydrological response is also highly heterogeneous. The highly heterogeneous landscape after fire is a mosaic of fire severity, soil-burn severity, partially to fully consumed litter and duff layers, and ash and char layers of varying thickness and characteristics. This implies that there is strong variability in a range of factors including canopy interception and raindrop impact, surface water storage in litter/duff/ash layers, soil physical properties, water repellency, erodibility, and so on. The interactions and relative hydrological importance of effects of ash, vegetation removal, soil-water repellency, and the various soil physical changes that can occur are poorly understood [*Doerr et al.*, 2009; *Larsen et al.*, 2009; *Moody et al.*, 2013]. The hydrological impact of fire in such a variable landscape is influenced by the location of the most severe hydrological effects and probably by the hydrological connectivity between the various patches [*Hyde et al.*, 2014; Reaney *et al.*, 2013] and other features such as the location of macropores [*Nyman et al.*, 2010]. A major uncertainty here is the specific threshold for plot-, hillslope-, and watershed-scale connectivity related to erosion response [*Reaney et al.*, 2007; *Reaney et al.*, 2013].

It is important to note that the above-mentioned heterogeneity is present not only spatially, but also temporally. Burned areas are also highly dynamic in time, for instance in terms of the rapid redistribution of ash and char as well as the evolution of soil-water repellency, runoff and erosion, and vegetation cover [*Pereira et al.*, 2013; *Pierson et al.*, 2008; *Shakesby et al.*, 2013; *Stoof et al.*, 2013b; *Woods et al.*, 2007]. The rate of ecosystem recovery is highly relevant in the debris flow hazard cascade, in particular when severe rain events occur following fire before vegetation regenerates or newly colonizes and restabilizes the soil surface. Many factors control natural revegetation of burned areas, including remaining seed stocks, seed environment, meristem tissue of remaining flora and sprouting potential, and weather conditions favoring germination [*Brown and Smith*, 2000]. Existing research focuses on the effects of vegetation recovery on runoff and erosion [e.g., *Gimeno-García et al.*, 2007; *Shin et al.*, 2013; *Wittenberg et al.*, 2014]. Work remains to directly address uncertainties about regeneration or advancing understanding of revegetation processes.

Several factors present major limitations to quantitatively assessing fire effects. Existing field methods to quantify and map fire effects are arguably subjective relying heavily on visual assessment [see *Key and Benson*, 2006; *Parsons et al.*, 2010] and raising questions of inter-observer reliability [*Gwet*, 2001]. Commonly used methods to map fire severity using remotely sensed imagery are designed to capture effects of fire on vegetation [*Chafer*, 2008; *Epting et al.*, 2005; *Hudak et al.*, 2007] but are routinely used as the basis for field mapping of fire effects on soils [see *Parsons et al.*, 2010]. Uncertainties in remotely sensed methods to map fire severity include highly variable accuracy of signal discrimination between types and levels of fire severity and concerns that the wavelengths chosen to characterize fire severity may not be sufficient to best measure fire effects [*Roy et al.*, 2006] and soil-burn severity. Furthermore, understanding of the linkages between the information about fire effects in the remotely sensed signal and hydrogeomorphic processes related to debris flows is limited [*Hyde et al.*, 2013]. Probable interaction of multiple disturbance processes (e.g., land use, fire history, and mortality by insects and disease) further confounds understanding of the degree to which fire effects on soil determine postfire erosion processes and the generation of debris flows [*Ebel and Mirus*, 2014].

19.5. RAINFALL TRIGGERS

During the recovery period, rainfall occurring over the disturbed landscape meets little or no resistance compared to vegetated hillslopes. The effect of rainfall on the burned landscape depends on storm timing relative to vegetation recovery, intensity, and duration [*Moody et al.*, 2013; *Shakesby et al.*, 2013]. Canopy loss decreases rainfall interception, both regarding its quantity [*Stoof et al.*, 2012] and its erosive power [*Gabet and Dunne*, 2003]. In burned landscapes, the erosive power of rainfall is typically greater than in unburned landscapes as more rain impacts exposed surfaces than under vegetated conditions. Combined with possible soil-water repellency, the net result may be the generation of overland flow. As illustrated in Figure 19.2, loss of surface vegetation, litter. and duff can permit rapid accumulation of surface flow and entrainment of fine material including vegetative ash, bulking the flow and potentially increasing its force [*Gabet and Sternberg,* 2008].

The uncertainties associated with rainfall triggers include the stochastic nature of rainfall events, the timing of rainfall relative to vegetation recovery, limited knowledge of changes in rainfall energy relative to vegetation loss, and how these factors interact with landscape steepness, curvature, and the mosaic of fire effects. Further uncertainties exist about thresholds of rainfall intensity and duration needed to initiate a debris flow and how these vary by terrain, soil properties, and fire severity patterns [e.g., *Cannon et al.*, 2008]. Rainfall presents a source of uncertainty from stochastic variability, since the timing and intensity of rainfall cannot be predicted. RADAR technology may provide some real-time warning of locations of potentially threatening rainfall that could trigger debris flows [*Nikolopoulos et al.*, Chapter 21, this volume]. However, in mountainous environments where wildfires typically occur, the capacity of RADAR to accurately identify storm intensity is substantially compromised [*Young et al.*, 1999].

Rainfall can be estimated statistically, by using historic distributions of intensity, duration, and timing. However, changing climate adds other layers of uncertainty to the predictability of the timing, magnitude, and spatial distribution of rainfall events [*Beniston*, 2006]. Assuming reliable rainfall estimates can be derived, these can be combined with maps of topography and fire effects to produce a probability of debris flow occurrence [*Cannon et al.*, 2010]. The reliability of these combined prediction tools is limited by the previously identified limits to consistently and objectively mapping fire effects.

19.6. DEBRIS FLOW INITIATION, MOBILIZATION, AND DEPOSITION

Debris flow initiation commences through two primary processes, progressive sediment bulking and landslides caused by saturation-induced failure. Progressive sediment bulking [*Cannon and Gartner*, 2005] is the most commonly recognized process following fire, and typically occurs within the first 5 yr postfire [*Riley et al.*, 2013]. Runoff generated by rainfall spawns sediment-laden flows that accumulate in headwater hollows and continue down-channel in first- or second-order catchments. Overland flow increases in volume and sediment content until some threshold at which down-cutting commences, the flow becomes highly viscous, and the downslope velocity rapidly increases. Initiation commonly occurs in low-order catchments near watershed divides and topography exerts strong effects through curvature and slope steepness [*Hyde et al.*, 2014]. Curvature affects debris flow initiation as concave contributing areas typically focus sediment-laden flows into existing swales, although debris flows have been observed to originate on planar slopes in very steep areas as well [*Neary et al.*, 2012]. Slope steepness is particularly important in relation to the size of contributing areas, with steeper slopes generally requiring smaller contributing areas for debris flow initiation than where slopes are shallower [*Stock and Dietrich*, 2006]. This inverse slope-area relationship is sensitive to fire severity [*Hyde et al.*, 2014; *Pelletier and Orem*, 2014], as debris flows may initiate from smaller and less-steep conditions where fire effects are severe. Saturation-induced failures related to fire have been identified in the US Pacific Northwest and have been observed as a delayed response that occurs 10 to 15 yr following fire [*Benda and Dunne*, 1997; *Roering and Gerber*, 2005; *Roering et al.*, 2003] where root strength fails as fire-killed trees decay.

Debris flow volume increases as the mass gains speed and moves downslope, typically within constrained channels in the case of postfire debris flows. The force of the flowing mass destabilizes the channel bed and scours material by abrading, dislocating, and plucking rocks and entraining soil and organic matter into the flow [*Hungr et al.*, 2005; *Stock and Dietrich*, 2006]. Entrainment exerts a positive feedback as the bulking mass gains velocity and becomes more erosive [*Iverson et al.*, 2011]. The cohesion of a debris flow mass influences the speed and travel distance down channel and depends on the availability of clay and probably wildfire ash [*Burns and Gabet*, 2014; *Gabet and Sternberg*, 2008]. Debris flows typically occur in surges interspaced with sediment-laden flood waters and hyperconcentrated flows [*Iverson*, 1997]. The flowing mass will slow and come to rest as a debris deposit as the steepness of the flow path decreases. This can occur within confined channels or on the debris fan, where flow typically transitions from a constrained channel to the broader depositional plane of the fan [*Rickenmann*, 2005]. Debris fans are formed by previous debris flow events over geologic time [*Kirchner et al.*, 2001; *Pierce et al.*, 2004]. Debris flow deposition occurs within low-gradient channels or on the debris fan as levees form on the edges of less viscous flow. Levees channelize debris flows thereby extending debris flow runout at various distances down the fan face. The debris fan is typically the primary location where a debris flow directly impacts values-at-risk. Obstacles within depositional areas may be inundated by a debris flow or change the flow direction and final area of deposition, adding another element of uncertainty.

Confidence in the prediction of debris flow initiation is confounded by the uncertainties of the interactions between the spatial patterns and connectivity of fire effects and landform leading to the accumulation and convergence of rainfall runoff [*Hyde et al.*, 2014; *Moody et al.*, 2007]. Further, while wildfire ash influences sediment bulking processes and debris flow formation by increasing viscosity [*Burns and Gabet*, 2014; *Gabet and Sternberg*, 2008], the influence of ash relative to other initiation factors remains to be established. Methods using light detection and ranging (LiDAR) technology to model erosion from burned landscapes provide insights into sediment source and deposition areas relative to hillslope structure [*Harman et al.*, 2014; *Pelletier and Orem*, 2014] but work remains to incorporate this knowledge into process-based models. Patterns of local controls, such as exposed bedrock and the existence of midslope seeps also influence the probability of debris flow occurrence [*Hyde*, 2013], yet the relative significance remains uncertain. Multiple methods may be employed to mitigate hillslope runoff and erosion leading debris flow initiation [*deWolfe et al.*, 2008; *Santi et al.*, 2007]. Treatment effectiveness varies [*deWolfe et al.*, 2008; *Robichaud et al.*, 2013] and treatments may not be feasible in remote locations or warranted where treatment costs exceed potential benefits [*Calkin*, 2007].

Entrainment processes introduce additional uncertainty related to flow kinematics or the physics of the motion of the entire mass and the debris within the mass, the volume of material available to be mobilized, and the rate and duration of bulking as the mass moves down channel before deposition occurs. The location of obstructions relative to decreasing flow-path steepness introduces uncertainty about where deposition occurs as well as destructive potential. The final depositional zone is also influenced by the intersection with prior debris flow pathways and may shift in unpredictable ways as surges of muddy flood waters, hyperconcentrated flows, and additional debris flows follow during the same event.

The area inundated by debris flows can be predicted by several approaches in terms of the total travel distance and runout length based on the volume of transported sediment and topography of the debris flow pathway [*Rickenmann*, 2005]. Most of these methods are statistically derived empirical models, limiting their application to locations with similar conditions. Modeling predictions such as these can also be significantly affected by uncertainty in inputs, for example, the choice of digital elevation model [*Anderson et al.*, Chapter 11, this volume].

19.7. VALUES-AT-RISK

Debris flows present hazards downstream where the flowing mass may impact values-at-risk (Fig. 19.3). The potential hazard posed by debris flow to highly valued resources can be derived from the mapped location and value of resources in the inundated area and susceptibility of the resources to a debris flow event [*Calkin et al.*, 2007]. Direct debris flow impacts may threaten life and damage or destroy infrastructure in populated areas. Fine sediments carried in the sediment-laden flows that often continue downstream from debris flows can compromise water quality [*Smith et al.*, 2011], rendering it unsuitable for intended uses (Fig. 19.3). Depending on the condition of the ecosystem, the volume of the debris flow, and the grain-size distribution of the debris flow, an ecosystem can be either positively or negatively affected by debris flow impacts. Debris flows may in some cases enhance stream habitat and riparian ecosystems by restoring system complexity [*Dunham et al.*, 2007; *Rieman et al.*, 2003]. Ecosystem structure and functions may be impaired, depending on the condition of a population or habitat

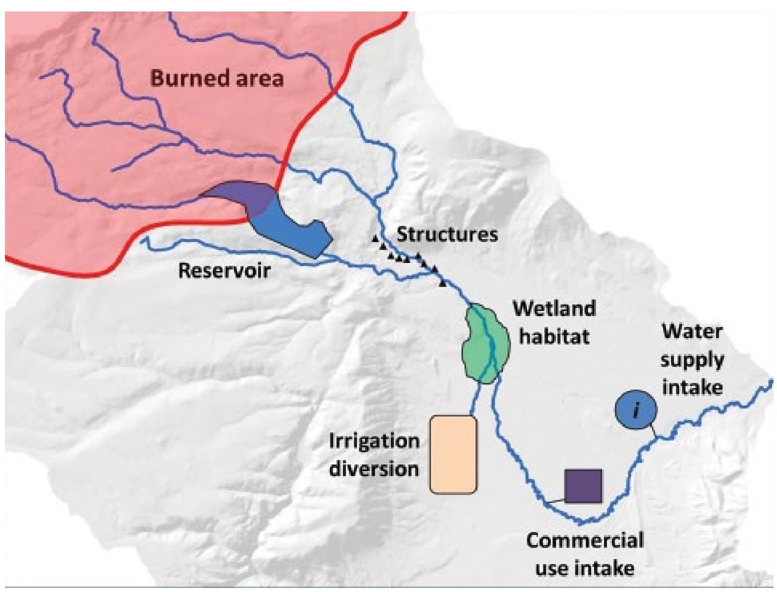

Figure 19.3 Conceptualization of values-at-risk downstream of burned areas, illustrating structures and infrastructure that can be damaged or destroyed, reflecting two phases of postfire debris flow hazards: direct impacts from a debris flow mass, and impaired water quality from sediments deposited into streams by debris flows. Sediments may compromise intended water use in reservoirs and at irrigation, commercial, and water supply intakes. While wetland habitat may be enhanced, it can also be disturbed beyond ecosystem tolerances depending on the resilience of the system, debris flow magnitude, and history of prior disturbances.

prior to the debris flow impact [*Gresswell*, 1999; *Rieman et al.*, 2003]. Where systems are already impaired, the additional disturbance may critically compromise ecosystem components and functions.

The uncertainties of predicting threats to values-at-risk begin with identifying if, in fact, valued resources are located along the relatively narrow paths of potential debris flows or within the areas on debris fans where they may potentially deposit. In the United States, multiple datasets exist to identify structures and infrastructure within or adjacent to stream channels. These data have been used to support wildland fuel reduction programs [*Stockmann et al.*, 2010], support active fire management [*Calkin et al.*, 2011b], and plan postfire emergency assessment and response [*Calkin et al.*, 2007]. However, the scale of existing geospatial data is often too coarse and locations are too imprecise for accurate discrimination of most threatened resources [*Calkin et al.*, 2011a; *Calkin et al.*, 2007; *Zerger and Smith*, 2003]. Data may be sufficient to conduct initial assessments and guide field observations to confirm locations. However, this time-consuming process can be impractical during especially large fires or busy fire seasons where personnel resources are limited.

Nonmarket resources, ecosystem components, and services without defined economic value are difficult to identify and assess [*Calkin et al.*, 2008; *Thompson and Calkin*, 2011], and are subject to uncertain valuation as decision makers decide which resources matter, and how they should make this decision. Mapping of critical habitat is generally inconsistent, often limited to public lands, and varies by land management agency. Different techniques, such as nonmarket valuation, exist to quantify debris flow impacts [*Calkin et al.*, 2008], but most rely on translating natural values into monetary values [*Sagoff*, 2011]. The commodification of ecosystem services is controversial and potentially counterproductive for environmental sustainability [*Gómez-Baggethun and Ruiz-Pérez*, 2011].

Assuming valued resources can be identified with reasonable certainty, the next challenge is to determine the probability that a debris flow of a certain force and volume will reach valued resources. Debris flow volumes vary widely [*Riley et al.*, 2013] and if a debris flow reaches a valued resource, losses can vary. A house could, for instance, be completely destroyed or the effect limited to a layer of mud and debris covering a portion of a yard or driveway. This uncertainty confounds the challenge of predicting potential losses. If the potential for loss has been identified, then the uncertainty arises of whether or not losses can be avoided or minimized through preventative mitigation. Possible strategies to mitigate debris flow impacts include engineering solutions such as check dams, deflection berms, debris racks, and debris basins [*deWolfe et al.*, 2008; *Santi et al.*, 2007]. These mitigation structures are typically engineered to meet expected forces of a design storm: a rainfall event of a certain magnitude, duration and return interval expected to produce runoff conditions sufficient to initiate debris flow [*Robichaud et al.*, 2000]. The effectiveness of mitigation structures depends on proper placement and installation [*deWolfe et al.*, 2008; *Robichaud et al.*, 2000]. However engineered solutions are costly [*deWolfe et al.*, 2008; *Santi et al.*, 2007] and might not be warranted where treatment costs exceed potential benefits [*Calkin et al.*, 2007].

Table 19.1 Summary of Uncertainties Associated with the Components of the Postfire Debris-Flow Hazard Cascade

Component	Uncertainties
Biophysical setting	Forest stand structure and susceptibility of vegetation to fire; interactions of hillslope geometry: curvature, steepness; soil properties
Fire processes	Knowledge gaps in fire physics; fire spread processes; fire intensity relative to nonuniform fuel beds; translating fire intensity to fire effects; ignition when planning for future fires
Fire effects	Process linkages between effects and hydrogeomorphic response; temperature reached by soils; changes in soil properties; macropore location, extent, and contribution; degree and spatial pattern; interaction with landscape geometry; mapping and quantifying fire effects; relative role of soil versus vegetation effects; timing and rate of vegetation recovery
Rainfall triggers	Distribution, intensity, and duration and rainfall thresholds; time since fire relative to vegetation recovery; interaction with fire effects: soil and vegetation disturbances; measurement of rainfall over burned areas; antecedent rainfall accumulations during prior season
Debris flow	Spatial pattern of fire effects and hydrologic connectivity relative to flow accumulation and convergence; role of ash and char in mobilization; rate and duration of bulking; flow path and depositional zone; effectiveness of landscape treatments and mitigation structures; destructive capacity
Values-at-risk	Location of valued resources relative to debris flow; availability, accuracy, and sufficiency of spatial inventories; susceptibility to debris impacts; magnitude of potential loss; valuation of nonmarket resources; effectiveness of mitigation

19.8. CONCLUSIONS

Prediction of debris flows can help protect and preserve values-at-risk (Fig. 19.3) but is currently hampered by a range of uncertainties. These uncertainties are related to each step of the debris flow hazard cascade (biophysical setting, fire processes, fire effects, rainfall, debris flow, and values-at-risk) and are related to knowledge gaps, variability driven by the stochasticity of natural systems, the uncertainties inherent in human decision-making processes, and inconsistent availability of data required for hazard prediction (Table 19.1). Awareness of these uncertainties and knowledge gaps can not only shed light on the potential error in current debris flow prediction models, but also highlight needs for fundamental and applied research to improve future models and build toward a comprehensive and integrated prediction approach. Arguably the greatest gaps may be closed through developing broadscale, integrated, and physically based analysis of fire effects and process-based understanding of the interactions between fire effects, especially vegetation disturbance, and terrain geometry. Deliberate team efforts will be needed to aggregate individual prediction components, those currently available and to be developed, and to build an integrated framework to predict postfire debris flow hazards. Clearly, uncertainties, both within each component and as compounded with integration, will require explicit articulation to identify and prioritize those that can be resolved and to define confidence boundaries on those uncertainties that are indeterminate.

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