IF IT BURNS, WILL IT FLOW? AND ABOUT THE MANAGERS WHO WOULD LIKE TO KNOW: PREDICTING POST-FIRE DEBRIS FLOWS IN THE RANGELAND FOOTHILLS OF BOISE, IDAHO & INVESTIGATING THE USE OF WILDFIRE SCIENCE BY DECISION MAKERS AT THE WILDLAND URBAN INTERFACE

By

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The following individual read and discussed the thesis submitted by student Katherine Gibble, and they evaluated her presentation and response to questions during the final oral examination. They found that the student passed the final oral exam.

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The final reading approval of the thesis was granted by Jennifer Pierce, Ph.D, Chair of the Supervisory Committee. The thesis was approved by the Graduate College.

DEDICATION

To my parents, for all of the road trips. Having been to all 50 states by the time I was 16, I am a geologist because of all the miles we drove, and the most entertaining thing to do along the way was to look out of the car window and out at the landscape.

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ABSTRACT

Wildfires increase erosion in mountainous landscapes. The most catastrophic form of post-fire erosion is the debris flow, viscous slurries of water and sediment capable of scouring and entraining larger sediment and rafting boulders. Post-fire debris flows are particularly hazardous when fire- and debris flow-prone landscapes intersect the Wildland Urban Interface (WUI). Homes built into the edge of the flammable WUI are at high risk of both wildfire and subsequent debris flows in mountainous landscapes of the western US, yet the WUI is expanding at an extraordinary rate. There are predictive models that inform citizens, land managers, and local governments of post-fire debris flow hazards they face, but they are rarely used at the WUI, where their use may be particularly beneficial.

Wildfire significantly increases the ability of landscapes to erode; post-fire soils are damaged, ash-laden and potentially hydrophobic. Damaged hillslopes previously protected by vegetation are directly exposed to rainfall where, on steep slopes, soil and ash are easily mobilized, channelized and capable of entraining larger and greater amounts of sediment as runoff moves downslope, forming a debris flow. Vegetation, soils and slopes vary across ecosystems; forested slopes have larger fuels that burn at higher severity, deeper, finer soils, and steeper slopes than those of rangeland ecosystems. While both ecosystems produce post-fire debris flows, more sparsely vegetated rangelands slopes may not be limited by fire to erode. Instead, rangeland systems may erode more continually and at lower magnitudes than forested slopes, whereas punctuated disturbance by fire on burned, previously forested slopes more often may lead to catastrophic failures, often by debris flows.

This thesis compares model estimates of post-fire debris flow probability and volume between forest and rangeland ecosystems within the fire- and erosion-prone rangeland-forest ecotone of the Boise Foothills above the Boise Metropolitan Area, Idaho USA. Models developed by the United States Geological Survey estimate post-fire debris flow probability and volume using soil, burn severity, topography and rainfall attributes, which have distinct characteristics between forest and rangeland ecosystems. This thesis also compares post-fire debris flow model estimates to a historic post-fire debris flow event that occurred within burnt range-grassland slopes after a summer convective storm in the Boise Foothills. We compare modeled volume and probability estimates to recorded debris flow locations and volumes of the 1959 “Boise Mudbath” to determine if models can accurately predict a real-world event.

Our findings show that models estimate higher post-fire debris flow probability and volume for forested basins vs. rangeland basins. The average modeled sediment yield is ~1.4x higher for forested basins than rangeland basins under both the low (2 yr) and high (100 yr) precipitation recurrence interval scenarios. The average post-fire debris flow probability is ~15% and ~32% greater for forested basins than rangeland basins under the 2yr and 100yr recurrence rainfall events, respectively. We also find that models over-predict sediment yields and under-predict probability of debris flow occurrence compared to the 1959 Mudbath event. We found that the post-fire debris flow model volume estimates were ~2-6x greater than those actually produced by the 1959 post-fire

debris flow event. True 1959 debris flow yields are similar to those calculated for regional depositional records of sparsely vegetated drainage basins. Interestingly, modeled 1959 debris flow yields more closely match (~<2x) known debris flow yields sourced from forested basins within the region. Additionally, the post-fire debris flow probability model underestimates debris flow occurrence under the 1959 debris flow scenario; only one drainage was modeled to have >50% probability of debris flow occurrence under the 1959 post-fire debris flow scenario, despite the fact that all basins did in fact produce debris flows. These findings show that debris flow sediment yields appear to be distinct between forest and rangeland basins and conclude that post-fire debris flow models are more suited to forested slopes, as sediment yields appear to be distinct between burned rangeland and forested drainage basins.

The science produced in the geology section of this thesis was provided to City, County and State land and hazard managers to inform decision making regarding post-fire debris flow hazards. This transfer of knowledge from science to decision-maker lends itself to a seemingly simple question: how will this science be used to make decisions? There is a growing supply and demand of science addressing wildfire hazards at the Wildland Urban Interface, yet what makes science usable and how it is used to make policy decisions is not well understood. In Chapter IV of this thesis, we merge quantitative and qualitative social science methods with public policy theory to identify how stakeholders at the Boise, Idaho WUI use science to inform wildfire hazard policy. We hypothesize that how a manager defines a wildfire problem will determine how that manager uses science to inform a policy solution to that problem. To test this hypothesis, we performed content analysis on policies of wildfire stakeholders at the Boise WUI, and

coded the policies into distinct categories that classify how they address wildfire hazards. We then conducted interviews with managers representing local, state and federal stakeholders in the Boise WUI to discuss how new, local science may address wildfire hazards they identify as needing policy solutions. Our findings show that stakeholders at the Boise WUI address the similar wildfire hazards with unique policy solutions. Interviews reveal that science is most useful when it is quickly understood, and when it can help draw boundaries from which wildfire hazard funding can be allocated and prioritized. We recommend the framework used in this study to provide policy context to scientists as they discuss their results with interested stakeholders, and to managers requiring policy context to the wildfire science they are asked to consider.

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CHAPTER I: LITERATURE REVIEW: POST-FIRE DEBRIS FLOWS ACROSS TWO LANDSCAPES

Overview

The following is a review of the literature regarding post-fire erosion as relevant to this thesis. The goal of this chapter is to compare post-fire erosion response by debris flow between forest and rangeland landscapes. Differences in slope, rainfall, vegetation, burn severity and intensity, and soils contribute to whether or not a debris flow will form after a wildfire; the rangeland-forest ecotone offers contrast between these attributes from which we can compare their influence on post-fire debris flow occurrence and magnitude. Post-fire erosion between sparsely vegetated slopes and forested slopes has been studied extensively through both experiment and observation. As such, this chapter provides 1) an overview of debris flow formation, 2) an overview of landscape controls on erosion 3) the impacts that fire has on erosion 4) a comparison of post-fire erosion response between forested and rangeland ecosystems and 5) a comparison of post-fire debris flow response between forested and rangeland ecosystems.

An overview of debris flows

A debris flow is a rapid water-driven mass movement of soil, sediment, debris and liquid that initiate in mountainous landscapes; debris flows move as a viscous fluid, distinguishing them from both landslide and streamflow processes (Johnson, 1970).

Debris flows initiate on steep hillslopes where there is abundant mobile soil and regolith for transport and moisture to initiate sediment transport (Costa, 1984). Debris flows may initiate as discrete shallow landslides of unconsolidated sediment that mobilize into a flow upon mixing with runoff (Johnson, 1970; Costa, 1984), or as sediment-laden rills coalesce, thereby increasing their ability to scour and entrain more sediment in a sediment bulking process (Johnson, 1970, Meyer and Wells, 1997; Ritter et al., 2011). Regardless of initiation process, debris flows have increased viscosity and pore fluid pressure compared to water that cause debris flows to scour channels and entrain large clasts as they flow downslope (Iverson, 1997). As such, debris flows behave as a non-Newtonian fluid; they possess high shear strength and high bulk density compared to water due to abundant sediment entrained in the flow. Debris flows are deposited when slope decreases, often atop alluvial fans debris flow deposits, are often lobate, and have an abrupt terminus (Iverson, 1997; Ritter et al., 2011).

Debris flows transform along their flow paths; contributions of water from tributaries can change the flow type from debris flow to hyperconcentrated flow and eventually normal streamflow as debris flows move downslope and down-gradient (Ritter et al., 2011). Debris flows have been observed to move in pulses; coarse fronts containing rafted boulders and debris are followed by viscous, muddy slurries capable of scouring and entraining coarse sediment and tailed by concentrated streamflow (Figure 1) (Pierson, 1986). As slope decreases along the flow path, debris flows lose momentum and, due to their high viscosity, deposit abruptly (Johnson, 1970), while the hypercontentrated flow debris flow tail may continue to flow downslope. Though their form may change from viscous debris flow to hypercontentrated flow as they move downslope, debris flow deposits have a bulk density between 1.8 – 2.6 g/cm^3 and contain ~50-80% sediment by volume.

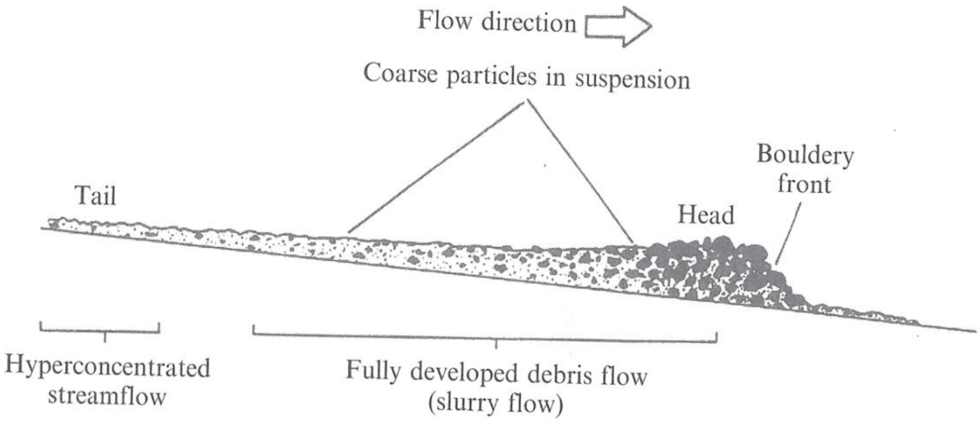

Figure 1.1 Longitudinal cross-section of a debris flow (Modified from Pierson, 1986).

<u>Factors Driving Erosion and Debris Flows</u>

Several attributes contribute to the initiation of a debris flow. Slope controls the ability of gravity to move soil and sediment; the infinite slope equation (Equation 1) explains that shear stress acts upon a mobile material. Each column of material has an inherent shear strength that varies with soil and bedrock type. When shear stress overcomes shear strength, slope failure occurs. As slope increases, the shear stress being placed on a column of mobile material increases. Therefore, sediment is more likely to be mobilized at higher slopes. However, shear stress may be too high for soils to develop on steep slopes, thereby limiting landslide occurrence, including debris flows, due to a limited sediment source. For example, a study within the Idaho Batholith of central Idaho found that landslides were rare above 41^0 (Megahan et al., 1978).

$\tau = (\rho)(g)(z)(\cos\theta)(\sin\theta)$ Equation 1

where τ=shear stress, ρ = density, g = gravity, z = soil thickness, θ = slope angle

Precipitation acts on the angle at which slope failure may occur by increasing the density of soil as soil absorbs water. Water absorption increases the density of the column of mobile material and lowers the slope at which a column of soil will fail. Studies indicate that debris flows commonly occur on slopes greater than 28.7-36.3% (15-20^0) (Costa, 1984), though the slope at which debris flows initiate is dependent on many factors intrinsic to the hillslopes on which they occur (i.e. bedrock, vegetation, soil type) as well as external factors (i.e. precipitation intensity and duration).

Precipitation alters slope stability both at the slope surface and subsurface by runoff and infiltration. At the surface, precipitation that is not intercepted by vegetation hits the ground surface and initiates erosion through rainsplash. When rainfall rates exceed infiltration rates, surface runoff will initiate on hillslopes. Sediment mobilized by rainsplash may become entrained in surface runoff. The Coulomb Equation (Equation 2) describes the controls on slope stability at the subsurface.

$S = c + \sigma' \tan \varphi$

Equation 2

where S = shear strength, c = cohesion, σ' = effective normal stress and
φ = angle of internal friction

Where $\sigma' = \sigma - u$

and σ= total stress and u = pore pressure

Slopes which experience either saturation-excess or infiltration-excess failure can produce debris flows (Wondzell and King, 2003; Meyer and Pierce, 2003). Both rainfall intensity and duration are primary factors responsible for debris flow initiation (Cannon et al., 2011), but the rainfall intensity-duration thresholds that produce debris flows will vary between locations due to bedrock type, vegetation and slope (Caine, 1980). Dry and partially saturated soils can stay stable at higher angles than once completely saturated. For unsaturated soils, negative pore pressure increases effective normal stress; when soils become saturated, positive pore pressure reduces the normal stress holding soils on hillslopes (Equation 2). The amount and intensity of rainfall dictates the initiation of a debris flow. Under low intensity rainfall, infiltration inhibits surface runoff. However, if low intensity precipitation persists for long periods of time, soils reach saturation-excess failure as shear strength reaches zero, especially in hillslope concavities where flow paths converge. In contrast, under high intensity rainfall, precipitation input may exceed infiltration rates and initiate surface runoff.

While the duration and magnitude of precipitation events are a primary control on debris flow initiation, characteristics of source material also is of primary importance. Soils which contain abundant fine materials (i.e. clay) contribute viscosity to fluid flows required to initiate debris flows (Iverson, 1997). On hillslopes, rain may either saturate soil or may mobilize soil at the surface by rainsplash action. Progressive addition of sediment via surface runoff, formation of rills, and addition of diffuse hillslope sediments to main channels may initiate debris flows. Runoff lacking fines material lacks the yield strength and viscosity required to produce debris flows, scour channels, and entrain larger sediment (Pierson and Costa, 1987). Flows lacking a continual source of fines will not persist owing to the lack of pore fluid pressure to propel the debris flow forward (Iverson, 1997). In contrast, an overabundance of fines may reduce the production of debris flows;

an upper threshold viscosity creates laminar flow conditions at the flow-bed boundary, preventing scouring and entrainment of more sediment (Costa, 1984; Iverson, 1997).

Vegetation stabilizes slopes by intercepting rainfall that may erode the soil surface, by transpiring water that would otherwise saturate soil, and by providing root cohesion below the soil surface. Rainsplash is a potential source of surface erosion initiation in on hillslopes (Morgan, 1978; Pierson et al., 2007). Hillslopes with high canopy cover receive less direct rainsplash at the surface because of interception by tree and shrub canopy; intercepted water evaporates off of vegetation or drips to the ground with less energy, providing less rainsplash action to do geomorphic work (McNabb and Swanson, 1990). Water that falls past the canopy and reaches the soil surface permeates into the soil where it either saturates the soil or is taken up by roots and does not contribute to soil moisture. In this way, vegetation acts to stabilize soil by taking up water that would otherwise decrease the shear strength of soil or add positive pore pressure to the soil column, decreasing the normal pressure keeping the soil in place. In addition, roots below the surface add cohesion to soil by binding to the soil matrix, further stabilizing soil from erosion.

Impact of Fire on Hillslope Erosion

Wildfire changes vegetation, rainfall and soils; therefore, wildfire also changes rates and processes of slope erosion. It is well known that wildfire increases erosion on hillslopes (Swanson et al., 1981, Neary et al., 2003; Roering and Gerber, 2005; Shakesby and Doerr, 2006; Pierson et al., 2011), and that post-fire erosion is greater than long-term erosion rates (Roering and Gerber, 2005; Riley, 2012) Wildfire is considered a primary driver of erosion in fire-prone landscapes (Shakesby and Doerr, 2006) and it is anticipated that erosion may double in some western US states because of the predicted increase in wildfire activity in the western US (Sankey et al., 2015).

Fire alters the soil by damaging soil structure and killing roots, adding or enhancing repellency, and by contributing fine mobile ash at the soil surface (Giovannini and Lucchesi, 1983; DeBano, 1981). Soil heating dehydrates soil, reducing soil cohesion, making it more readily available for mobilization (DeBano, 2000; Neary and Gottfried 2003). Fire may create or enhance water repellency (DeBano, 2000). Hydrophobicity of soil at shallow depths have been reported in shrublands, forest and chaparral ecosystems in the absence of fire, but may also be induced by fire (DeBano, 1981). Fire volatilizes organic compounds that either rise above the soil surface as smoke or are expelled below the soil surface where they cool and recondense along a steep temperature gradient (DeBano, 2000). The resolidified organic compounds bond to soil and sediment grains in the shallow (<5 cm) subsurface, sealing pore space within the soil to create a hydrophobic layer. This barrier layer prevents precipitation from infiltrating past this depth, and may induce shallow soil failures and surface runoff (DeBano, 1981; DeBano, 2000). Gabet (2003) found that hydrophobicity at the shallow subsurface may lead to discrete failures at the near-surface (~1-2 cm) because it acts like a perched water table. Because rainfall cannot permeate past the hydrophobic layer, rainfall is able to quickly saturate soil above the hydrophobic surface, thereby lowering the amount of precipitation needed to produce a shallow discrete failure that may induce sediment bulking and subsequent debris flow. As such, in post-fire landscapes with hydrophobic soils, severe storm events are not required to produce debris flows.

Fire contributes fine ashen materials to the soil surface. A surface ash layer may block soil pores, reducing infiltration rates and inducing surface runoff (Lavee et al., 1995). Ash may also hinder post-fire erosion. Ebel et al., (2012) found that ash delays surface runoff; ash is able to absorb all rainfall if rainfall intensity does not exceed infiltration rates, and limits surface runoff (Cerdà 1998; Cerdà and Doerr, 2008). However, if rainfall intensity does exceed infiltration rates, surface runoff may initiate the sediment bulking process. Ash may also prevent precipitation from flowing past the ash-soil interface. When this occurs, the ashen layer becomes saturated, leading to shallow, saturation failure of the ash layer (Cerdà and Doerr, 2008; Ebel et al., 2012).

Fire alters vegetation through combustion, reducing canopy cover and killing vegetation, thereby reducing or eliminating root cohesion, and reducing the removal of soil water by roots. Decreased canopy cover results increases rainsplash action over a burn area (Stoof et al., 2012), and mobilizes material at the damaged soil surface. The combustion of subcanopy vegetation during wildfire removes low-lying vegetation that acted as sediment traps (Roering and Gerber, 2005). Vegetation death resulting from fire has immediate effects on soil moisture. Vegetation loss from fire shuts off transpiration processes that remove water from soil through roots to vegetation (Silva et al., 2006; Stoof et al., 2012). The excess water that remains in the soil creates slope instability by decreasing shear strength by creating positive pore pressure in the soil matrix (Ebel, 2013). Additionally, roots from dead vegetation will decay over time (6-10 yr), and their absence reduces cohesion of soil provided by root systems (Swanson et al., 1981).

Comparing erosion response between forested and rangeland ecosystems

Slope, vegetation and soil as well as fire continuity, severity and intensity are dissimilar between rangeland and forest ecosystems, creating disparity in their erosion response in both the absence and presence of fire. Research from Dry Creek Experimental Watershed in southwestern Idaho identified that forested slopes have steeper slopes than sparse, rangeland slopes (Poulos, 2016). Poulos found that forested, north-facing forested drainage basins have a mean slope of ~31^0, while south-facing, sparsely vegetated drainages have a mean slope of ~25^0; similar disparity between forested and sparsely vegetated slopes have been noted by Riley (2012) and Nelson (2009) within the same study region. Shear stress will be higher within soils of steeper, forested slopes than rangeland slopes. However, canopy cover and root cohesion counteract the effects of slope prior to fire; while forested drainage basins are often steeper than sparsely vegetated slopes, lower canopy cover and shallow root systems on sparsely vegetated slopes result in more continual exposure to rainfall and subsequent erosion than more densely vegetated forest slopes. After fire, however, reduced canopy cover and root cohesion may cause more erosion on steeper, forested slopes than on shallower, sparsely vegetated rangeland slopes that erode regardless of fire. Continuous erosion in the absence of fire is described for rangelands of the Great Basin region, USA; the interspace between shrubs and bunchgrasses experience greater runoff and erode more sediment (15- to 25-fold) than underneath shrub canopies because of limited ground cover and soil stability (Pierson et al., 1994; Pierson et al., Smith, 2013). However, after fire, erosion may be even greater. Pierson et al., (2009) found that, after fire, erosion within sagebrush steppe increased between 7- and 125-fold on 30 m^2 plots.

Burn severity is driven by fuel type, wildfire intensity and fire duration. Large fuels (i.e. mature trees) associated with forests burn intensely and for prolonged periods of time due to their size (1000 hr fuels) compared to those of rangelands (1-100 hr fuels) containing grasses and shrubs. High severity fires in forests damage soil, introduce large volumes of ash and can induce hydrophobicity. In contrast, rangeland ecosystems often burn most intensely in patches of sagebrush and in riparian areas, where larger fuel is concentrated, but burns quickly and incompletely through shrub interspace grasses and forbs. The resulting runoff is often discontinuous and hindered by erosion barriers of unburned patches of vegetation (Lavee et al., 1995).

Soil thickness and texture vary with vegetation type. Aspect-induced differences in vegetation within the foothills of Boise, Idaho influence soil thickness; soils on forested, north-facing slopes are 1.1-2.3 times thicker soils than those found on south-facing, sparsely vegetated slopes (Smith, 2010). Additionally, coarser-textured soils on south-facing, sparsely vegetated slopes in the Boise Foothills drain more quickly than north-facing forested soils (Tesfa et al., 2009). However, wildfire over rangeland soils introduce fine ash that may reduce infiltration and initiate surface runoff. In contrast, forest soils have abundant fine soils in the absence of fire, and water infiltrates more slowly, and the onset of infiltration-excess induced failure may occur more readily.

Post-fire Debris Flow Response between Forest and Rangeland Landscapes

Fire-induced debris flows occur on both sparsely vegetated rangeland slopes (Thomas, 1963; Riley, 2012; Poulos, 2016; Friedman and Santi, 2013) and forested slopes (Riley, 2012; Poulos, 2016, Meyer et al., 2001; Cannon et al., 2003). Generally, post-fire debris flows are not observed within basins ~>10 km^2, but are instead frequently sourced from low-order drainage basins, often <1 km^2 (Cannon et al., 2010). Fire changes the type of slope failure that induce debris flows. Reduced infiltration and subsequent sediment bulking initiates widespread debris flow in post-fire landscapes, as opposed to discrete debris flow failures induced by soil saturation that commonly occur in unburned landscapes. (Cannon, et al. 2010). Additionally, post-fire debris flows commonly occur within two years of fire (Cannon et al., 2010), before vegetation has begun to recover. Landslides and debris flows are also common ~6-10 year post-fire, when root systems of vegetation killed by fire begins to decay, causing deep-seated slope instability.

The abundance of debris flow records from forested basins used to build post-fire debris flow models (Cannon et al., 2010) indicate that that fire-induced debris flows are more prevalent on forest slopes than rangelands. A lack of debris flow response in rangeland slopes is further indicated by a lack of reports and studies of debris flows exclusively within rangeland study areas. A 2016 synthesis of the ecohydrologic impacts of rangeland fire on erosion only briefly discusses debris flow activity, and cited debris flow locations are not explicitly with rangeland ecosystems (Pierson and Williams, 2016). It has been posited that because rangeland slopes are typified by lower vegetation density, sediment delivery by fire-induced debris flows is less likely. Sparser vegetation leads to more frequent, lower magnitude erosion that is not always induced by fire (Pierce et al., 2011; Riley, 2012). Conversely, dense vegetation produces high canopy cover and creates stable slopes that are more dramatically disrupted by wildfire. The sudden loss of dense vegetation protecting steeper slopes expose less-frequently disturbed slopes to erosional processes (Riley, 2012).

Contrasting erosion between forest and rangeland slopes prior to fire “primes” these ecosystems for debris flows differently when a fire does occur. Within the Boise Foothills, soils are courser-textured on south-facing, sparsely vegetated slopes than those of north-facing forested soils (Tesfa et al., 2009). Importantly, ash produced from fire contributes fine material that is required to initiate and maintain a debris flow, in areas where fine hillslope material was previously absent or lacking (Cannon et al., 2001). The importance of ash in the initiation of debris flows is noted by Cannon et al. (2001). Debris flows following the Cerro Grande Fire in New Mexico were only initiated after the first precipitation event, when ash was present. However, subsequent storms lacked the previously mobilized ash, and debris flow activity was notably absent.

Soil thickness may also vary with vegetation. Aspect-induced differences in soil depth are seen within the Boise Foothills; forested, north-facing drainages of the Boise foothills have 1.1-2.3 times thicker soils than those found on south-facing, sparsely vegetated slopes (Smith, 2010). Soil depth limits the maximum amount of material that can be mobilized by a debris flow, and may ultimately control debris flow volume.

Because large fuels associated with forests burn more intensely and for prolonged periods of time compared to smaller, less dense fuels of rangelands, wildfire severity is commonly higher in forests than in rangeland. High severity fires in forests damage soil, introduce large volumes of ash and can induce hydrophobicity. In contrast, rangeland ecosystems often burn most intensely in patches of sagebrush and in riparian areas, where larger fuel is concentrated, but burns quickly and incompletely through shrub interspace grasses and forbs. The resulting runoff is often discontinuous and hindered by erosion barriers of unburned patches of vegetation (Lavee et al., 1995). Burn severity is thought to play a role in post-fire deposition type seen in alluvial fan records along the Middle Fork Salmon River and South Fork Payette River. Fire-related debris flows are inferred to result from high severity wildfires whereas low severity fires reflect sparsely vegetated hillslopes, and limits sediment deposition in post-fire erosion events (Pierce et al., 2004; Riley, 2012).

Rangeland slopes erode more continuously than forested slopes and in the absence of fire. Conversely, forest slopes may be dependent on fire for significant erosion (Pierce et al., 2011). This disparity is exemplified by a study comparing post-fire erosion within a burnt forested basin to an unburnt sparsely vegetated basin along the South Fork Payette River within the Idaho Batholith of west-central Idaho (Meyer et al., 2001). Both basins deposited similar sediment yields, despite only the forested basin having been disturbed by fire. The unburnt, sparsely vegetated basin deposited episodic sheetfloods, while the burnt, forested basin produced a single debris flow induced by a single large colluvial failure (Meyer et al., 2001). Fire did not limit abundant erosion within the undisturbed, rangeland-type basin. The foothills of Boise, Idaho also provide a recent example of rangeland slope erosion not limited by fire. A prolonged rainfall event in March, 2017 caused several small, saturation-induced failures within unburnt rangeland slopes atypical to the coarse soils.

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CHAPTER II: COMPARING PREDICTED POST-FIRE DEBRIS FLOW PROBABILITY AND VOLUME BETWEEN RANGELAND AND FORESTED BASINS OF THE BOISE FOOTHILLS

Abstract

The objective of the modelling component of this thesis is to identify post-fire debris flow hazards within drainage basins of the foothills above Boise, Idaho. Additionally, we compare modeled post-fire debris flow hazards between forested and rangeland drainage basins. Debris flows are thought to be common after fire within forested basins, where sediment storage is high prior to fire. In contrast, wildfire is not a prerequisite for erosion events in rangeland drainage basins, where sediment storage is low and runoff is frequent between wildfire. We modelled debris flow hazards for 856 drainage basins within the Boise Foothills using empirically derived models produced by the USGS (Cannon et al., 2010). The models estimate the probability and volume of a debris flow occurring in a given basin after fire in response to rainfall. We ran the models through four burn severity scenarios and two precipitation scenarios to obtain a range of possible post-fire debris flow hazard outcomes within the Boise Foothills. We found that the average modeled sediment yield was ~1.4x higher for forested basins than rangeland basins under both the low (2 yr) and high (100 yr) precipitation recurrence interval scenarios. The average post-fire debris flow probability was ~15% and ~32% greater for

forested basins than rangeland basins under the 2yr and 100yr recurrence rainfall events, respectively. The maps resulting from this study are currently in use by the City of Boise, and are included in the 2016 Ada County Enhanced Wildfire Riskmap to identify potential post-wildfire debris flow risk to Boise citizens. Identifying and understanding contrasting debris flow potential between rangeland and forested hillslopes are an important consideration when planning for post-fire erosion hazards, especially in urban areas.

Introduction

The previous chapter discussed the mechanisms by which debris flows occur in mountainous landscapes after wildfire and identified different post-fire erosion mechanisms and thresholds in forested and rangeland systems. Slopes in post-fire landscapes erode as a function of fire severity and intensity. In addition, topography, and precipitation intensity and duration, and decreased vegetation influence erosion after wildfire. Fire may reduce soil cohesion, and heat may break apart soil aggregates, making them more susceptible to erosion (McNabb and Swanson, 1990). The breakup of aggregates and the introduction of ash to the soil surface may reduce pore space by filling former voids, decreasing infiltration rates, leading to erosive surface runoff (McNabb and Swanson, 1990). Ash smooths the slope surface, promoting a continuous runoff surface (Lavee et al., 1995; Woods and Balfour, 2010). Conversely, ash may store precipitation and reduce runoff overall (Cerda and Doerr, 2008). Burnt vegetation may volatilize and be expelled into the topmost portion of the soil profile where it cools and solidifies within pore spaces, and induce hydrophocity from which near-surface runoff may be initiated (DeBano, 2000). Vegetation loss also increases the exposure and susceptibility of the burned surface to rainfall as the result of a reduced canopy (Shakesby and Doerr, 2006; Pierson et al., 2008; Miller et al., 2013). Reduced cohesion, decreased pore space, hydrophobicity and the introduction of an ashen surface leads to decreased infiltration and an increase in overland flow, which is exacerbated by a reduction in canopy cover.

Generally, debris flow response within the first ~2 years of fire is dominated by runoff-initiated debris flows, rather than infiltration-initiated debris flows that often occur in unburned landscapes (Cannon et al., 2010). In the post-fire landscape, runoff-initiated debris flows form when rainfall over burn areas leads to overland flow, merging to form rills and gullies that entrain susceptible soils (Meyer and Wells, 1997; Cannon et al., 2003). Entrainment of fine soils and ash increase the fluid density of runoff, which allow flows to entrain larger sediment and debris as the flow moves downslope in a sediment bulking process (Gabet and Sternberg, 2008; Pierson et al., 2009). Because debris flows <2 yrs after fire frequently form by sediment bulking rather than by deep-seated saturation failures, traditional infiltration-based slope stability analyses (Carson and Kirkby, 1972; Montgomery and Deitrich, 1994) that are appropriate for burn areas >10 yrs after fire or on unburned slopes are not sufficient, and other mechanisms such as hydrophobicity, fire severity and precipitation-intensity thresholds must be considered to determine whether or not a fire-induced debris flows may occur.

As discussed in the previous chapter, there is disparity in erosion between burnt rangeland and forest slopes that may ultimately dictate whether a debris flow may occur. Rangelands, with lower slopes, less vegetation cover and coarser soils, erode more continually. Fires are not a prerequisite for mass-wasting events on sparsely vegetated slopes (Pierce et al., 2011). In contrast, forests often have steep slopes protected from erosion by high canopy cover, deep root support, and thick, cohesive soils that do not erode continuously, but may do so under disturbance by wildfire.

Given the disparity of these attributes between rangeland and forest slopes, we anticipate that the post-fire debris flow probability and volume models will predict higher probability and higher sediment volumes for debris flows occurring in forested basin than within rangeland basins. To test this hypothesis, we run the post-fire debris flow predictive models over the Boise Foothills above the Boise Metropolitan Area in southwest Idaho, USA. The foothills of Boise encompass the rangeland-forest ecotone that separates the Great Basin region from the Rocky Mountains. Steep (~30%) foothills are comprised of sagebrush-steppe and grassland slopes at lower elevations (~850-1550 m) and open Ponderosa Pine and Douglas Fir forest at higher elevations (~1550-2000 m). We run the post-fire debris flow predictive models though four burn severity and two precipitation scenarios over 856 small drainage basins (~0.1-1.5 km^2) within the Boise Foothills study area and compare the resulting debris flow probability and volume predictions between rangeland and forested basins. Importantly, the models we use in this study were designed to predict post-fire debris flows in the western US, and were built using debris flow occurrence data from primarily forested drainage basins.

Fire-related debris flow risks in the Wildland Urban Interface

Mountainous regions of the western US, particularly the Great Basin region, contain many cities built adjacent to or within rangeland-forest ecotones. Metropolitan areas like Reno, Salt Lake City, the Colorado Front Range and Boise have been built adjacent to lower elevation, rangeland-dominated ecosystems that transition to coniferous forest ecosystems at higher elevations. These areas are particularly prone to wildfire. Dry grasses ignite and spread rapidly, carrying fire upslope into forested areas. Human ignitions exacerbate the wildfire frequency in the region that were lower prior to human settlement. These cities are growing rapidly (Bramwell, 2015), and the hazard posed by wildfire will increase as more developments are built in the mountainous portions of these cities.

Dense populations within cities create conditions by which debris flows threaten the most human life and infrastructure. Debris flows in urban settings frequently damage infrastructure, are costly to mitigate for and clean up after and, in extreme cases, lead to loss of life. Mountainous western U.S. cities are disproportionately impacted by fire-induced debris flows. For example, after the ~150,000 Grand Prix Fire of 2003 burned steep slopes in the San Bernardino Mountains outside of San Bernardino, California, intense rains triggered debris flows in several drainage basins. The debris flows killed sixteen people and reported to cost over a billion dollars in damages and clean up costs (Sassa and Canuti, 2008).

Identifying where debris flows may initiate after fire is especially important in areas that may experience a loss of life and property. Such knowledge can be used to prevent and mitigate for losses. Hazard assessments often identify landslide hazards for a given area, including debris flows, especially if the area has experienced landslides in the past. Commonly, what is known about debris flow hazards in an area is limited to historic accounts of previous events. Recently, however, new predictive models were developed to predict where debris flows may occur after a wildfire. The development of these models is timely, as erosive, fire-prone areas become more populated and as fires have become more abundant throughout the West (Cannon and DeGraff, 2009).

Models produced by the USGS Landslide Hazards Program empirically isolate the variables most responsible for post-fire debris flow activation using 388 post post-fire debris flow recorded in the Intermountain western US (Cannon et al., 2010). Currently, post-fire debris flow models are applied almost exclusively over post-fire areas within Forest Service land, after a wildfire has occurred. However, by simulating fire and precipitation scenarios, the models can be applied over areas of interest prior to fire. The data inputs required to run the predictive models are publically and easily accessible, making them easy to run with access to ArcGIS. Pre-fire application of post-fire debris flow models increases the amount of time land and hazards managers have to decide how to prepare and manage for debris flow hazards in fire-prone landscapes. In 2015, Ada County, Idaho sought to identify post-fire debris flow prone slopes in their hazard assessment, providing an opportunity to apply post-fire debris flows models in pre-fire setting.

Study area

The Boise Foothills study area extends west from Lucky Peak Reservoir to Interstate 55, and from the Boise Metropolitan area up to the foothills ridgeline. The drainages of this study area flow into the Boise Metropolitan area. The Boise Foothills study area (Figure 1) is located at the boundary between the Snake River Plain and the Idaho Batholith. Bedrock in the foothills study area is comprised of medium to coarse grained Idaho Batholith granite and Tertiary sand and mudstone lake sediments (Othberg & Stanford, 1992). The 325 km^2 study area contains steep foothills with a mean slope of 27% (15.1^0). Eight main ephemeral and perennial drainages flow through Ponderosa Pine (*Pinus ponderosa*) and Douglas Fir (*Pseudotsuga menziesii*) forests at high elevations

(~2400 m) and north facing slopes. At lower elevations and south-facing slopes, hillslopes are comprised of shrubs and grasslands when extend into the Boise River valley (800 m). Cool, wet winters provide spring snowmelt runoff-dominated flow through foothills streams into the Boise River. In contrast, summers are dry and hot, and only occasional thunderstorms providing moisture (*Watershed Description*).

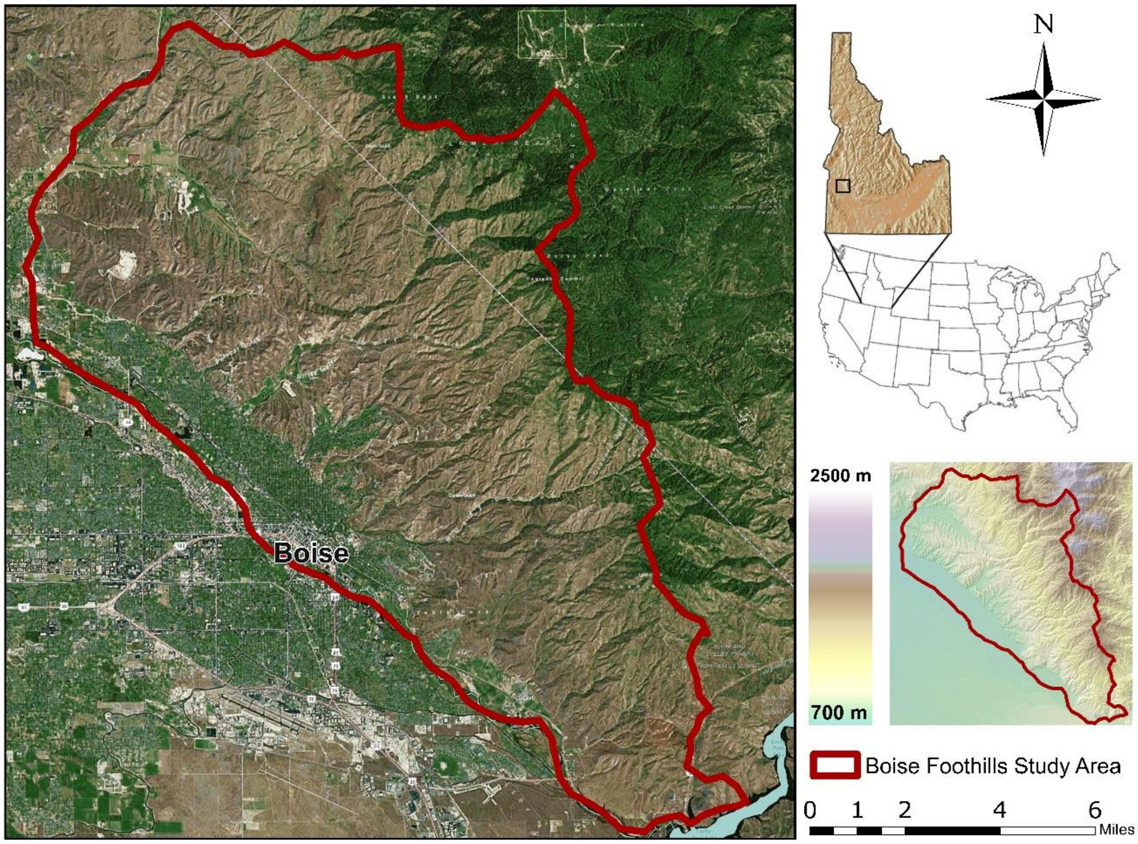

Figure 2.1 Map of Boise Foothills study area, delineated in bold red. The area encompasses the greater Boise metropolitan area north of the Boise River, rangeland and forested foothills extending from Lucky Peak Reservoir in the East to Interstate 55 to the west and northward to the foothills ridgeline.

Fire season within the Boise Foothills study area extends through the summer months, from May to September. Summer convective storms provide lightning-caused fire ignitions. However, humans exacerbate wildfire, and are the dominant cause of ignitions in the Boise area, starting ~86% of fires in the Boise WUI (Figure 2).

Historically within the study area, Ponderosa forests burned at moderate to low severity at 20-30 year intervals, with infrequent, stand replacing high severity fires (Barret et al., 1997). A dendrochronological study in the Boise National Forest, north of the study area, found that fires burned though old growth Ponderosa Pines at a frequency between fifteen and fifty years. However, that return interval ends in tree ring records, with no fires occurring since 1889, likely indicating in initiation of fire suppression policy in the region. (Cutter, 2013). At lower elevation slopes, sage-steppe ecosystems have a relatively unknown fire return interval, due to the difficulty in acquiring tree ring records or depositional records from within the ecosystems. However, it is estimated that these fuel limited systems historically have fire return intervals of approximately a century in *Artemisia tridentate* var. *wyomingensis* (Mensing et al., 2006), though studies have also identified return intervals in Big Mountain sage between 12-30 years (Miller and Rose, 1999). However, wildfire return intervals shorten in sage-steppe ecosystems invaded by non-native grass species that outcompete native species after wildfire. The grass species, *Bromus tectorum*, commonly known as cheatgrass, fills interspace, allowing fire to spread where it would have otherwise not. Cheatgrass also cures early in the summer season, extending the season during which fuels are flammable, and are adapted to grow well after fire, thereby replacing and outcompeting species that would otherwise maintain a higher fire return interval. This process, known as the cheatgrass fire cycle, increases the potential for frequent wildfires in locations including the Boise Foothills study area, where human activities including grazing, recreation and development aid in the spread of the flammable grass.

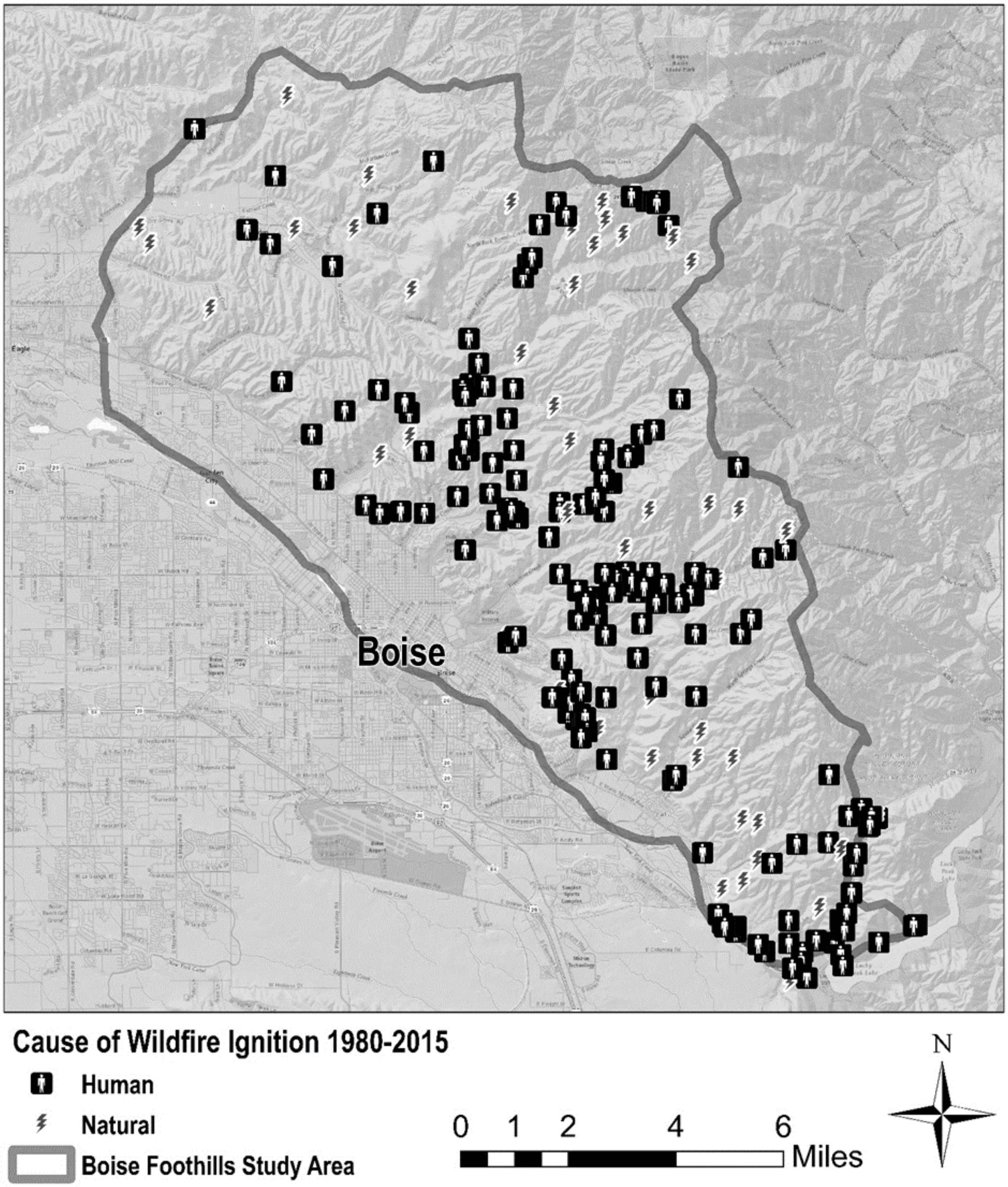

Figure 2.2 Human- and lightning-caused wildfire ignitions in the Boise, Idaho USA area.

The Boise Foothills have written and geologic records of post-fire erosion. Poulos (2016), identified several post-fire deposits within the Dry Creek Experimental

Watershed, which is encompassed by the Boise Foothills study area. Alluvial fans of first-order channels with small contributing basins (<0.3 km^2) were interpreted to be comprised of both sheetflood and debris flow deposits, some of which contained charcoal (Figure 3A), indicating that fire created conditions by which erosion could occur. These records indicate that post-fire erosion activity in the Boise Foothills extend beyond 8000 BCE. Evidence of post-fire erosion is also evident in ~1-10 km^2 alluvial fans of 3rd order channels that extend from confined foothills drainages onto the Boise River floodplain. Deposits found closer to the Boise Foothills, at Squaw Creek, contain poorly sorted, matrix supported cobble and boulder-sized clasts and charcoal, indicating that debris flows have been generated after fire in this area (Figure 3B). Similar deposits can be found in Cottonwood Creek drainage, whose outlet is near Boise city center; exposed sheetflood deposits located ~0.5 km from foothills contain charcoal, indicating that post-fire deposition can be extensive. Together, these deposits indicate that post-fire erosion occurs at a range of magnitudes, in multiple modes, and that at least a portion of erosion occurring in the foothills is carried out by mass wasting events. Interestingly, as neighborhoods continue to be developed atop alluvial fans of the Boise Foothills, deposits like those described will become lost; the debris flow deposit photographed in Figure 3B has since been graded and paved into a road leading to a development.

Figure 2.3 Fire-related deposits and their location in the Boise Foothills Study area. 3A: Sheetfloods containing charcoal are interpreted as being fire-induced, and overlay an interpreted debris flow deposit where charcoal is absent. 3B: A ~0.5 m boulder within a matrix-supported deposit containing charcoal indicates a debris flow deposit at the outlet of Squaw Creek, and is likely a 1959 debris flow deposit.

More recent records indicate the fire-induced flooding and mudslides have caused extensive damage to Boise residents. Flooding and mudslides in 1959 followed three fires in the foothills (1957 Rocky Canyon Fire, 1958 Toll Gate Fire, and 1959 Lucky Peak Fire). Sediment and debris from the mudslides covered 50 city blocks as well as hundreds of acres of agricultural land that have since been developed into neighborhoods (Thomas, 1963). Sediment was likely sourced from both thick, forest soils of higher elevation slopes and from rills and gullies that formed on lower elevation rangeland slopes, as evinced by photos and footage of the aftermath of the event (Thomas, 1963; *When the*

Pot Boiled Over). The damage and clean-up cost and estimated $4,000,000 (Ada County). To prevent future erosion from causing damage to homes downslope, the Soil Conservation Service, Forest Service and Bureau of Land Management terraced hundreds of acres of foothills.. Other historic and recent records of post-fire erosion in the Boise Foothills study area include sedimentation and flooding on September 11, 1997 after 0.4 inches of rain fell in nine minutes over the 1996 8th Street Fire. Flooding took place around Crane Creek and Hulls Gulch, but was contained by retention ponds and did not produced debris flows. The flooding response was likely significantly reduced due to rehabilitation efforts including terracing, contour fell logging, reseeding, straw wattles and check dam construction that took place shortly after the fire to protect foothills soils and watersheds (Fend et al., 1999).

Methods

We modeled post-fire debris flow hazards of drainage basins in the Boise Foothills (Figure 4) using the post-fire debris flow probability and volume models developed by the USGS (Cannon et al., 2010). The models require topographic, soils, fire and precipitation data, described more thoroughly in Table 1. The following section describes the steps taken to acquire the model input data.

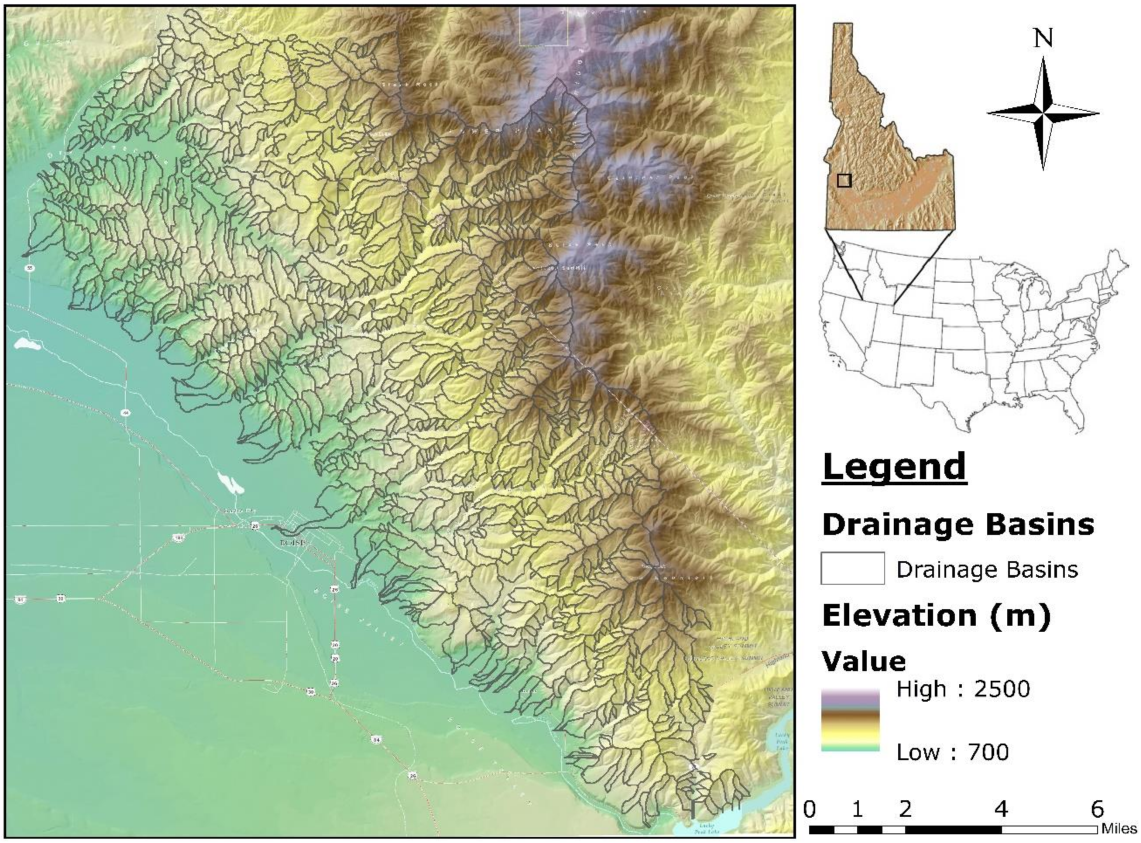

Figure 2.4 Drainage basins of the Boise Foothills study area (delineated in gray) assessed for post-fire debris flow hazards.

Table 2.1 Post-fire debris flow model (Cannon et al., 2010) inputs, their descriptions and sources.

Input Category	Debris Flow Probability		Debris Flow Volume		Data Source
Fire	% of basin burned at moderate and high severity	$\%B$	% of basin burned at moderate and high severity	B	10%, 25%, 50%, 75%, 100%
Soil	% clay	C	none		NRCS Web Soil Survey, field collection
	Liquid limit	LL			
Topography	% of basin ≥ 30% gradient	$\%A$	% of basin > 30% gradient	A	USGS National Map Viewer and Download Platform, 1/3 arc second DEM
	basin ruggedness	R			
Weather	Average stormfall intensity (mm/hr)	I	Total storm rainfall (mm)	T	NOAA Atlas 2

Post-fire debris flow models

USGS post-fire debris flow models were developed using logistic regression of 388 basins that burned within 15 fire perimeters throughout the Intermountain West (Cannon et al., 2010). Debris flow probability (equation 1) is estimated using soil, topographic, burn severity and precipitation data in the probabilistic model (Equation 1):

$$P=e^{x}/(1+e^{x}) \qquad \text{Equation 1a}$$

and

$$x=0.03(\%A)-1.6(R)+0.06(\%B)+0.07(I)+0.2(\%C)-0.4(L)-0.7 \qquad \text{Equation 1b}$$

where %A is the percent of basin area having slopes greater than or equal to 30%, R is basin ruggedness using the Melton Ruggedness Number (basin relief divided by the square root of the basin area), %B is the percent of the drainage basin burned at moderate and high severity, I is the average stormfall intensity (mm/hr), C is the clay content in percent, and L is the liquid limit.

Debris flow volume (m^3) is estimated using topographic, burn severity and precipitation data using the multivariate regression model (Equation 2):

$$\ln(V) = 7.5+0.6(\ln(A))+0.7(B)^{1/2}+0.2(T)^{1/2} \qquad \text{Equation 2}$$

where A (km^2) is the area of the drainage basin having slopes greater than or equal to 30%, B is the area (km^2) of the drainage basin burned at moderate and high severity, and T is the total storm rainfall amount in millimeters.

The post-fire debris flow models are capable of predicting debris flow probably and volume within the range of area of drainage basins used to develop the model. Therefore the maximum basin size that can be assessed with the models is ~10 km^2. Post-fire debris flow hazards are determined by assessing the model estimates of probability and eroded volume together for each drainage basin. Debris flow predictions with high probabilities of occurrence but low estimated volumes are lower hazards than basins predicted to have both high probability of debris flow occurrence and high estimated volumes. We assigned values 1-4 for binned probability and volume ranges to consider both probability and volume in hazard rankings (Table 2). Probability and volume rank values were summed for each drainage basin. The summation provides a scaled hazard ranking 2-8 for drainage basins in the Boise Foothills.

Table 2.2 Rank value of probability and volume values. Probability and volume rank values are summed for each basin to provide an overall hazard rank per drainage basin.

Rank	**Probability**	**Volume (m^3)**
1	**<25%**	**<100**
2	**25-50%**	**1,000**
3	**50-75%**	**10,000**
4	**75-100%**	**100,000**

Topography

We delineated drainage basins and extracted slope and ruggedness values for hillslopes within the Boise Foothills study area using a 10-meter digital elevation model (DEM) and Spatial Analysis tools in ArcMap 10.2 (Dollison, 2010). To delineate drainage basins, we used the Flow Accumulation, Con, Watershed, Spatial Statistics and Raster Calculator tools in ArcMap 10.2. Post-fire debris flow models can only be used to model basins between 0.1-10 km^2. We used records of debris flow deposition in the Boise Foothills (Poulos, 2016) to select the basin size for analysis; the study found that deposits were sourced from basins $<0.3\ km^2$ in area. Ruggedness was calculated using the Melton Ruggedness Number (Eq. 3):

$$(Zmax-Zmin) / Sqrt(A) \qquad \text{Equation 3}$$

where Zmax and Zmin are the maximum and minimum elevations of a given basin (m), respectively, and A is the area of the basin (m^2). Drainage basin area, percent slope above 30% and basin ruggedness were appended to an attribute table for the all the delineated drainage basins. The mean elevation and slope of each drainage basin were also calculated and appended to the drainage basin attribute table as supplemental data for analysis.

Soil

We acquired clay content and liquid limit data for soils of the Boise Foothills study area using the Soil Survey Geographic Database (SSURGO), available for download through the Web Soil Survey. Prior post-fire debris flow hazard assessments use the State Soil Geographic (STATSGO) (1:250,000) dataset, however Cannon et al. (2010) encourage the use of higher resolution data, where available. Therefore we used SSURGO maps for the Boise Foothills, which are mapped at 1:12,000 and 1:63,000 scale. We used Spatial Statistics and Raster Calculator tools to calculate the average clay content and liquid limit within each drainage basin. The accuracy of soils data for the Boise Foothills is unknown. To determine the accuracy of soil clay content data mapped by SSURGO, we compared SSURGO values to field samples whose clay content was measured using the hydrometer method. The results of this comparison can be found in Appendix A, and will be included in the discussion section of this chapter.

Burn Severity

Burn severity is the degree to which soil, flora and fauna have been altered or disrupted by fire (Miller et al., 2013). A burn area may contain patches of low, moderate and high severity burns. The USGS post-fire debris flow models require the percent at which a basin burned at moderate and high severity. While USGS post-fire debris flow models are often used within burn perimeters where fire severity across the landscape is known, modelling over a pre-fire landscape, where burn severity cannot be known, we instead apply a range of percentages of low, moderate and high burn severity to drainage basins at 25% increments. Applying incremental burn severity scenarios provides the range of potential post-fire debris flow hazards within the Boise Foothills study area.

Precipitation

The post-fire debris flow models require inputs of 1hr stormfall intensity (mm/hr) and 1hr total rainfall (mm) to estimate both debris flow probability and volume. We calculated 1hr stormfall intensity for 2- and 100-year recurrence interval storms using equations specific to the Snake River Valley (Miller et al., 1973) and rainfall intensity, duration and frequency curves for Boise, Idaho (City of Boise Public Works, 2010).

Vegetation

We used LANDFIRE Existing Vegetation Type to determine the vegetation cover for the Boise Foothills study area (LANDFIRE, 2017). The Boise Foothills study area contains twenty cover types classified by LANDFIRE (Table 3). We reduced these classifications to forest, rangeland or urban for bimodal vegetation analysis of the post-fire debris flow models. We classified each drainage basin as a rangeland or forested basin based upon which of the two classifications had the greater percent coverage within a basin. Basins dominated by urban cover were not included in vegetation-type basin comparisons.

Table 2.3 LANDFIRE Existing vegetation Types and their classification as a Forest or Rangeland vegetation type

Cover ID	Description	Range or Forest
3001	Intermountain Basin sparse vegetation	Rangeland
3045	Northern Rocky Mountain dry-mesic montane mixed conifer	Forest
3053	Northern Rocky Mountain ponderosa Pine woodland and savanna	Forest
3080	Intermountain basin big sagebrush shrubland	Rangeland
3081	Intermountain basin mixed salt desert scrub	Rangeland
3106	Northern Rocky Mountain montane foothill deciduous shrubland	Rangeland
3123	Columbia Plateau steppe and grassland	Rangeland
3124	Columbia Plataeu low sagebrush steppe	Rangeland
3125	Intermountain basins big sagebrush steppe	Rangeland
3126	Intermountain basins montane sagebrush steppe	Rangeland
3139	Northern Rocky Mountain lower montane foothill-valley grassland	Rangeland
3181	Introduced upland vegetation – annual grassland	Rangeland
3182	Introduced upland vegetation – perennial grass and forb	Rangeland
3220	Artemisia tridentata ssp. Vaseyana Shrubland Alliance	Rangeland

3227	Dry mesic montane Douglas Fir forest	Forest
3296	Developed – low intensity	Developed
3299	Developed – roads	Developed
3903	Western cool temperate urban herbaceous	Developed
3904	Western cool temperate urban shrubland	Rangeland
3923	Western cool temperate developed Ruderal shrubland	Rangeland
3965	Western cool temperate close-row crop	Developed
3967	Western cool temperate pasture and hayland	Developed
3968	Western cool temperate wheat	Developed

Results

The Boise Foothills study area contains 857 drainage basins between 0.39 km^2 and 1.4 km^2. Forty-nine of the basins are classified as forested basins and 771 are classified as rangeland basins (Figure 5). The remaining 37 basins are classified as urban development, and are not included further in this assessment. The average slope within a drainage basin ranges from 5 to 63 percent ($2.8\text{-}32.2^0$). The average slope of basins increases with elevation (Figure 6). Forested basins have an average slope of 49.8 percent while rangeland slopes have an average slope of 30.6 percent (Figure 7).

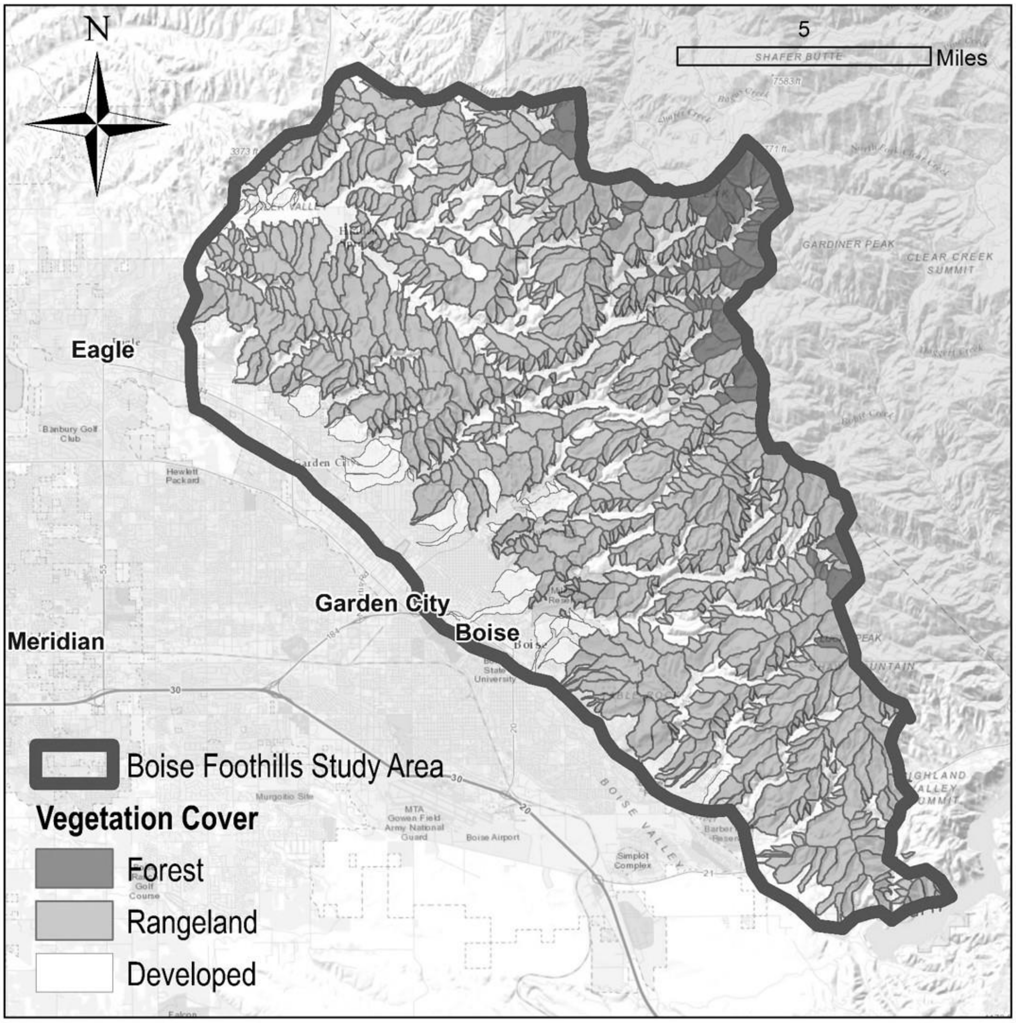

Figure 2.5 **Drainage basins of the Boise Foothills study area, classified by dominant vegetation type within each basin.**

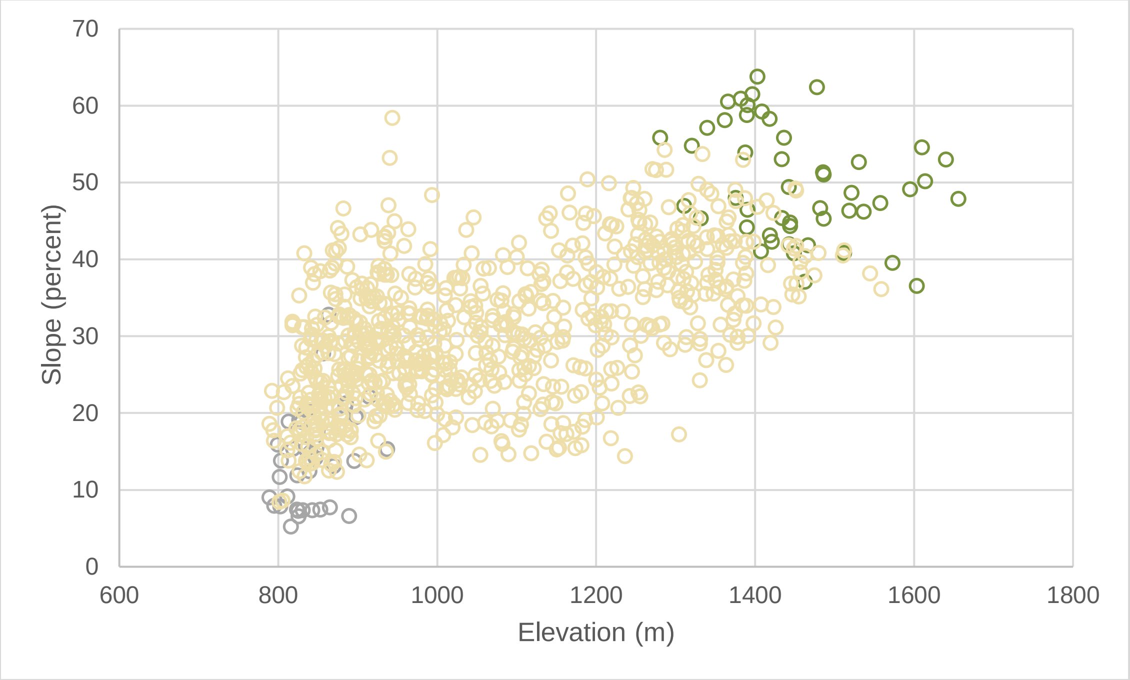

Figure 2 6 Average slope of drainage basins plotted against mean drainage basin elevation and divided by dominant cover types, forest (green), rangeland (tan) and urban (gray).

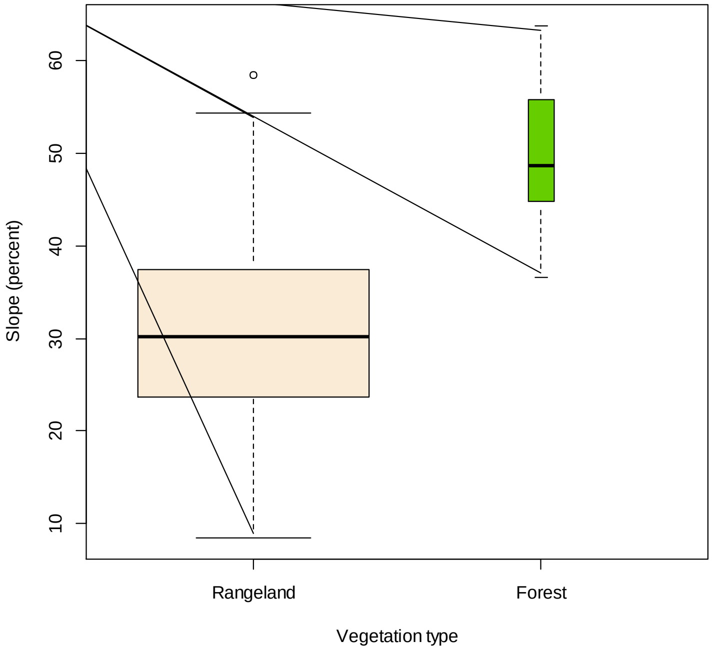

Figure 2.7 Comparison of average basin slope between dominant vegetation cover types. Boxplots are scaled along the x axis by basin population. Box width indicates sample size, where forest n = 41, rangeland n = 771.

The ruggedness of drainage basins in the Boise Foothills ranges from 0.08 to 1.5, with a mean ruggedness of 0.42. Forested basins have an average ruggedness of 0.72 while rangeland basins have an average ruggedness of 0.41.

The average clay content within a drainage basin ranges between ~5% to ~36%. Clay content decreases as elevation increases (Figure 8). The average clay content for forested basins is ~8% and ~17% for rangeland basins. Because we used digitized (SSURGO) clay content instead of field-verified clay content values, we compared the SSSURGO clay content values to soil samples taken from the southeast region of the Boise Foothills study area. The results of that comparison can be found in Appendix A.

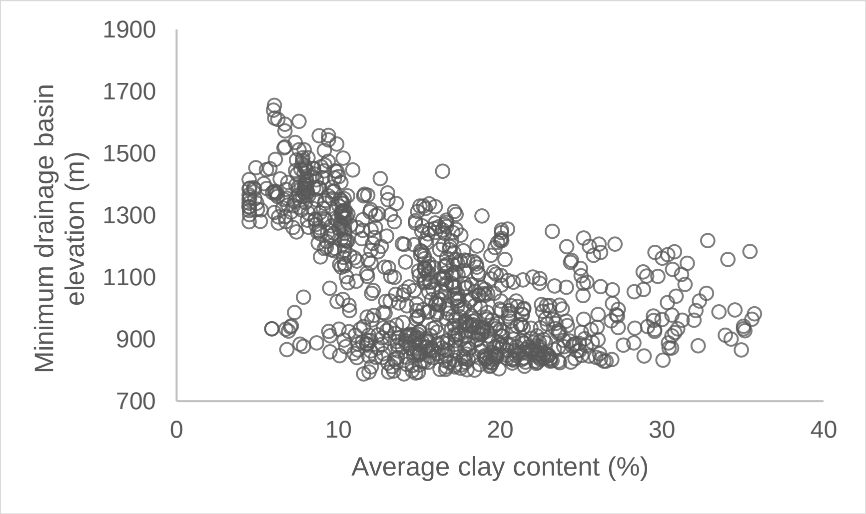

Figure 2.8 Clay content (%) plotted against drainage basin outlet elevation.

The average SSURGO liquid limit within drainage basins ranges from 9% to 48%. The average SSURGO liquid limit for forested basins is ~41% and ~44% for rangeland basins in the Boise Foothills study area.

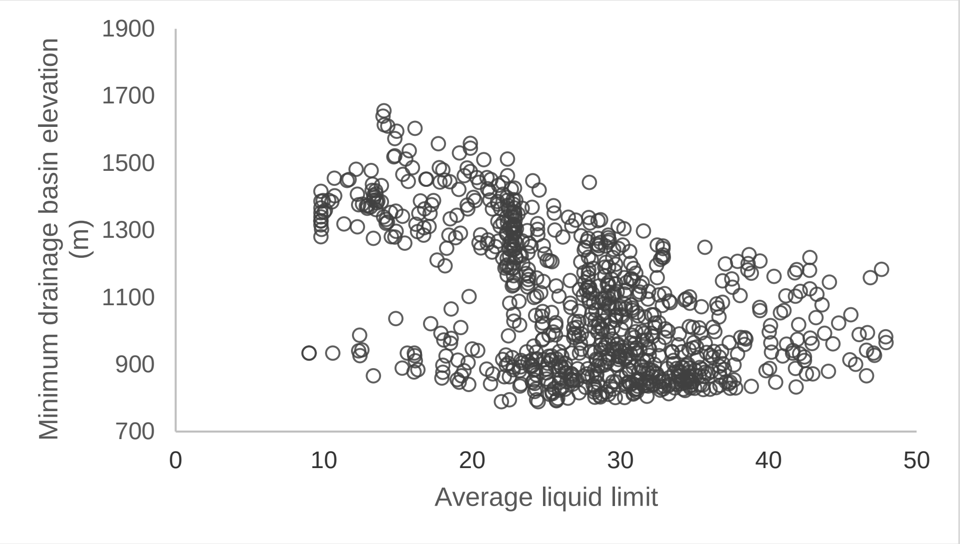

Figure 2.9 Drainage basin average liquid limit plotted against drainage basin outlet elevation.

Post-fire debris flow scenarios

We modeled eight post-fire debris flow scenarios by applying four burn severity scenarios, (25%, 50%, 75% and 100% at moderate and high severity) with two precipitation scenarios (1hr duration, 2- and 100- yr recurrence storms). A two-year recurrence, one hour storm intensity for the Boise Foothills is 10.1 mm/hr, while a 100-year recurrence, one hour storm intensity is 27.0 mm/hr. To simplify the discussion of different scenarios, we will refer to each scenario as named in Table 4.

Table 2.4 Burn severity and rainfall description of eight post-fire debris flow scenarios

Scenario Name (L = low recurrence, H = high recurrence)	**Burn Severity Scenario** % area burned at moderate & high severity	**Precipitation Scenario** (recurrence interval)	**Stormfall Intensity** (mm/hr)	**Total stormfall** (mm)
L25	25%	2 yr	10.1	10.9
L50	50%	2 yr	10.1	10.9
L75	75%	2 yr	10.1	10.9

L100	100%	2 yr	10.1	10.9
H25	25%	100 yr	27.0	29.3
H50	50%	100 yr	27.0	29.3
H75	75%	100 yr	27.0	29.3
H100	100%	100 yr	27.0	29.3

Modeled post-fire debris flow volume estimates ranged between ~13 m^3 and ~8255 m^3 for basins L25 and L100, respectively, and as high as 12,586 m^3 for basins under the H100 scenario. Under all burn scenarios, debris flow volume estimates were as much as 52% higher under a 100-yr storm than a 2-yr storm. Models estimate the average post-fire debris flow volume to be 847 m^3 and 1292 m^3 higher in forested basins than rangeland basins under 2- and 100-year storm scenarios, respectively (Figure 10).

When normalizing post-fire debris flow volumes by basin size, forested basins produce 269 m^3/m^2 and 411 m^3/m^2 more sediment than rangeland basins under 2- and 100-year storm scenarios, respectively (Figure 11). Volume estimates for each scenario are broken into 2000 m^3 intervals, and displayed in Table 5. The average post-fire debris flow volume produced by drainage basins under a two-year recurrence storm is 1237 m^3, while the average volume produced by a 100-yr recurrence storm is 1885 m^3.

Modeled post-fire debris flow probability estimates ranged from <0.1% and 93.7% for L25 and L100, respectively, and as high as 99.9% for basins under the H100 scenario (Table 6). Under all burn scenarios, a 100-year recurrence, one hour storm increased debris flow probability within a single drainage basin by as much as 94% as compared to the two-year recurrence storm (Figure 12). The average probability of a basin producing a post-fire debris flow during a two-year recurrence storm is 6.4%, while the average probability of a basin producing a post-fire debris flow during a 100-yr recurrence storm is 45.0%.

Table 2.5 Count of basins that fall within 2000 m^3 intervals of volume estimates under post-fire debris flow scenarios *(n=857)*

Volume (m^3)	L25	H25	L50	H50	L75	H75	L100	H100
<2000	721	618	708	597	691	578	675	571
2000-4000	125	168	121	164	130	164	135	156
4000-6000	11	58	26	66	33	75	40	79
6000-8000	0	12	2	27	3	32	6	34
8000-10000	0	1	0	3	0	6	1	14
10000-12000	0	0	0	0	0	2	0	2

Table 2.6 Number of basins that fall within 25% probability intervals under post fire debris flow scenarios (n=857)

Probability (%)	L25	H25	L50	H50	L75	H75	L100	H100
<25	850	788	812	575	768	177	721	0
25-50	7	40	40	135	47	152	51	39
50-75	0	27	5	48	38	170	44	67
75-100	0	2	0	99	4	358	41	751

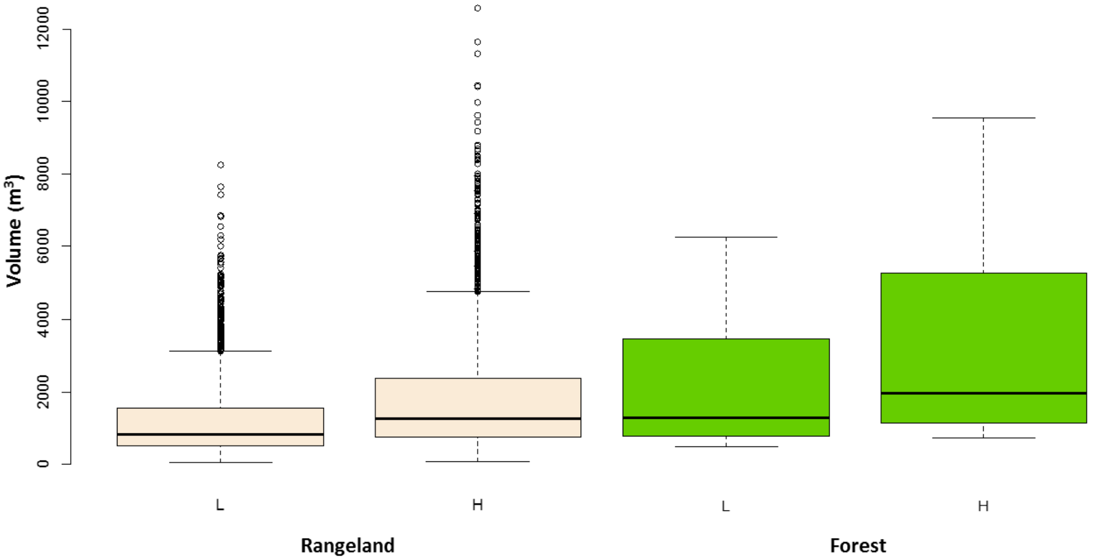

Figure 2.10 Comparison of modeled post-fire debris flow volumes between low (L) and high (H) recurrence interval storms (2- and 100-yr rainfall events) within rangeland (tan) and forested (green) drainages under all burn scenarios. Median values for each scenario are indicated by bold horizontal lines. Rangeland n = 771, Forest n =41

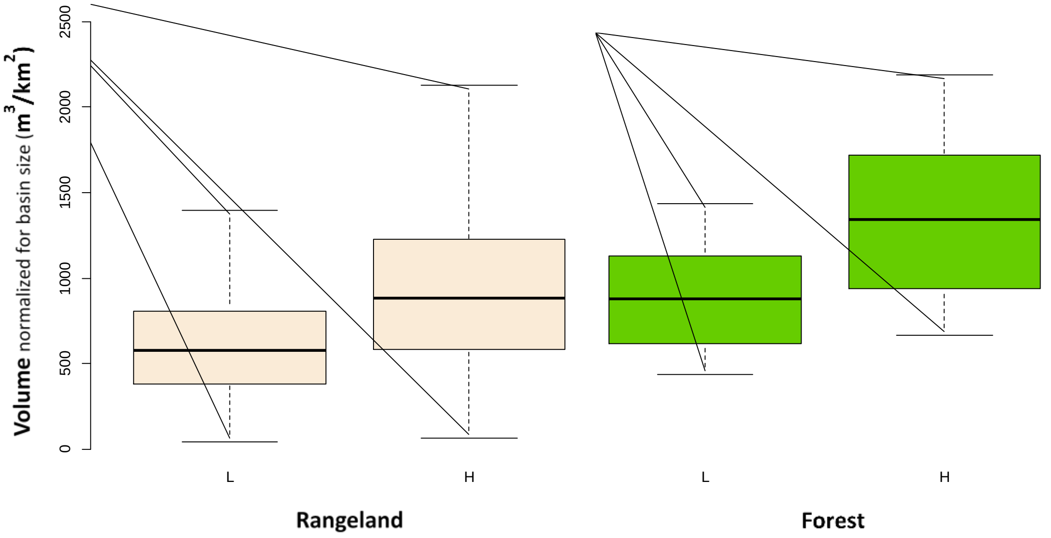

Figure 2.11 Comparison of modeled post-fire debris flow volumes, normalized for basin size, between low (L) and high (H) recurrence interval storms (2- and 100-yr rainfall events) within rangeland (tan) and forested (green) drainages under all burn scenarios. Median values for each scenario are indicated by bold horizontal lines.

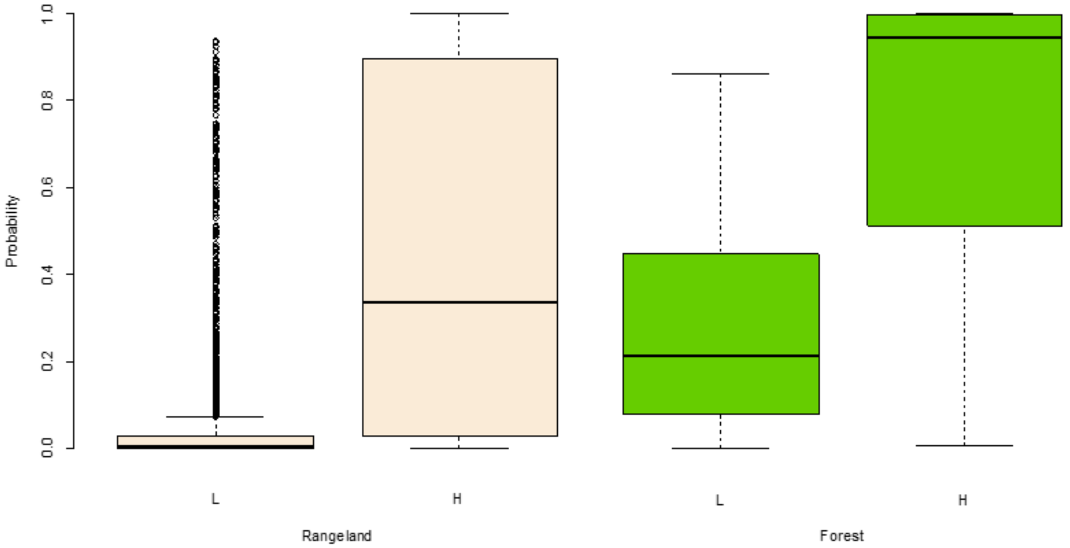

Figure 2.12 Comparison of modeled post-fire debris flow probability between low (L) and high (H) recurrence interval storms (2- and 100-yr rainfall events) within rangeland (tan) and forested (green) drainages under all burn scenarios. Median values for each scenario are indicated by bold horizontal lines.

Discussion

Across all fire and precipitation scenarios, post-fire debris flow probability and resulting volume are higher in forested basins than rangeland basins. The average modeled sediment yield was ~1.4x higher for forested basins than rangeland basins under both the low and high precipitation recurrence scenarios. The average post-fire debris flow probability was ~15% and ~32% greater for forested basins than rangeland basins under the 2yr and 100yr recurrence rainfall events, respectively.

Higher predicted debris flow occurrence and higher sediment volumes for forested drainage basins can be explained by disparities in soil properties, vegetation and fuels, and basin characteristics. Conceptually, the disparity of volume estimates between forested and rangeland slopes may be explained by soil thickness between forest and rangeland slopes. Poulos (2016) found that soils are thicker on forested, north-facing slopes than on sparsely vegetated, south-facing slopes in the Boise Foothills. Therefore, per unit area, there is less mobile sediment available to contribute to a debris flow on rangeland slopes than forested slopes. Hypothetically then, if drainage basins of equal size and slope were comprised of contrasting vegetation types (rangeland and forest) and both failed in a post-fire debris flow, a rangeland debris flow would have a lower sediment yield than that of a forested basin.

While this study controlled for burn severity within the post-fire debris flow scenarios, forests often burn at higher severity than rangelands. Therefore, fire in forests damage soil more severely than fire in rangelands. There is also more biomass to burn in forests than in rangelands, which may produce more ash than in rangelands, contributing more fine material from which debris flows initiate after fire. Additionally, forested soils within the study area are finer with forested slopes than rangeland slopes (Smith, 2010; Poulos, 2016). Fine sediment is thought to induce sediment bulking to initiate the debris flow-forming process. Fine sediment reduces infiltration rates, inducing overland flow. Fine sediment also increases the viscosity of flows that are able to entrain larger sediment, transitioning the sediment bulking process into a debris flow.

In reality, however, the soils data used to predict post-fire debris flows in the Boise Foothills study area map lower clay content within forested basins than within rangeland basins. Unlike the majority of the basins within the Boise Foothills study area, low elevation drainage basins are comprised of lacustrine parent material. Lacustrine sediment of ancient Lake Idaho is comprised of fine sediment, and increase the abundance of fines that contribute to increased debris flow probability. Clay content values modeled by SSURGO maps used in this study have been found to have inaccurate clay content measurements. Within lower-elevation soils of the Boise Foothills, SSURGO has been found to overestimate clay content by ~10%, which induces overestimation of post-fire debris flow probability in rangeland slopes (Appendix A).

Dissimilarity of post-fire debris flow probability between forested and rangeland slopes may also be explained by higher slopes within forests compared to those of rangelands. Slopes within forested basins were ~19% higher than in rangeland basins, increasing the likelihood the failure would occur on burnt forested slopes than rangeland slopes.

Interestingly, while post-fire debris flows are predicted to be less likely in rangelands than in forested basins, the Boise Foothills have produced fire-induced debris flows in recent history. In 1959 a ~9000 acre burn area produced debris flows from six large drainage basins, burying much of the Boise Metropolitan area in sediment in debris (Thomas, 1963). The basins that produced these debris flows are ~9-22 km^2, approximately one order of magnitude higher than the basin size modeled in this study (0.1-1.4 km^2). Cannon et al. (2010) describe that post-fire debris flow-producing basins are commonly no larger than 1 km^2. Because basins that produced debris flows in the rangeland-sourced 1959 post-fire event were larger than those of forested basins, it may be that, because of the limited sediment source of basins that typify rangeland ecosystems, a larger drainage area is required to source sediment in order to produce post-fire debris flows. This theory is supported by Pierson et al. (2014), who describe that, in rangeland systems, there is increasing soil loss at increasing scales of study (i.e. from plot to hillslope scale) on post-fire slopes.

Conclusion

This study found that, using USGS post-fire debris flow models, the average modeled sediment yield for forested basins are predicted to be ~1.4x higher for than rangeland basins under low and high intensity rainfall events. Additionally, post-fire debris flow probability is predicted to be ~15% and ~32% greater for forested basins than rangeland basins under low (2 yr) and high intensity (100 yr) rainfall events, respectively. The disparity of these model predictions are the result of contrasting soils and slopes between these ecosystems within the Boise Foothills study area and, under real world events, may be further driven by contrasting burn severity between forests and rangeland. Identifying and understanding contrasting post-fire debris flow response between these ecosystems is important when attempting to inform potential hazards. Our findings show that debris flow hazards may be lower when sourced from rangeland basins as opposed to forested basins when controlling for fire severity and precipitation intensity. However, wildfire and subsequent rainfall is often complex and unpredictable, and understanding individual circumstances is vital when attempting to assess potential risks to life and property. As such, by applying post-fire debris flow models in a pre-fire environment serves only as a starting point for assessing post-wildfire debris flow hazards, and may aid in making decisions regarding how to prepare for and mitigate this hazard in an urban setting.

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CHAPTER III: COMPARISON OF POST-FIRE DEBRIS FLOW MODELS TO A HISTORIC POST-FIRE DEBRIS FLOW EVENT IN THE BOISE FOOTHILLS UNVEIL LIMITATIONS FOR MODEL USE IN RANGELAND LANDSCAPES

Abstract

Like many cities in the western US (e.g. Denver, Reno, Salt Lake City), the Boise Wildland Urban Interface (WUI) is located at the base of a mountain front. These vegetative communities are typified by shrubs (sagebrush-steppe) and grasslands at lower elevations, with open forests at higher elevation and on north-facing slopes. After fire, these mountainous slopes are highly susceptible to catastrophic flooding and erosion by post-fire debris flows. Despite increasing WUI development concurrent with growing fire and erosion hazards in these ecosystems, post-fire debris flow models are not developed or calibrated for sparsely vegetated systems, and have gone largely untested in these particularly vulnerable WUI landscapes. In this study, we test model post-fire debris flow probability and volume models developed by Cannon et al. (2010) against a historic record (Thomas, 1963) of post-fire debris flow erosion in the rangeland-dominated foothills of Boise, Idaho USA. Our work seeks to identify discrepancies in post-fire debris flow models that may arise as the result of applying models used in forested environments to areas for which they were not calibrated; namely the Boise Foothills and, more generally, rangeland ecosystems. Prior studies in Idaho show that lower severity fires burning on open grassland and sagebrush-steppe dominated slopes produce more

frequent erosion events of lower magnitude (smaller debris flows and sheetfloods) compared to post-fire erosion following high-severity fire in forested landscapes, where sediment storage capacity is higher and debris flows predominate (Pierce et al., 2004; Weppner et al., 2013: Riley et al., 2015). Therefore, we hypothesize that the models constructed from forest-sourced debris flow data will overestimate the volume of sediment and will under-predict the probability of debris flow occurrence compared to the actual 1959 post-fire debris flow event. We found that the post-fire debris flow volume model estimates yields (Mg/km^2) ~2-6x greater than those produced in the 1959 post-fire debris flow event. The 1959 debris flow yields are similar to those estimated in regional depositional records (Riley, 2012; Poulos, 2016) sourced from sparsely vegetated drainage basins, while modeled yields of the 1959 debris flow event are similar to those sourced from forested basins within the region. Additionally, only one drainage was modeled to have >50% probability of debris flow occurrence under the 1959 post-fire debris flow scenario, and only under the highest modeled burn severity scenario, despite the fact that all basins did produce debris flows. We conclude that post-fire debris flow models are more suited to forested slopes, as sediment yields appear to be distinct between burned rangeland and forested drainage basins with the region.

Introduction

Wildfires in the western United States have increased in size and severity in response to earlier snowmelt (Westerling, 2016) and hotter ambient temperatures (Scasta et al., 2016) induced by climate change. As a result, the fire season is expanding due to both climatic (Abatzaglou et al., 2016) and human influence on wildfire activity and ignitions (Balch, et al., 2017). Subsequent to wildfire over a mountainous landscape, the potential for erosion landscapes increases after fire (Swanson et al., 1981; Moody and Martin, 2009). Increases in wildfire activity may double erosion in some western US regions (Sankey, GSA/AGU).

Debris flows constitute the most hazardous form of fire induced erosion and are an anticipated erosional response to wildfire in mountainous landscapes (Cannon and Gartner, 2005). When humans inhabit regions prone to both wildfire and debris flows, fire-induced debris flows pose a serious hazard to life and property. Human ignitions expand the wildfire season in the western United States (Balch et al., 2017). The population of the western US is predicted to continue expanding into the Wildland Urban Interface (Bramwell, 2015). As these fires increasingly burn slopes in the WUI, the risk of post-fire erosion also increases. Consequently, human expansion will likely partially occur in debris flow deposition zones, and the number of people threatened by post-fire debris flows will increase over time.

Anticipating the location and magnitude of debris flows in recently burned areas has been a subject of study in recent years (Cannon et al., 2001; Cannon et al., 2008; Cannon et al., 2010; Staley et al., 2016). These studies culminated into the creation of models that predict where debris flows are most likely to occur after fire, and estimate the amount of sediment that the debris flow will deposit (Cannon et al., 2010, Staley et al., 2016). The most recent iterations of these models are commonly used within wildfire perimeters on Forest Service land to target and manage for areas where high debris flow potential intersects resources of interest (e.g. roads, streams).

Notably, these post-fire debris flow hazard models were built using data from debris flows sourced primarily from forested drainage basins. However, while many fire induced debris flows occur in forested areas, their occurrence has been reported in rangelands and sparsely vegetated hillslopes (Thomas, 1963; Pierson et al., 2008). Due to contrasting soils, vegetation, and burn severity between forests and rangelands, it is possible that post-fire debris flow models built using data from forest debris flows may not be suitable to forecast debris flow hazards in rangeland landscapes. The utility of post-fire debris flow models in rangelands has not been tested. Because many communities abut mountainous rangelands (Colorado Front Range, Reno, Salt Lake City, Boise), it is important to test the ability of post-fire debris flow models to predict debris flow hazards in this unique ecoregion. The Boise Foothills of southwestern Idaho mark the northern extent of the Great Basin sage-steppe ecosystem and have a rich history of both wildfire and post-fire erosion, providing an ideal location to compare post-fire debris flow events within mountainous rangelands, to those predicted to occur through a modeling exercise.

This study compares post-fire debris flow sediment yields produced from rangeland drainages after a ~100 yr rainfall event mobilized sediment within a ~9500 acre fire in the Boise Foothills to those predicted by post-fire debris flow models. We then compare the event and model yields to local and regionally relevant sediment yields extrapolated from Holocene alluvial fan records to answer the following questions 1) do rangeland post-fire debris flow sediment yields differ between model predictions and measured volumes; 2) do local and regional depositional records reflect differences in post-fire debris flow sediment yields sourced between contrasting ecosystems (i.e. forests vs rangelands) and 3) do post-fire debris flow models accurately predict debris flow hazards for burnt rangeland hillslopes?

Because previous studies observe contrasting soil traits, fire severity, basin morphology and depositional expression between forested and rangeland slopes, we hypothesize that these debris flow models will overestimate the probability of debris flows occurring on rangeland slopes, recognizing that geologic records reflect sheetflood deposition on these less-vegetated slopes. We also postulate that models will overestimate the volume of debris flows on rangeland slopes, recognizing that less sediment is stored in rangeland soils, and when sediment is transported, it is by sheetflood rather than debris flow.

Background

Contrasting Post-Fire Erosion Response Between Rangelands and Forests

Slopes in post-fire landscapes erode as a function of fire severity and intensity. In addition, topography, and precipitation intensity and duration, and vegetation influence erosion after wildfire. Fire may reduce soil cohesion, and heat may break apart soil aggregates, making them more susceptible to erosion (McNabb and Swanson, 1990). The breakup of aggregates and the introduction of ash to the soil surface may reduce pore space by filling former voids, decreasing infiltration rates, leading to erosive surface runoff (McNabb and Swanson, 1990). Ash smooths the slope surface, promoting a continuous runoff surface (Lavee et al., 1995; Woods and Balfour, 2010). Conversely, ash may store precipitation and reduce runoff overall (Cerda and Doerr, 2008). Burnt vegetation may volatilize and be expelled into the topmost portion of the soil profile where it cools and solidifies within pore spaces, inducing hydrophobicity and subsequent runoff (DeBano, 2000). Vegetation loss resulting from fire also increases the exposure and susceptibility of the burned surface to rainfall as the result of a reduced canopy

(Shakesby and Doerr, 2006; Pierson et al., 2008; Miller et al., 2013). The impacts of wildfire on soil and vegetation often compound to create highly erosive slopes. Reduced cohesion, decreased pore space, hydrophobicity and introduction of an ashen surface as the result of fire leads to decreased infiltration and an increase in overland flow, which is exacerbated by less canopy protecting the surface from rainfall.

The impact of fire on erosion at the plot and hillslope scale (as described above) contribute soil, ash and sediment to erosional processes that occur at the drainage basin scale. Hyperconcentrated flows, sheetfloods and debris flows produced by drainages <2 yr after wildfire transport ~40-90% sediment (by weight) and are capable of transporting $>10^4$ Mg/km^2 in a single erosion event (Pierce et al., 2004; Riley, 2012). The form of sediment transport (i.e. hyperconcentrated flows, sheetfloods and debris flows) will vary with the fraction of water available to mobilize material. Despite the form it takes, each post-fire sediment transport type is often the result of sediment bulking by runoff from the coalescence of hillslope-scale sediment transport into main channels (Cannon et al., 2010).

The type of mass sediment transport that takes place within a burn area will vary by burn severity and extent, the intensity and duration of a rainfall event, soils, and drainage basin size and morphology (e.g. Cannon and Reneau, 2000, Pierce et al., 2004, Cannon et al., 2010; Staley et al., 2016). High burn severity damages soils, creates ashen material and may induce continuous hydrophobicity across hillslopes, conditions that promote the formation of debris flows. In contrast, low severity fires burn discontinuously over hillslopes, rendering them incapable of producing continuous runoff required to mobilize and entrain sediment needed to form debris flows through the sediment bulking process. Precipitation alters slope stability at both the slope surface and subsurface. At the surface, precipitation that is not intercepted by vegetation hits the ground surface and initiates erosion through rainsplash. When rainfall rates exceed infiltration rates, surface runoff will initiate on hillslopes and entrain sediment through overland flow and rilling which may initiate the sediment bulking process. In contrast, when infiltration rates exceed rainfall rates, soil will absorb water until saturated, at which point discrete, saturation-induced slope failures may occur. Both infiltration and runoff-induced slope erosion can promote post-fire debris flows, which is partially controlled by the nature of the sediment being subjected to erosion. Course soils lacking fine material often have abundant pore space compared to finer soils, increasing the ability for rainfall to infiltrate during periods of intense rainfall. Additionally, soils lacking fines are unable to supply the initial fine material to runoff that required to increase the viscosity of runoff, thereby entraining ever-courser sediment in the sediment bulking process. Fire introduces ash that contribute fines to this process. The basin morphology also dictates the formation of debris flows. Steep (~>30%), rugged slopes are often found to produce debris flows, while shallow, smooth slopes promote surface runoff (Cannon and Reneau, 2000). Additionally, Cannon et al. (2010) found that post-fire debris flows are not observed within basins ~10 km^2, and are instead frequently sourced from low-order drainage basins, often <1 km^2. Soil depth has been found to vary by vegetation type within the study region. Interestingly, these attributes vary by ecosystem type, and have been studied intensely within the study region.

Burn severity is driven by wildfire intensity and duration. Large fuels associated with forests are able to burn intensely and for prolonged periods of time due to their size

(1000 hr fuels) compared to those of rangelands (1-100 hr fuels) containing grasses and shrubs. High severity fires in forests damage soil, introduce large volumes of ash and induce hydrophobicity and promote debris flow activity. In contrast, rangeland ecosystems often burn most intensely in patches of sagebrush and in riparian areas, where larger fuel is concentrated, but burns quickly and incompletely through shrub interspace grasses and forbs. The resulting runoff is often discontinuous and hindered by erosion barriers of unburned patches of vegetation. The patchiness of the erosion reduces the total sediment transported from a rangeland basin, thereby reducing the total deposited volume. Burn severity is thought to play a role in post-fire deposition type seen in alluvial fan records along the Middle Fork Salmon River and South Fork Payette River; fire-related debris flows are inferred to result from high severity wildfires whereas low severity fires reflect sparsely vegetated hillslopes, and limits sediment deposition in post-fire erosion events (Pierce et al., 2004; Riley, 2012).

Soil texture and thickness vary with aspect-induced vegetation differences within the Boise Foothills. Forested, north-facing drainages of the Boise foothills have 1.1-2.3 times thicker soils than those found on south-facing, sparsely vegetated slopes (Smith, 2010). Soil depth limits the maximum amount of material that can be mobilized by a debris flow, and may ultimately control debris flow volume. Additionally, soils in the Boise Foothills have courser-textured soils on south-facing, sparsely vegetated slopes than those of north-facing forested soils (Tesfa et al., 2009). Coarse rangeland soils drain more quickly than fine soils, prolonging the induction of infiltrated-induced runoff that may initate sediment bulking. However, wildfire over rangeland soils introduce fine ash that may reduce infiltration and initiate surface runoff. Forested soils, with abundant fines, in contrast, infiltrate water more slowly, and the onset of infiltration-excess induced failure may occur more readily.

Slope-area thresholds are a well-studied aspect of post-fire debris flow induction. Slopes >30% are thought to have the gradient required to produce post-fire debris flows. Recent work from Dry Creek Experimental Watershed identifies that forested slopes have steeper slopes than sparse, rangeland slopes (Poulos, 2016). Poulos found that forested, north-facing drainage basins adjacent to the this study area have a mean slope of ~60%, while south-facing drainages have a mean slope of ~47%. While both forested and rangeland basins have slopes exceeding the 30% threshold, north-facing slopes have more gravitational potential to fail in a debris flow. Ruggedness of slopes also influences debris flow activity. Cannon et al. (2010) found that high ruggedness increases the probability of debris flow occurrence. In Chapter 3, we found that forested basins have an average ruggedness of 0.72 while rangeland basins have an average ruggedness of 0.4. Therefore, rangeland slopes would be less likely to produce debris flows. Additionally, post-fire debris flows have been observed to occur in basins <0.1 km^2 - ~30 km^2 (Cannon et al., 2010). Sediment produced by larger basins are thought to become diluted with water flowing in streams, thereby transitioning sediment transport from debris flow to concentrated flow (Cannon et al., 2001).

Post-fire Debris Flow Prediction

To predict post-fire debris flow hazards in the western US, the USGS developed empirically derived models that calculate the probability of debris flow occurrence and its resulting volume over a burn area and under a specified precipitation intensity and duration (Cannon et al., 2010). The models were developed using a logistic regression of

388 basins that burned within 15 fire perimeters within the Intermountain West. The models calculate debris flow probability using soil, topography, burn severity and precipitation attributes, and calculates debris flow volume using topography, burn severity and precipitation attributes. Debris flow probability (equation 1) is estimated using soil, topographic, burn severity and precipitation data in the probabilistic model (Eq. 1):

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

(Equation 1a)

and

$$x =0.03(\%A)-1.6(R)+0.06(\%B)+0.07(I)+0.2(\%C)-0.4(L)-0.7$$

(Equation 1b)

where %A is the percent of basin area having slopes greater than or equal to 30%, R is basin ruggedness using the Melton Ruggedness Number (basin relief divided by the square root of the basin area), %B is the percent of the drainage basin burned at moderate and high severity, I is the average stormfall intensity (mm/hr), C is the clay content in percent, and L is the liquid limit.

Debris flow volume (m^3) is estimated using topographic, burn severity and precipitation data using the multivariate regression model (Eq.2):

$$\ln(V) = 7.5+0.6(\ln(A))+0.7(B)^{1/2}+0.2(T)^{1/2}$$

(Equation 2)

where A (km^2) is the area of the drainage basin having slopes greater than or equal to 30%, B is the area (km^2) of the drainage basin burned at moderate and high severity, and T is the total storm rainfall amount in millimeters.

The post-fire debris flow models are capable of predicting debris flow probability and volume within the range of area of drainage basins used to develop the model; therefore the maximum basin size that can be assessed with the models is ~30 km^2.

Study Event

On August 3, 1959, a human-caused grass fire ignited at the base of the Boise Foothills along Rocky Canyon Road (Gress, 2014). The fire quickly spread upslope through cured cheatgrass (*Bromus tectorum*), bunchgrasses, and sparse stands of sagebrush and rabbitbrush (Thomas, 1963) into small stands of open Ponderosa Pine forest of southern Boise National Forest, where the flames were contained at the ridgeline marking the transition from the Great Basin to the Northern Rocky Mountain Region. The fire burned >9,000 acres over six drainages that flow ephemerally into the Boise Metropolitan area. The fire burned 8-100% of the drainage basins. Only ~8% of Cottonwood Creek burned in the 1959 Lucky Peak Fire. In contrast, Picket Pin was burned entirely.

The 1959 Lucky Peak Fire burned adjacent to two fire perimeters that burned in the two previous years (Figure 1). The 1957 Rocky Canyon Fire burned ~3200 acres within the Cottonwood and Curlew drainages. The 1958 Curlew Fire burned ~1200 acres in the Curlew Creek and Hulls Gulch, which is excluded from this study.

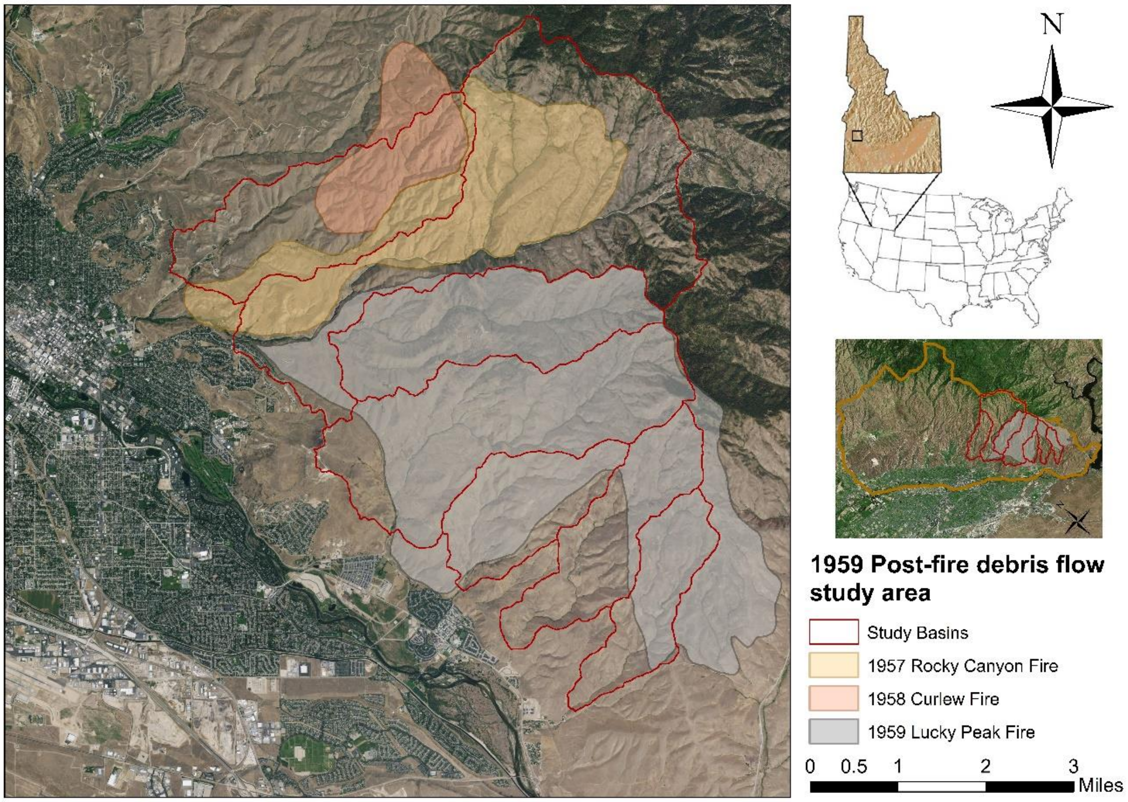


Figure 3.1 Aerial image of modern (2016) eastern Boise metropolitan area and Boise Foothills. Drainage basins from which debris flow sediment tonnage was estimated by Thomas (1963) are delineated and overlain with 1957-1959 wildfire perimeters (BLM).

The fires burned through steep foothills slopes (average 32.5 % slopes) comprised of Tertiary sand and mudstone lake sediments at lower elevations and medium to coarse grained Idaho Batholith granite at higher elevations, both of which are overlain by thin, xeric soils (Othberg & Stanford, 1992). While cool, wet winters provide spring snowmelt runoff-dominated flow through the Boise foothills, the drainages are ephemeral, as summers are dry and hot. However, convective thunderstorms produced by orographic uplift into the southwestern Rocky Mountains provide high intensity summer precipitation over the study area (*Watershed Description*).

The 1959 post-fire debris flow event occurred two weeks after the Lucky Peak Fire. On August 20, 1959, a summer convective storm event produced a 50-100 yr recurrence precipitation event, releasing a total of 53.3 mm of water at a high elevation site with an average stormfall intensity of of 27.94 mm/hr. The storms initiated surface runoff over the recently burned slopes and ultimately mobilized damaged soil and sediment that deposited onto the Boise Metropolitan area. The erosion event occurred at night and, as a result, there are few descriptions of the flows as they exited the confined foothills drainages onto the floodplain of the Boise River. However, one witness described boulders exiting Curlew Creek as rolling atop the surface of the flow “like tumble weeds”. Flows exiting the Warm Springs Creek were described by a farmer as exiting the mouth of the foothills and spreading more than 0.75 miles wide, as typified by the alluvial fan form. Geologists observed that the deposits reflected flow behavior typical of low viscosity fluids, not as translational landslides or rockfalls.

Descriptions of the 1959 Boise Mudbath deposits indicate that debris flows were the predominant form of post-fire erosion response to the August 20th storm event. Direct geologic observations are only available for Maynard Gulch and Highland Valley Gulch, and mapped for Cottonwood Creek. Deposits within Maynard Gulch were described as being well-graded, indicative of a sediment-laden flood rather than debris flow (Thomas, 1963). However, pebbles described as being covered in silt indicate that the flow viscosity was likely elevated by suspended silts and clays. Along the long profile of Maynard Gulch, there were segments of scour where valley confinement is highest and deposition where valley confinement is low. Along one sharp bend in Maynard Gulch, Thomas noted that a mudflow-type event would have scoured the outer bend, but instead, grasses were intact. He noted that grasses inundated by the flow had only bent stems, and noted that “only a liquid-type turbulent flow could have moved through these channels without making radical changes in the channel geometry" (Thomas, 1963). A 1960 map of sediment deposition sourced from Cottonwood Creek show that sediment was deposited at the outlet of Cottonwood Creek as an alluvial fan with ~0.5 mile radius, but that streets channelized sediment and flood waters that were transported as far as ~2 miles from the fan apex of Cottonwood Creek (see Figure 2).

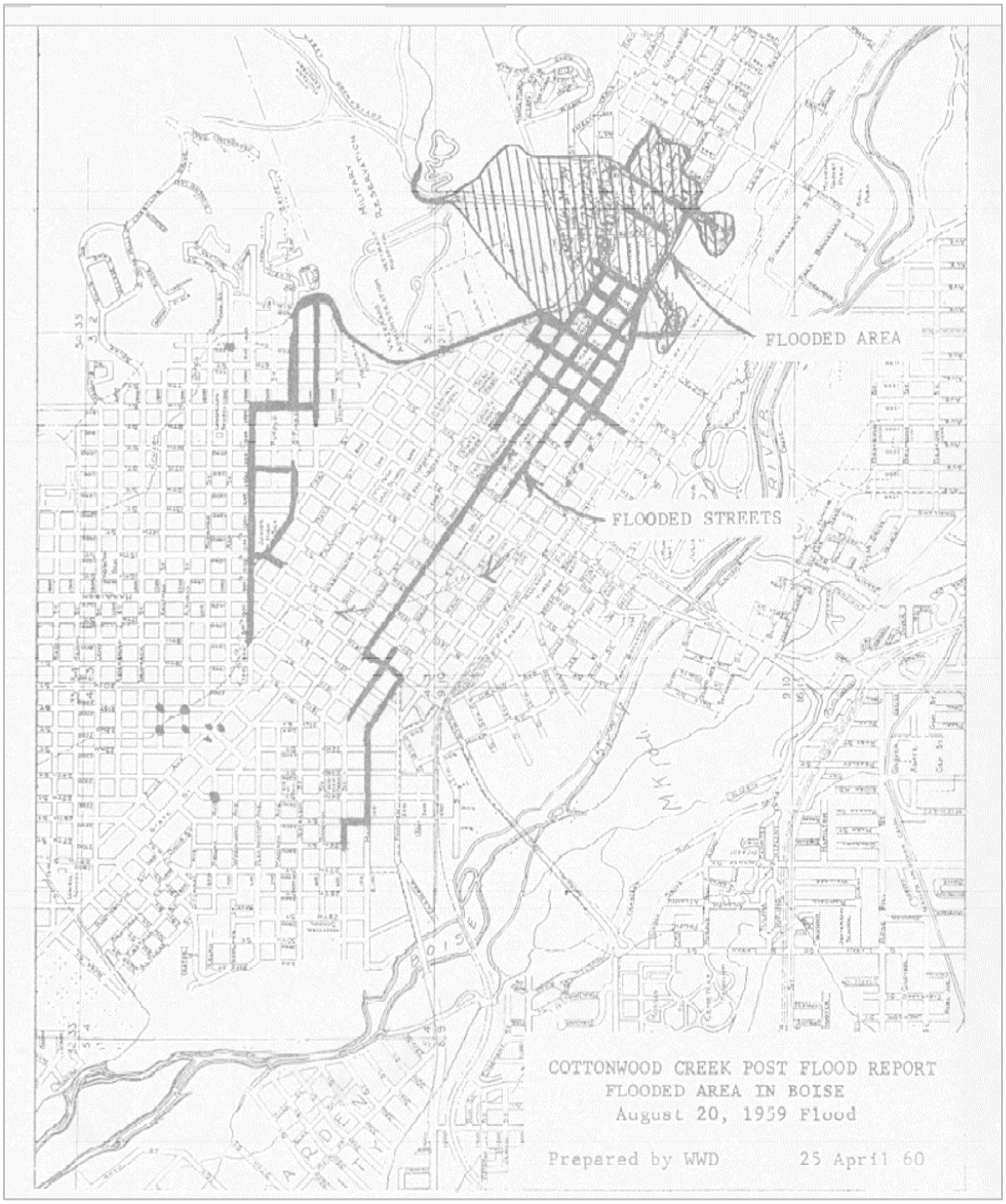


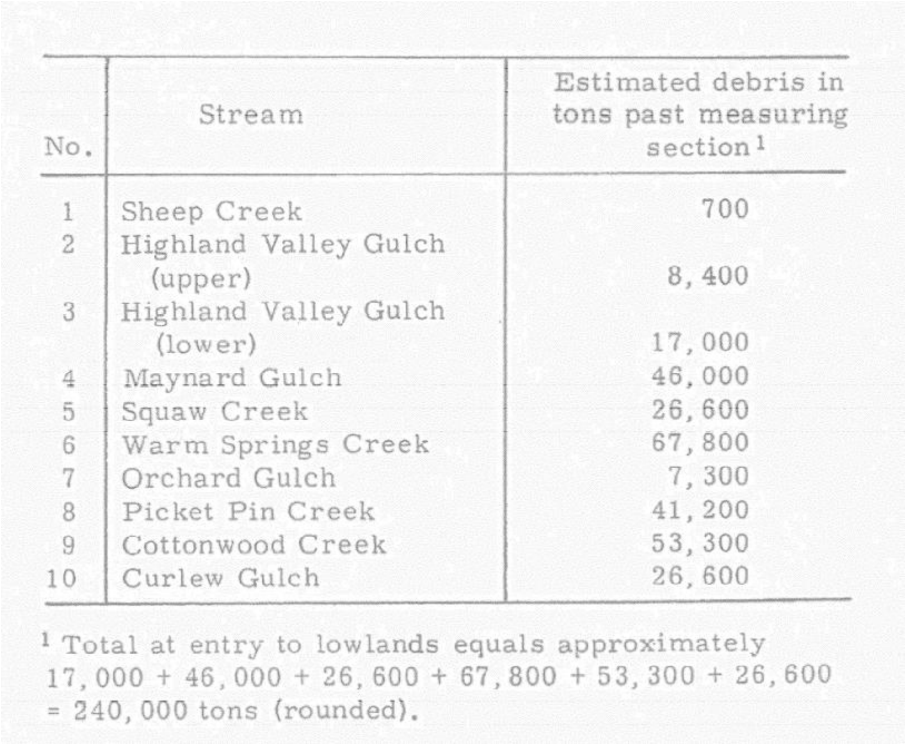
Figure 3.2 Original map depicting the extent of post-fire debris flow deposition (hashed) and flooding extent (solid) after the August 20th, 1959 ~100 yr rainfall event.

Though direct observations of post-fire sedimentation are not reported for the other drainages that produced mudflows, preserved deposits of 1959 mudflows provide more information about the depositional events sourced from Squaw Creek and Highland Valley Gulch. Intact deposits <0.1 km above the outlet of Squaw Creek that contain matrix-supported boulders (Figure 3) are interpreted as being from the 1959 mudflow events. The granitic boulders were likely transported from points of incision similar to that reported by Thomas (Figure 4) in Maynard Gulch. Additionally, debris flow and sheetflood deposits below the outlet of Highland Valley Gulch are interpreted as being deposited after the August 20th storm event and subsequent smaller storms that rained over the Highland Valley drainage area. Debris flow deposits at this site contain abundant charcoal, and are topped by several sheetflood deposits, indicative of a high-intensity storm event following several smaller precipitation events. Other deposits that would aid in the interpretation of the mudflow events have been built over, disturbed or destroyed due to the expansion of the Boise Wildland Urban Interface. However, interpretation of aerial videography taken after the August 20th events (*When the Pot Boiled Over*) show that sediment from Maynard Gulch reached the Boise River, and that deposits from Squaw Creek and Highland Valley Gulch intersected Highway 21. Sediment at these locations distant from stream outlets were described as thin tongues of sand and silt deposited as the slope gradient lessened and the channel widened as each flow exited confined stream channels onto the Boise River Floodplain.

Figure 3. 3 Charcoal-bearing matrix supporting a granitic boulder exposed by incision of the modern Squaw Creek indicates transport by post-fire debris flow. The unsorted bouldery debris flow deposit with a silt and clay-sized matrix contains contrast with the sorted coarse the modern sandy stream depoists seen at the bottom of the photo.

Figure 3.4 A photo taken from the 1963 USGS Report of the 1959 Boise Mudbath of bouldery debris flow deposits in Maynard Gulch above Boise Idaho (Thomas, 1963). The angularity of the boulders may indicate that incision reached bedrock, and eroded out boulder-sized material for transport. See circled onlooker for scale.

The excessive volume of sediment deposition resulting from the August 20th flows were attributed to “the lack of live vegetative cover on the drainage areas, the looseness of the soils, the cover of ash from recent fires, the steep slopes and the intensity of the storm” (Thomas, 1963), The amount of sediment that was deposited beyond the outlets of the study drainage basins was estimated by Thomas in tons (Figure 5). The flows were estimated to have concentrations of approximately 50 percent by weight with flows containing 60 percent sediment by weight at their peaks (Thomas, 1963). Due to the contribution of organic material and ash, the specific gravity of these post-fire debris flow deposited was estimated to be 2.0 kg/m^3, lower than that of the rock source, Idaho Batholith Granite, which has a specific gravity of 2.65 kg/m^3. From these values, we can convert tons of debris to volume (m^3), displayed in Table 1.



No.	Stream	Estimated debris in tons past measuring section[1]
1	Sheep Creek	700
2	Highland Valley Gulch (upper)	8,400
3	Highland Valley Gulch (lower)	17,000
4	Maynard Gulch	46,000
5	Squaw Creek	26,600
6	Warm Springs Creek	67,800
7	Orchard Gulch	7,300
8	Picket Pin Creek	41,200
9	Cottonwood Creek	53,300
10	Curlew Gulch	26,600

[1] Total at entry to lowlands equals approximately 17,000 + 46,000 + 26,600 + 67,800 + 53,300 + 26,600 = 240,000 tons (rounded).

Figure 3.5 Image of original table reporting the estimated tonnage of the August 20th, 1959 post-fire debris flow deposits (Thomas, 1963).

Table 3.1 Post-fire debris flow volumes calculated from reported debris amount estimated in tons (Thomas, 1963).

		Debris Est. (ton)	**Est. Density of debris (kg/m^3)**	**Volume (m^3)**	**Mg/km^2**
Drainage Name	Picket	41000	2000	18688	4154
	Cottonwood	53300	2000	24176	2188
	Warm	67800	2000	30754	4719
	Squaw	26500	2000	12065	4630
	Maynard	46000	2000	20865	7067
	Highland	25400	2000	11521	5334
	Curlew	26600	2000	12066	2423

Methods

We modeled post-fire debris flow probability and volume within the 1959 Lucky Peak Fire area using the post-fire debris flow probability and volume models described in Chapter 2. However, unlike in Chapter 2 where we modeled post-fire debris flow hazards under a range of theoretical burn and precipitation scenarios, the fire perimeter, stormfall intensity (mm/hr) and total rainfall (mm) are known. However, the burn severity within the 1959 burn perimeter is unknown. As such, we apply the same burn scenarios within the 1959 fire perimeter as were used in Chapter 2 (25%, 50%, 75% and 100% moderate and high severity burn). In contrast to Chapter 3, where we apply USGS post-fire debris flow models to first-order channels where debris flows are interpreted to have occurred within the depositional record (Poulos, 2016), and where differences in modeled debris flow probability and volume could be compared, we apply the models over the drainage basins (third order channels) from which debris flows have been recorded in more recent, written history (Thomas, 1963). The most recent iteration of USGS models (Staley et al., 2016) provide an upper limit of basin size to be used to assess post-fire debris flow hazards, the former models (Cannon et al., 2010) can be used to determine post-fire debris flow hazards over basins as large as 30 km^2. In the 1959 Lucky Peak Fire study area, the largest drainage basin, Cottonwood Creek, is ~22 km^2 and, therefore, within range of assessment under post-fire debris flow models.

We ran post-fire debris flow probability and volume models (Cannon et al., 2010) using the same procedures as Chapter 2, but using stormfall and burn perimeter data specific to the 1959 post-fire debris flow event. We acquired topographic and soil data using the same procedures described in Chapter 2. Total storm rainfall was acquired through the Thomas Report (1963) and stormfall intensity was calculated using equations specific to the Snake River Valley (Miller et al., 1973). We ran the post-fire debris flow models through four burn severity scenarios, summarized in Table 2. The 1959 fire perimeter was obtained from the Bureau of Land Management Historic Fire Perimeters dataset available through Inside Idaho. We calculated the percent burned area within each basin using Zonal Statistics in ArcGIS 10.2.1. We used specific gravity and tonnage estimates provided in the Thomas, 1963 report to calculate the volume of debris flow deposits to provide a direct comparison between the field-estimated deposits and the USGS post-fire debris flow volume model.

Table 3.2 Modeled 100-yr stormfall event fire severity scenarios

Scenario Name (L = low recurrence, H = high recurrence)	**Burn Severity Scenario** % area burned at moderate & high severity	**Precipitation Scenario** (recurrence interval)	**Stormfall Intensity** (mm/hr)	**Total stormfall** (mm)
LP25	25%	50-100 yr	27.94	53.3
LP50	50%	50-100 yr	27.94	53.3
LP75	75%	50-100 yr	27.94	53.3
LP100	100%	50-100 yr	27.94	53.3

Results

Modeled post-fire debris flow volume estimates for drainage basins within the 1959 Lucky Peak Fire burn area spanned an order of magnitude among the six drainages. Highland Valley Gulch and Warm Springs Creek are modeled to produce the lowest and highest debris flow volumes, respectively, and are estimated to produce an average of ~33,200 m^3 and ~163,200 m^3, respectively (Table 3). All drainages produced less sediment than estimated by all modeled storm scenarios (Figure D). Assuming a debris flow density of 2000 kg/m^3 (Thomas, 1963), Highland Valley Gulch and Warm Springs Creek produced ~11500 m^3 and ~31000 m^3, respectively.

Table 3.3 Post-fire debris flow model volume estimates within each study drainage of the 1959 debris flow event under four burn severity scenarios

		Volume (m^3)						
	Scenario	LP25	LP50	LP75	LP100	Average	True 1959 Volume	Drainage area (km^2)
Drainage Name	Picket	59402	91703	127963	169463	112133	18688	8.99
	Cottonwood	63533	76898	89030	100734	82549	24176	22.11
	Warm	79203	129007	187580	257185	163244	30754	13.08
	Squaw	30401	40556	50595	60965	45629	12065	5.10
	Maynard	30492	38182	45375	52481	41632	20865	5.90
	Highland	23631	30166	36381	42605	33196	11521	4.31
	Curlew	22201	22201	22201	22201	22201	12066	9.94

Modeled post-fire debris flow sediment yields (Table 4) normalized by their drainage areas (Mg/km^2) allow for direct comparisons of volume estimates among drainages of different sizes, and are displayed in Figure 6. The post-fire debris flow model estimates that Cottonwood Creek would produce the lowest sediment yields (~7500 Mg/ km^2) under 1959 post-fire debris flow conditions, while Warm Springs Creek would produce the highest sediment yields (~25000 Mg/ km^2). Modeled sediment yields (~4500-25000 Mg/km^2) are higher than the actual 1959 sediment yields (~2188-5334 Mg/km^2), in many cases by over half an order of magnitude.

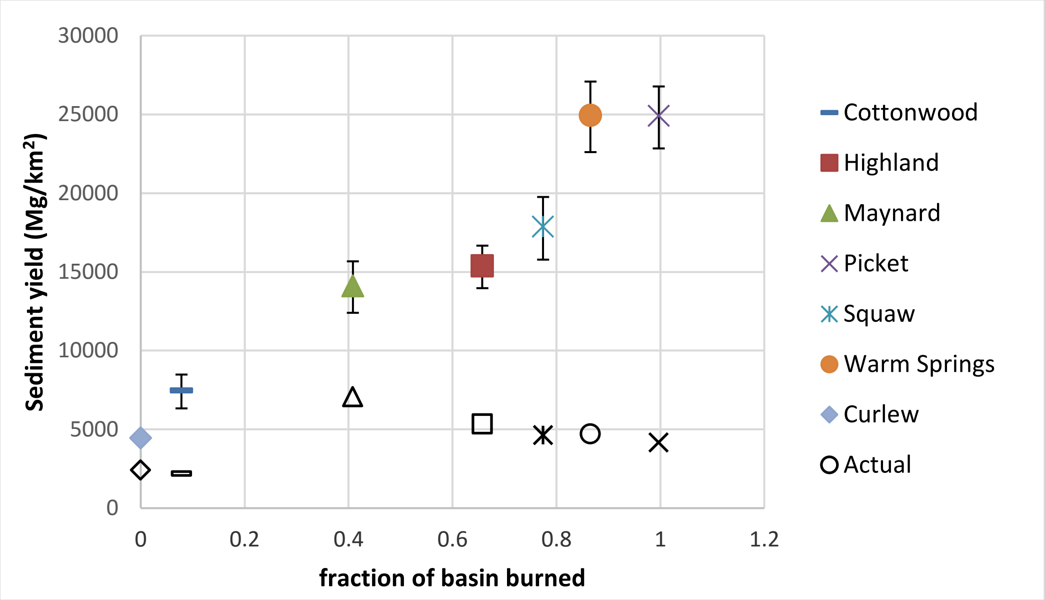


Figure 3.6 Model averaged (colored shapes) and true (hollow black) post-fire debris flow sediment yield estimates plotted against the percent to which each basin burned in the 1959 Lucky Peak Fire. Error bars correspond to the highest and lowest modeled sediment yield estimates, under LP25 and LP100 scenarios, respectively.

Table 3.4 Post-fire debris flow modeled sediment yield within each study drainage of the 1959 debris flow event under four burn severity scenarios

		Modeled Sediment Yield (Mg/km^2)						
	Scenario	LP25	LP50	LP75	LP100	Average	*True 1959 yields	Drainage area (km^2)
Drainage Name	Picket	13203	20382	28441	37665	24923	4154	8.99
	Cottonwood	5747	6956	8053	9112	7467	2188	22.11
	Warm	12109	19723	28678	39319	24957	4719	13.08
	Squaw	11913	15893	19827	23891	17881	4630	5.10
	Maynard	10343	12952	15392	17802	14122	7067	5.90
	Highland	10957	13987	16869	19755	15392	5334	4.31
	Curlew	4466	4466	4466	4466	4466	2423	9.94

Single event sediment yields of the 1959 post-fire debris flow event (~2200-7100 Mg/km^2) are comparable post-fire debris flow sediment yields sourced from Idaho Batholith Granite within sparsely forested and rangeland drainage basins along the Middle Fork Salmon River (MFSR) (Figure 7). Drainage basins along the MFSR containing sparse vegetation of comparable size (~3.4-7.4 km^2) to the 1959 Lucky Peak basins were measured to have post-fire debris flow sediment yields ~1800-5600 Mg/km^2 (Riley, 2012). The study found that wetter, forested basins produced higher single event post-fire sediment yields (~22950-34550 Mg/km^2) (Riley, 2012). While sediment yields from the sparsely vegetated MFSR study basins are comparable to the 1959 post-fire debris flow yields, they are an order of magnitude smaller than those modeled for the same 1959 debris flow event (~7500-17900 Mg/km^2).

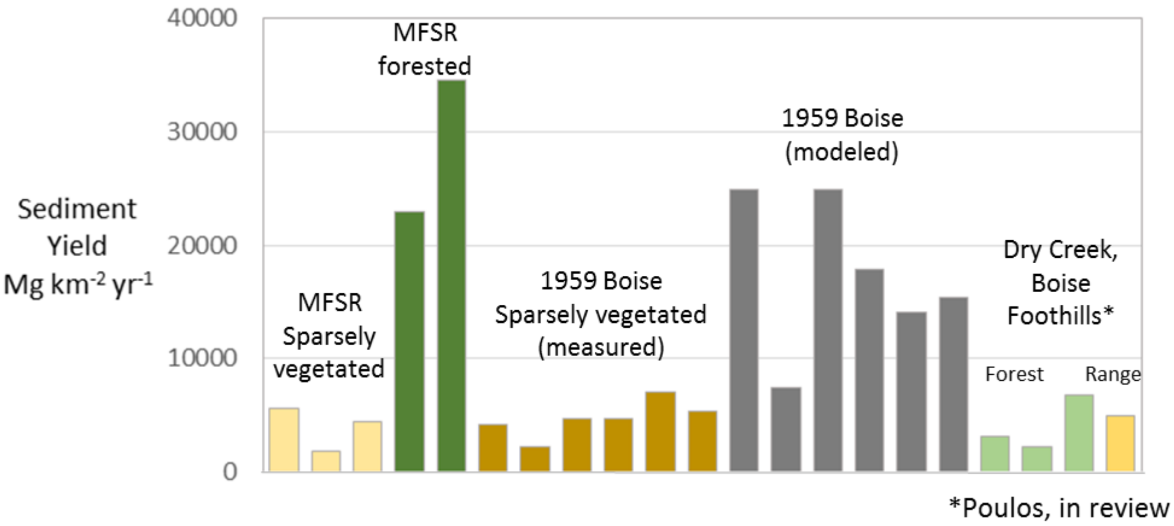


Figure 3.7 1959 Lucky Peak Fire post-fire debris flow yields Boise, Idaho (dark yellow), modeled post-fire debris flow yields for the Lucky Peak Fire (gray). Single event post-fire debris flow deposits from sparsely vegetated (light yellow) and forested (dark green) basins of the Middle Fork Salmon River (MFSR) measured by Riley, 2012. Estimated single-event post-fire deposits within the Dry Creek Experimental Watershed of Boise, Idaho (forested = green, rangeland = yellow).

Modeled post-fire debris flow probabilities for the six burnt drainage basins ranged from <1%- ~6% under the LP25 scenario, and ~8-78% under the LP100 scenario (Table 5). Post-fire debris flow probability increases with the amount of moderate and high burn severity burn within the Lucky Peak Fire perimeter. The probability of post-fire debris flow occurrence within a drainage positively correlates with the percent of which the drainage basin burned as burn severity increases under the four burn scenarios (Figure 8). Curlew Creek, despite not having burnt in 1959, is calculated to have a ~1% probability of producing a debris flow. Interestingly, even under the LP100 burn scenario, no basin was modeled to have more than a ~78% probability of producing a debris flow following the 1959 Lucky Peak Fire, despite the fact that each basin did fail.

Table 3.5 Calculated post-fire debris flow probability for each burned 1959 drainage basin under four burn severity scenarios.

		Probability (%)			
	Scenario	LP25	LP50	LP75	LP100
Drainage Name	Picket	3.76%	14.85%	43.75%	77.63%
	Cottonwood	5.50%	6.14%	6.85%	7.64%
	Warm	0.80%	2.87%	9.77%	28.40%
	Squaw	0.74%	2.32%	7.06%	19.52%
	Maynard	3.78%	6.76%	11.80%	19.79%
	Highland	1.48%	3.86%	9.73%	22.41%
	Curlew	0.64%	0.64%	0.64%	0.64%

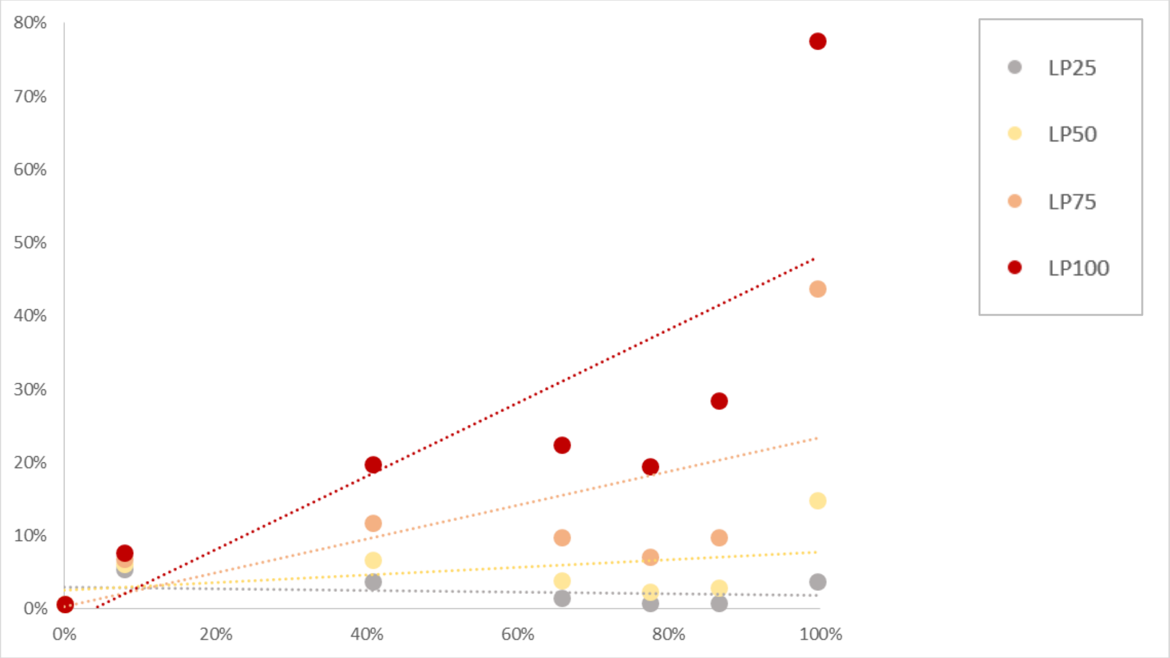


Figure 3.8 Post-fire debris flow probability within each drainage basin (separated along the X axis by their burn percent) under the four burn severity scenarios.

Discussion

Estimated sediment yields from individual basins in the 1959 post-fire storm (~2200-7100 Mg/km^2) are comparable to those of a single event sediment yield (~3140 Mg/km^2) in a small (<0.5 km^2), sparsely vegetated, south-facing catchment ~10 km from the 1959 burn area (Poulos, 2016). The 1959 debris flow sediment yields (~2170-6835 Mg/km^2) are also comparable to three small (~0.5 km^2), forested, north-facing catchments directly adjacent to the south-facing catchment (Poulos, in review). Due to limitations in the sampling process, these yields are calculated from the minimum constrainable deposit thicknesses, and are likely higher than can be confirmed.

Sediment yields observed in 1959 are also comparable to single event fire-related debris flow yields sourced from sparsely vegetated 2.4-13.3 km^2 basins (~1840-5600 Mg/km^2) calculated from modern fire-related debris flow deposits along the Middle Fork Salmon River. Soils that supplied debris flow material in this study are derived from the same erodible Idaho Batholith rocks that comprise the 1959 study area. Forested basins produced sediment yields ~23,000-35,000 Mg/km^2. Contrasting sediment yields (~0.5 order magnitude) between sparsely vegetated and forested slopes observed in these studies provide insight to the range of sediment that post-fire debris flows can produce under contrasting vegetative conditions. This contrast aids in our understanding of the disparity of 1959 debris flow sediment yields and those modeled using the post-fire debris flow volume model.

The modeled post-fire debris flow volumes of rangeland drainages burnt in the 1959 Lucky Peak Fire are higher than those reported across all six study basins. While models predict that, on average over the four burn severity scenarios, burnt basins would produce a minimum of ~33000 m^3 under the August 20th, 1959 rainfall scenario, not even Warm Springs, the largest volume-producing basin, deposited that amount (~31,000 m^3). Similarly, modeled debris flow volumes normalized by drainage area indicate that post-fire debris flow models overestimate post-fire debris flow sediment yields within rangeland drainages. The highest individual drainage basin sediment yield produced by the August 20, 1959 rainfall event was from Maynard Gulch, which produced ~7100 Mg/km^2. Under the average burn severity scenario, however, the model estimates that Maynard Gulch would produce 2x that yield (~14100 Mg/km^2). The average modeled sediment yield for Picket Pin (~24900 Mg/km2) was over half and order of magnitude higher than its true yield of ~4200 Mg/km^2.

It is unknown how post-fire debris flow sediment yields were estimated from the 1963 USGS report. Thomas (1963) reported that the deposits of the 1959 event “attest to the large amounts of debris moved”, but there is no description how the quantity of the debris was estimated. We do know, however, that Thomas assumed that the flows were 50 percent sediment by weight and that the specific gravity of the debris was 2.0. Thomas used this information to estimate the quantity of debris, in tons, that the debris flows produced. Thomas notes in his report that the calculated estimated debris quantities “are speculative, and indicate only the general order of magnitude of the movement.” Due to the lacking description of how debris tons were estimated, we must speculate potential error in resulting sediment volume estimates that we use in this study’s comparison between post-fire debris flow model estimates and reality. It is possible that the estimates made by Thomas do not account for sediment that reached the Boise River. In the informational video *When the Pot Boiled Over*, which documents the 1959 Boise Mudbath, aerial footage shows that sediment reached the Boise River, and was transported out of the study area. If this sediment was not accounted for, then sediment yields calculated by Thomas would be underestimated. Additionally, Thomas assumes the specific gravity of the 1959 Mudbath sediment to be the same as the value reported for a post-fire debris flow event sourced from the Paria River at Lees Ferry, Arizona. It is possible that the specific gravity of the post-fire debris flow sediment for the 1959 Boise Mudbath was lower than the Lees Ferry reported value, which would impact post-fire debris flow sediment yield estimates. Fire-related debris flows in Idaho have been found to have a specific gravity of 1.5 (Kirchner et al., 2001; Meyer et al., 2001). If the debris flow density was lower than reported by Thomas, then the modeled post-fire debris flow sediment yields would be higher than modeled under the assumed 2.0 specific gravity value.

Overestimation of post-fire debris flow volumes using models built using debris flow data from primarily forested basins is indicative of differences in post-fire erosion response between forest and rangeland basins. While debris flows are observed to occur after fire on both rangeland and forested slopes, wildfire is not required to initiate erosion on rangeland slopes (Pierce, et al., 2011). Coarse grained, better sorted deposits sourced from sparsely vegetated, south-facing slopes in the Boise Foothills indicate that surface runoff may be a more continual form of erosion in rangeland catchments in this study region (Poulos, 2016). Sparsely vegetated rangeland slopes are posited to create more opportunity for continual surface runoff and erosion, reducing the likelihood of catastrophic erosion thought to be typified by forested slopes, where protection of soil by vegetation and sediment storage is comparably high (Riley, 2012). Additionally, it is possible that more frequent, but less severe fires may stimulate more persistent erosion on rangeland slopes. The invasion of flammable cheatgrass (*bromus tectorum*) over much of the Boise Foothills exacerbates continual erosion. Wildfires >100 acres in size burn annually in the foothills. Erosion from these areas often increases markedly, not catastrophically, and evacuate soil and sediment that would contribute more volume during a mass-wasting post-fire debris flow event.

Model overestimation of rangeland post-fire debris flows may also be explained by the disparity in available soil and sediment between forested and rangeland slopes. Poulos (2016) found that soils are thicker on forested, north-facing slopes than on sparsely vegetated, south-facing slopesin the Boise Foothills. Therefore, per unit area, there is less mobile material to contribute to a debris flow on rangeland slopes than forested slopes. Hypothetically then, if drainage basins of equal size and slope but of different vegetation types (rangeland and forest) were both to fail by post-fire debris flow, the rangeland debris flow would have a far lower sediment yield than the forested basin.

From a hazards perspective, overestimating debris flow volumes is preferable to underestimating sediment production. In contrast, under-predicting debris flow occurrence may lead to under-preparation for erosion after wildfire. The post-fire debris flow probability model did poorly to express the likelihood of failure within the drainages. Each drainage burned by the Lucky Peak Fire produced debris flows. However, only under the LP100 burn severity scenario did one drainage, Picket Pin, have >50% probability of producing a debris flow. Conservative estimates of post-fire debris flow probability may create issues for hazard managers to prepare for and communicate debris flow hazards within threatened neighborhoods of the Boise metropolitan area. From a hazard mitigation perspective, it is far better to prepare for a false positive (non-event) than be unprepared for a false negative (unanticipated event).

Potential post-fire debris flow sediment yields appear to decrease markedly ~1yr after fire. Curlew Creek, which burned the year prior to the 1959 Lucky Peak Fire, produced a debris flow during the August 20th rainfall event, but the sediment yield (~2400 Mg/km^2) was lower than those produced by most basins that had burned only weeks before the rainfall event (~2200-7100 Mg/km^2). The comparatively lower sediment yield of Curlew Creek can likely be attributed to the prevalence of cheatgrass in the Boise Foothills. The Lucky Peak Fire burned primarily through dry cheatgrass-covered slopes, and was also likely present during the 1958 Curlew Creek Fire. Cheatgrass is able to reseed the year following fire. It is likely that cheatgrass had already reestablished over the Curlew Creek burn area in 1959, thereby contributing root cohesion, canopy cover and surface roughness to the drainage basin, and reducing the erodibility of hillslopes. Cottonwood Creek, the largest basin (~22 km) to deposit sediment in the 1959 rainfall event, produced a lower sediment yield (~2200 Mg/km^2) than Curlew Creek. Though the majority of it burned in the 1957 Rocky Canyon Fire, <5% of Cottonwood Creek burned in the 1959 Lucky Peak Fire, so vegetation recovery likely aided in its low sediment yield. The low yield was likely also the result of sediment storage within the large Cottonwood Creek channel that was not measured after the 1959 debris flow event.

Interestingly, a similar wildfire and subsequent rainstorm occurred within the 1959 post-fire debris flow study area nearly 40 years later. On September 11, 1997, 0.4 inches of rain fell in nine minutes over the ~15,000 acre 1996 8th Street Fire. Flooding took place around Crane Creek and Hulls Gulch, but was contained by retention ponds and did not produced debris flows. The flooding response was likely significantly reduced due to rehabilitation efforts including terracing, contour fell logging, reseeding, straw wattles and check dam construction that took place shortly after the fire to protect foothills soils and watersheds (Fend et al., 1999). Additionally, erosion and post-fire debris flows may have been prevented due to erosion mitigation efforts that took place shortly after the 1959 Mudbath; to prevent future erosion from causing damage to homes downslope, the Soil Conservation Service, Forest Service and Bureau of Land Management terraced hundreds of acres of previously forested foothills that burned in the 1959 Lucky Peak Fire. The terracing of 1959 and 1997 can still be seen in the foothills today, and may have prevented another Boise Mudbath during the intense 1997 rainfall event.

Additionally, there may not have been a post-fire debris flow response in 1997 because the sediment source evacuated in the August 20th, 1959 post-fire debris flow event has not been re-supplied through weathering and soil development processes. Excavation of mobile regolith and soil from the 1959 drainages may have reduced their potential sediment yields for future post-fire debris flow events.

The evacuation of sediment during a debris flow event in rangelands may further add to the discrepancy between the post-fire debris flow predictive models and reality. If the evacuation of sediment from the 1959 rainfall event means that debris flows are less likely to occur in those drainages in the future, then it may be that rangeland debris flows form less frequently, and require a “recharge” of transportable hillslope material before another debris flow is possible. However, because rangeland slopes lack canopy cover and burn frequently when invaded by flammable grasses, they erode more continuously, though less catastrophically, reducing the opportunity for a “recharge” of erodible material. This may explain why few records of post-fire debris flows exist for sparsely vegetated mountain front regions like those adjacent to the Colorado Front Range, Salt Lake City and Reno.

Conclusions

Historic reports of the August 20th, 1959 post-fire debris flow event offers comparisons of model predictions to real-world occurrence of post-fire debris flows. Few comparisons of post-fire debris flow model predictions and real world post-fire debris flow events have taken place. Post-fire debris flow models are currently used by the

Forest Service within recently burned areas in the western US to anticipate and prioritize where erosion mitigation action needs to be taken. However, verification of the accuracy of the model predictions within these burn areas is not frequently or formally reported, though debris flow occurrence within burn areas may be reported by Forest Service Ranger District websites or on the news. Verifying models through historic records offer an alternative to testing the predictive capabilities of post-fire debris flow models. Verifying models is especially useful when attempting to predict debris flow occurrence at the Wildland Urban Interface, where life and property are at risk. Knowing where and at what magnitude debris flows have occurred in the past can aid in understanding the potential hazards of future debris flow events.

We found that the post-fire debris flow volumes estimated by the USGS model were ~2-6x greater than those produced actually produced by the 1959 post-fire debris flow event. Interestingly, the 1959 debris flow yields are similar to those calculated in regional depositional records (Riley, 2012; Poulos, 2016) sourced from sparsely vegetated drainage basins. Conversely, the model yields of the 1959 debris flow event more closely match known debris flow yields sourced from forested basins within the region. These findings show that debris flow sediment yields appear to be distinct between forest and rangeland basins. Rangeland basins with thin, coarse soils produce less sediment in debris flows than forested basins, with thick, finer soils after a wildfire disturbance. Models built from forested basins that are run over rangeland basins predict sediment yields typified by forest debris flows and over-predict their volume. Under the 1959 post-fire debris flow scenario, models over-predicted sediment yields by as much as 6x the true sediment yield. Additionally, the post-fire debris flow probability model underestimates debris flow occurrence under the 1959 debris flow scenario. Only one drainage modeled to have >50% probability of debris flow occurrence under the 1959 post-fire debris flow scenario, despite the fact that all basins did in fact produce debris flows. We conclude that post-fire debris flow models are more suited to forested slopes, as sediment yields appear to be distinct between burned rangeland and forested drainage basins.

This study demonstrates the need to have a local understanding of post-fire debris flow hazards. While models exist that predict post-fire debris flow hazards, the influence of local topography, vegetation and precipitation reflected in distinct ecosystems appear to play a major role in determining post-fire debris flow occurrence and magnitude. Understanding local post-fire debris flow hazards is especially necessary where fire-induced debris flow-prone slopes intersect the Wildland Urban Interface, where life and property may be at risk. The importance of having a local understanding of post-fire debris flow hazards at the WUI of Boise, Idaho and other western US WUIs will to grow in tandem with wildfire size and severity under future climate change.

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CHAPTER IV: WHAT THE SCIENCE TELLS US: UNDERSTANDING THE ROLE OF WILDFIRE SCIENCE IN DECISION MAKING AT THE BOISE WILDLAND URBAN INTERFACE

Abstract

There is a growing supply and demand of science addressing wildfire hazards at the Wildland Urban Interface (WUI), yet what makes science applicable and how it is used to make policy decisions is not well understood. In this mixed methods study, we merge quantitative and qualitative social science methods with public policy theory to identify how stakeholders at the Boise, Idaho WUI use science to inform wildfire hazard policy. We hypothesize that how a manager defines a wildfire problem will influence how that manager uses science to create a policy solution to that problem. To test this hypothesis, we performed content analysis on WUI policies of Boise wildfire stakeholders, and coded the policies into distinct categories that classify how they define wildfire problems. We then conducted interviews with managers representing local, state and federal stakeholders in the Boise WUI to discuss how new, local science may address wildfire hazards they identify as needing policy solutions. Our findings show that stakeholders at the Boise WUI address the wildfire hazards with unique policy solutions. Interviews reveal that, contrary to our hypothesis, unique problem definition does not result in unique use or usefulness of science; across managers, science is useful when it is quickly understood, and when it helps draw boundaries from which wildfire hazard

funding can be allocated and prioritized. While policies may reflect unique problem definition among stakeholders, when knowledge sharing and collaboration is high, WUI stakeholders are workingtoward the same problems, and may see the same utility in science. We recommend this framework to provide policy context to scientists as they discuss their results with interested stakeholders, and to managers requiring policy context to the wildfire science they are asked to consider.

Introduction

Prolonged droughts and increasing temperatures are driving longer fire seasons and increases in burnable area on a global scale (e.g. Westerling, 2016; Jolly et al., 2015). Climate change and increased development in the Wildland Urban Interface (WUI) are escalating both the size and likelihood of fire (Jolly et al., 2015). Human fire ignitions triple the length of the natural wildfire season in the US (Balch et al., 2017). Thirty-two percent of U.S. housing units and one-tenth of all land with housing is located in the WUI (Radeloff et al., 2005), and growth is expected to continue (Hammer et al., 2009). As a result, communities in mountainous areas across the West must address the risk of wildfire hazards.

At the Wildland Urban Interface (WUI), where undeveloped landscapes meet the built environment (e.g. neighborhoods, towns and metropolitan areas), there is a complex interaction among local, state and federal land and hazard stakeholders that ultimately must work together to protect life and property from wildfire (Rogers et al., 2005; National Action Plan, 2014) Strategies for successful wildfire management often note the need for collaboration amongst stakeholders, and an effective use of science (e.g. National Action Plan, 2014. However, strategy and management documents do not recommend how successful stakeholder collaboration might take place, or how science may be effectively used in wildfire management. The result may be that existing science is not shared among agencies, science needs are not being met or new science is either not useful, or is simply not being placed into the hands of managers who could use the information. Therefore, policy decisions in fire-prone areas should be informed by the best available science. But is this the case?

In this study, we use the Multiple Streams Framework (MSF), a well-established policy process model that outlines the components of policy creation, as a lens through which to examine the role science plays in wildfire policy making. The MSF lens identifies that the problems, policies and politics of a political arena (e.g. municipality, county or state) influence how, and under what circumstances new policies are made. Indicators of wildfire risk provide insight into what problems require policy attention, and influence each of the three streams. Indicators can include rates (e.g. increase in the number of highway deaths per year), costs (e.g. the average cost to live in a city) and ranks (e.g. a state's national education ranking). Science often contributes or identifies these indicators

We postulate that land and hazards managers, hereafter referred to as 'managers', uniquely define wildfire problems at the WUI, and address those problems with equally distinct policy solutions. As a result, we hypothesize that managers also use science to address the wildfire problems they face. The results of this study may aid to increase the utility of wildfire science at the WUI, thereby increasing the capacity of communities to prepare for and adapt to wildfire.

Background

Overview of Past and Present Wildfire Policy in the United States

Wildfire's influence on land and hazard management policy as evolved dramatically in the western United States over the past century. The Big Blowup of 1910, which burned >3 million acres in Idaho, Washington, and Montana, set the stage for suppression that dominated the early Forest Service policy (Pyne, 2017). The strive to repress all wildfires during the early days of the Forest Service is best illustrated by the 10AM Policy Fire, which mandated that every fire be suppressed by 10:00 AM the day following being reported. Suppression in the western US reached its peak after World War II, when men, heavy equipment and air tankers became available after being relieved of military duty (Dombeck et al., 2004). Abundant resources during this time led to efficient and effective wildfire suppression.

Change to wildfire policy came in 1988, when several small conflagrations merged under optimal wind and humidity conditions and ultimately burned ~36% of Yellowstone National Park (Young, 2016). This disaster spawned policies encouraging controlled burns and fuel reduction in forests. Importantly, new policy recognized that wildfire provides ecological benefits to the landscape, and that several, small natural fires can prevent one, large wildfire disaster. Despite national change in policy, ~98% of today's wildfires are suppressed during the initial attack (Dombeck et al., 2004), yet modern wildfires burn more acres annually, despite fewer ignitions. The increase in wildfire size and severity is the result of climate change (Abatzaglou and Kolden 2013) and the so-called 'fire deficit' induced by fire suppression of the pre-Yellowstone era (Marlon et al., 2012). The trend of increasingly large, severe and complex wildfires is anticipated to continue in forests throughout the 21st century (Gergel et al., 2017). Managers have responded to this trend by employing an “All hands – all lands” approach (Pyne, 2017). Wildfires increasingly cross jurisdictional boundaries, and so too must wildfire management.

The “All hands – all lands” approach is at the center of the National Cohesive Wildland Fire Management Strategy, which guides today’s wildfire management. The Cohesive Strategy provides direction for planning, risk analysis and collaboration among local, state and federal agencies, and tribal and non-governmental partners to restore and maintain resilient landscapes, create fire-adapted communities, and respond to wildfires (*The National Strategy*). Importantly, the Cohesive Strategy is structured around using the best-available science, while the National Action Plan, which supports the implementation of the Cohesive Strategy, underscores the need to use science and data to support decision-making at all levels (*National Action Plan,* 2014*; The National Strategy*, 2015).

How science is used in wildfire decision-making

Science is often framed as being capable of providing solutions to modern wildfire management problems and fire-adapted communities, and is considered to the key to successfully preparing for wildfire at the WUI (*Integrating the Local Natural Hazard Mitigation Plan into a Community’s Comprehensive Plan*, 2013). Management strategies, including the Cohesive Strategy, highlight the importance of the distribution and production of science from which sound decisions can be made at the local to national level. For example, Calkin et al. (2011) highlights the use of science by stating that “the creation of fire-adapted human communities is based on an interagency cohesive wildland fire strategy that […] is grounded in scientific research”.

Yet while there is a push for wildfire managers to use science, there is also continually a pull by managers and funders to make science “useable”. For example, the Joint Fire Science Program, which is tasked with allocating funding for emerging wildfire issues in the United States, has a slogan of “Research Supporting Sound Decisions”. Additionally, there is an entire group, the Fire Science Exchange Group, dedicated to aid in the transfer of science to decision-makers.

Despite the motivation of these groups, what exactly makes science “useable” remains poorly and broadly described in the literature. For example, the National Wildfire Coordinating Group describes usable science as that which is capable of “integrating [with] the missions of resource management in fire-adapted ecosystems” (Machlis, 2002), while Brunner (2005) simply states that current natural management “relies on science as the foundation of policies.” However, a review of the literature reveals little about what actually makes fire science useful to decision makers. In fact, little is known about how fire managers make decisions given the information in front of them (Machlis, 2002).

According to Machlis (2002), what makes knowledge usable to decision-makers requires it to provide information (e.g. data), insight (rounded understanding of the system be worked in), prediction (forecasts) and actions (e.g. suggested ways that the impacts of wildfires can be reduced). In addition, science must address a decision-maker’s needs at a level of detail appropriate to the decision (Machlis, 2002). This outcome is understandably challenging when one form of science is being delivered to stakeholders at many levels. Different decision-makers have different problems that science can inform. In a more tangible context, wildfire science has been found to be useful when it is provided as a general technical report that provides user guides and synthesizes major findings (Barbour, 2007). Additionally, Barbour found that distributing science through seminars and publications were less favored to active learning through field trips. These findings shed light on how to successfully transfer fire science to users (decision makers). The science needs to be succinct, informed and tangible.

Conversely, studies attempting to understand the use of wildfire science by decision-makers have successfully identified what makes science unusable. Broadly, science may not have use for managers because of differences in cultures and values (Finch & Patton-Mallory, 1993). A noteworthy finding by Wright (2010) found that it was far more common for practitioners with graduate degrees and employees of higher pay grades to use science than those without. Similarly, Sicafuse et al. (2011) found that managers lacking trust in scientists acted as a barrier to the use of science. Similarly, science may not be used because scientists distributing research findings use language different than the managers who would otherwise use the science (Finch & Patton-Mallory, 1993). Time available for managers to seek out and assess wildfire science is also cited as a common barrier to science use (Wright, 2010; Seeholtz 2008; Hunter, 2016). Many surveys and interviews have found that when there is no time allocated to seeking out and understanding new and pertinent wildfire science, it is unlikely that it will be used (Hunter, 2016).

In regards to wildfire science distributed through the Joint Fire Science Program (JFSP), Hunter (2016) sought to determine whether or not science produced through the

JFSP was used to inform management, and under what conditions science was used. Interviews identified that most science produced through the fire-specific Program was used, at some point, by managers, and that science was most frequently utilized during the planning phase of management (Hunter, 2016). Importantly, this research revealed that, of those interviews, no respondents indicated that science influenced policy (Hunter, 2016). While the study notes that the methods applied during the research may have been inadequate to assess the influence of science on policy, this result sheds light on the disconnect between science and policy. It is important to note that this research was conducted by interviewing scientists and “boundary spanners” (those in the fire community who interact with both scientists and managers), rather than by interviewing the managers themselves. In addition, while it was determined that science is often used during the planning phase of management, which may have implications for policy, there is no indication of what attributes made that science useful.

The studies summarized above reveal the necessity to understand what makes science useful to decision makers. Though the studies reveal that some attributes of science, including succinctness and tangibility, provide utility to managers, a comparison of science’s utility among managers, especially at different levels of management, has yet to be seen. For example, is wildfire science that is considered useful to a county hazard manager the same as what is useful to a state forester? Additionally, the studies do not focus on the transfer of science to management at the WUI. Lastly, the aforementioned studies do not divulge how science is used in the policy making process. The need to understand the role that wildfire science plays when managers make wildfire policy decisions is growing as more people expand into the WUI.

Problems, Policy and Politics: a Background on the Multiple Streams Framework

Broadly, public policies are created when decision makers provide government authority to address a problem. There may be many policy solutions that can address a problem. In order to put a policy in place, the problem the policy addresses must be considered important, salient and, most importantly, solvable (Henstra, 2010). The problem must have a solution. Whether or not any one policy solution is chosen for implementation will be contingent on how the problem is defined (is the policy addressing a compelling problem?), the resources available to the policy maker (is there time and manpower to work on carrying the policy forward?), and whether or not the public recognizes the problem and agrees with the policy solution (Kingdon, 1995). The government implementing the policy can exist at any level (e.g. city, state or federal level), and the policy may take the form of an ordinance, law or general course of action. These key steps are all recognized and outlined by the Multiple Streams Framework (MSF).

MSF is a popular model that explains the policy-making process from its earliest stages in the policy "primeval soup" (Kingdon, 1995) to the implementation of the new policy. MSF explains how policies are made under ambiguous conditions. Ambiguity in the policy-making process refers to having multiple ways of thinking about the same condition (Sabatier and Weible, 2014). Ambiguity in policy-making results in an accumulation of ways to define problems, and results in the introduction of multiple policy solutions to address the same problem.

Importantly, more information does not reduce ambiguity in the policy-making process. As stated by Sabatier and Weible (2014), "while information may reduce uncertainty, more information does not reduce ambiguity.” As an example, new information may tell us that wildfire smoke contains a newly-discovered toxic hydrocarbon, but that information does not aid in determining if the potentially-toxic smoke is a management, ecological, health, or climate change issue. Under ambiguous conditions, problems and solutions are brought forth by many stakeholders (i.e. anyone interested in the problem at hand) and are thrown into a “garbage can” from which only a few are selected for consideration, and reducing the ambiguity of the issue. Continuing the prior example, stakeholders (e.g. Forest Service) may select a policy that limits the number of days that they can implement prescribed fires. A management policy solution addressed the smoke problem. MSF attempts to explain why a particular policy solution is selected from numerous options that sit within that ‘garbage can.

MSF is comprised of four main components: problems, policies, politics, and a window of opportunity. The problem stream contain all of the possible problems that a government may be attending to at any given time. Decision makers in government are often aware of problems due to indicators. Indicators are often simple statistics, and may comprise of a single value (e.g. ninety firefighters died on-duty in 2015), or a trend in values (e.g. the number of acres burned annually in wildfires has increased since the 1980s, the number of days in the wildfire season has increased due to drought).

Decision makers are also made aware of problems through focusing events. A focusing event is a sudden development, such as a disasters or crisis, which calls the attention of policy makers and, likely the public (Kingon, 1982). An example of a focusing event would be the 2016 Fort McMurray Wildfire, which burnt ~1.5 million acres and destroyed 2400 homes in Alberta, Canada. Perhaps the most important aspect of the problem stream is how the problem is described. How a decision maker describes a problem is called ‘problem definition.’

Perhaps one of the best examples of problem definition comes from the issue of drug abuse in the United States, spanning from the late Nixon to the Obama Administration. Nixon and Obama used very different language to define the drug problem in the United States. President Nixon initiated the ‘war on drugs,’ whereas President Obama defined it as a ‘drug epidemic.’ While both of these refer to the same issue, the definitions provide very different outlines for policy; a war is something that needs to be fought, whereas an epidemic is something that needs to be cured. Understandably, how a problem is defined influences the selection of a policy used to address that problem.

The policy stream is comprised of potential policy solutions to problems and the advocates that support those policies, called policy entrepreneurs. The policy stream contains a “primeval soup” of policy ideas that are supplied by policy entrepreneurs and policy communities. Importantly, there are stakeholders within a policy communities. For example, the wildfire policy community can include local, state and federal land managers, municipal fire stations, private land owners and nonprofits. Each of these stakeholders have their own solutions to a given problem, but only policy solutions that are technically feasible and acceptable by fellow stakeholders are seriously considered (Kingdon, 1995). Additionally, policy entrepreneurs with a vested interest in a given policy may invest time and energy to have that policy implemented successfully. Ultimately, within a “primeval soup” of potential solutions to problems, only some become policies. The unity or fragmentation of policies within a policy community is dictated by the collaborative nature of the community. Fragmented policy communities often lead to fragmented polices over a given policy issue (Kingdon, 1995), leading to disconnect between solutions to a similar problem.

The final stream, the politics stream, is comprised of attributes including the public mood and changes in government authority (e.g. a new president is elected) (Kingdon, 1995). The mood of the public alters how receptive civilians are to government decisions, and will ultimately result in either majority support or opposition of a given policy. Changes in government authority will alter how a policy community defines a problem which, in turn, will alter the favor of policy solutions under consideration. For example, separating the politics of Presidents Nixon and Obama in regards to the drug issue in the United States results in two distinct problem definitions (i.e. The War on Drugs versus The Drug Epidemic) and distinct policy solutions (i.e. police authority versus medical aid). Each of these aspects of the politics stream drive the salience of a given problem and, as a result, affect the potential for a given policy to be emplaced.

Multiple Streams Framework describes how problems, policies and politics streams flow independently of each other until the streams merge and flow through a window of opportunity, during which time a new policy is implemented. A window of opportunity may open and close quickly. A new administration may have the momentum from a recent election to push new policies through the window in quick succession while the public mood favors the new administration, but lose momentum over time. Similarly, a window of opportunity may open suddenly as the result of a disaster. Hypothetically, a city may have several new earthquake-oriented building codes drafted for implementation, but it is not until an earthquake destroys several homes and businesses that the building codes pass as new ordinances. Windows of opportunity may also open and close slowly. Climate change, for example, may act as a slow opening window through which several policies may flow through. For example, Sweden seeks to become a fossil-free nation and, as a result, new energy policies replace old ones as the nation reaches towards its goal.

Science plays a key role in all three streams of MSF. Science can identify new problems (i.e. newly-discovered toxic hydrocarbon in wildfire smoke), and is often the source of indicators used to identify problems. Countless measurements, calculations, analyses and interpretation have culminated into the recognition that wildfires have increased in size and severity since 1980 (Westerling, 2016). Spatial analyses and statistical assessment have further parsed apart that growing fire size and severity can be both attributed to fire suppression (Marlon et al., 2012) and climate change (Westerling, 2016; Abatzaglou and Kolden, 2013). Science may also aid in creating and informing policy solutions. Science can create or be the source of the discovery of new things that may act as an exciting new solution to a problem. New advances in medical technology, for example, may offer solution to health problems where current policies have stagnated the issue. Science may also influence the politics stream. New scientific discoveries may become salient to the public around a given issue, and change the public mood surrounding a problem. For example, the information influx regarding climate change has permeated the news for several years, and the public’s concern regarding the issue is at an eight-year high (Gallup Poll, 2016), and may aid in passing new energy, transportation and technology policies that combat the effects of human-induced climate change.

Multiple Streams Framework and the Wildland Urban Interface

MSF provides a formalized framework to observe the policy-making process, making it appropriate for observing the use of science when producing wildfire policy at the WUI. At the WUI, wildfire policies are made by a diverse policy community. City, state, and federal stakeholders each have policies that address wildfire hazards. The jurisdictions and policies of these stakeholders often abut or overlap one another, creating management complexity within shared space. MSF, however, allows us to examine the policy-creation process of each stakeholder at times when the window of opportunity is open and new science is being considered in the decision-making arena. By examining how each stakeholder defines a problem, identifies a solution to said problem, and brings it through the window of opportunity with information that wildfire science provides, we can better understand how diverse sets of stakeholders ultimately use science to make decisions at the WUI.

Study Area

Boise, Idaho USA provides an example of a WUI where diverse land and hazard managers must work in close proximity to one another. Five land management agencies and two hazard management agencies have a stake in the wildfire activity at this interface. These stakeholders collaborate frequently, and share knowledge that informs wildfire hazards in the ignition-prone, topographically complex WUI. Like much of the western United States, the population of Boise is growing rapidly. The City of Boise is expected to grow ~35% from its current ~237,000 population to ~320,000 by 2040 (*Communities in Motion 2040 Vision*).

Like many western US WUIs, Boise is threatened by wildfires every summer. Boise's wildfire season extends from May to September, though human ignitions can extend the fire season significantly (Balch et al., 2017). Boise sits at the base of the Boise Foothills, and marks the southwestern extent of the Rocky Mountains in Idaho (Figure 1). The Boise Foothills encompass the ecotone between low elevation, sage-steppe to high elevation open coniferous forests. Fires often ignite at low elevations closer to development and spread quickly through dense, invasive grasses within the sage-steppe, to higher elevation, forested slopes.

Approximately 86% of wildfires in the WUI are human-caused. In 2016 alone, three human-caused fires burned ~7300 acres of the Boise Foothills, threatening hundreds of homes (see Figure 2), destroying one home and several uninhabited structures. Erosion following fire in the foothills is common, extending the hazards that wildfires cause long after the fire is extinguished. Several historic records of mudslides and sedimentation from the Boise Foothills indicate that fire drives erosion, and threaten residents of the city of Boise, whose homes are built in deposition zones.

We define the Boise Wildland Urban Interface as the combination of the WUI delineated by Ada County (Figure 1 – red hashed) and the Boise Foothills drainage area between Lucky Peak Reservoir and I-55 (Figure 1 – red perimeter). We include the Boise Foothills drainage area outside of the Ada County WUI perimeter because we chose to include the foothills that are geographically connected to Boise's wildfire hazards, which extend beyond the political boundary of Ada County to the Boise Foothills ridgeline.

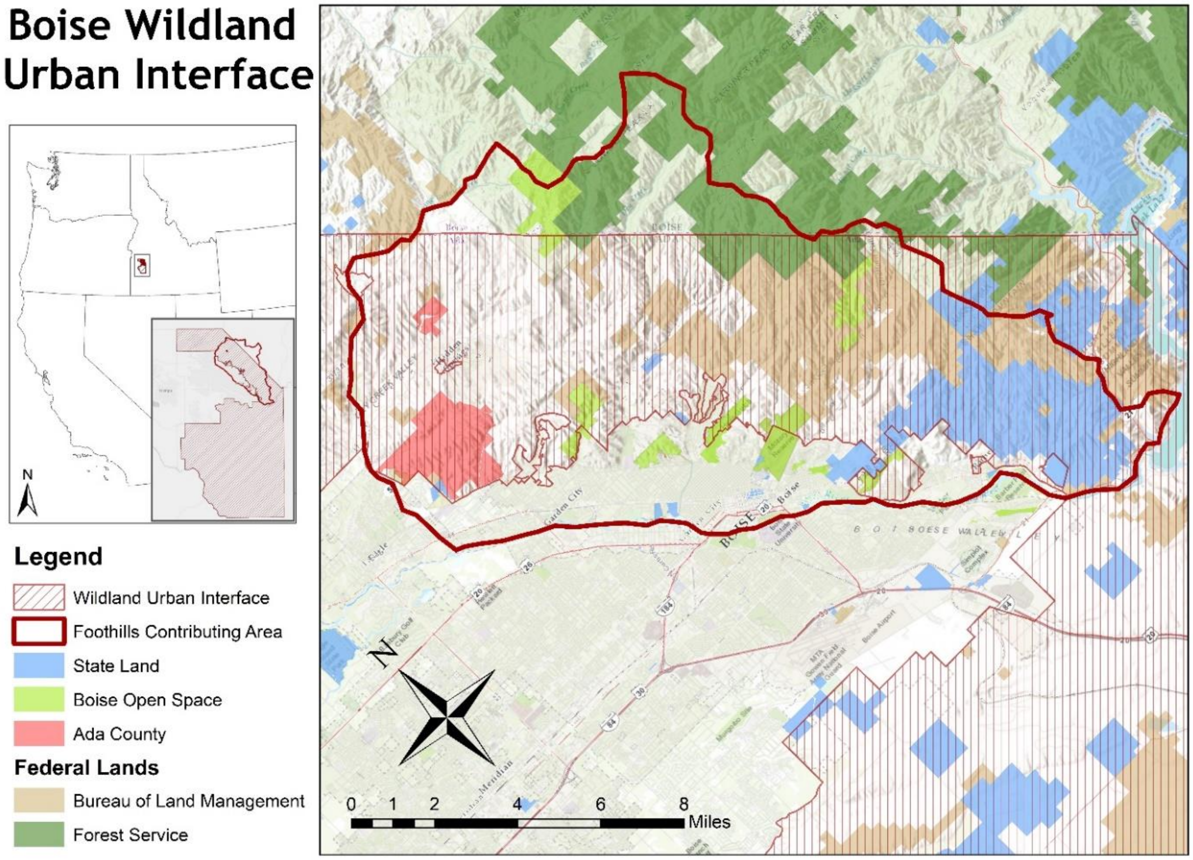

Figure 4.1 Map of the Boise Wildland Urban Interface (WUI). In this study, the Boise WUI is a combination of both political and topographic boundaries. The Ada County WUI (red hashed ends at the county line in the northeast. We extend the WUI beyond the county line to include the Boise Foothills ridgeline (bold red) further northeast.

Local, state and federal land management have authority within the Boise WUI, and include the City of Boise, Ada County, Idaho Department of Lands (IDL), and the Bureau of Land Management (BLM). Hazards within the Boise WUI are managed by Ada County Emergency Management (ACEM) and the Idaho Office of Emergency Management (IOEM). Generally, land closest to the Boise Metropolitan area is owned and managed by the City and County. The BLM land encompasses lower elevation, sage-steppe and grassland slopes while FS land is located furthest from the city, at high elevations within the forest. In the eastern extent of the Boise Foothills, much land is managed by the IDL directly adjacent to BLM land.

County and State hazard officials coordinate wildfire hazard mitigation within the Boise WUI. ACEM is tasked with coordinating emergency management activities for all potential hazards in Ada County, and to make Ada County resilient to hazards. Wildfire is one of eight natural hazards that ACEM considers in their coordination efforts. However, because wildfire is a frequently occurring hazard in Ada County, ACEM’s attention is often dominated by wildfire, especially during the summer months. Because a majority of Ada County’s population resides in Boise, Idaho’s largest city, much of ACEM’s emergency efforts focus on the city. The IOEM is tasked with both preparing for and responding to hazards in the state of Idaho.

County and state hazard agencies work closely with local, state and federal land managers to prepare for wildfire hazards and mitigate its potential effects on life and property. This policy community gathers annually for the Southwest Idaho Wildfire Mitigation Forum, where managers and practitioners share new information, discuss ongoing projects and consider lessons learned during the previous wildfire season. Additionally, it is common for these stakeholders to work together to supply education and outreach to the public, share data and collaborate on wildfire prevention projects, including fuel breaks, mowing projects and Firewise gardens.

Multiple Streams in the Boise WUI

Each wildfire stakeholder at the Boise WUI can be framed under MSF as members of a policy community that push problems, policies and politics through a window of opportunity. At the Boise WUI the window of opportunity may open suddenly, during wildfire events that threaten the city, or during updates to county and state hazard assessments, recurring period of time when managers discuss new wildfire knowledge. The window may also open more slowly, as salience of wildfire hazards are high, perhaps during a drought year or during a particularly active wildfire season.

While stakeholders often make decisions independent of each other, Boise represents a WUI where stakeholders are tied closely to one another, and decisions are often reached through collaboration and information sharing. Despite having different goals and jurisdictions, these stakeholders confront similar wildfire risks, namely that wildfire may burn on their land and threaten life and property at the WUI. Similarly, members of this closely confined policy community have a similar science-based knowledge of wildfire hazards in the foothill because information sharing among agencies is high. Managers have the same science at their disposal from which they can make decisions. However, despite having similar sets of knowledge about the area, each stakeholder addresses the same risks with different policies.

In this study, we examine how wildfire science influences problems and policies under local politics at the Boise WUI. By examining decision-making at the Boise WUI through the MSF, we can attempt to understand how science influences the problems and policies that land and hazard managers must address when making wildfire hazard decisions. The Boise Foothills WUI provides an excellent case study location on this topic. A diverse set of managers work collaboratively while representing diverse jurisdictions and goals. Additionally, several windows of opportunity have been recently opened in the Boise WUI. Both the County and State updated their hazard mitigation plans in 2016 (the year of this study) and a ~2500 acre wildfire threatened hundreds of homes in the WUI. As such, 2016 provided an optimal chance to examine the three streams as they interacted to identify new policy problems and potential policy solutions.

Methods for analyzing the Boise WUI through the Multiple Streams Framework

We used MSF to frame the Boise WUI policy community, and collected quantitative and qualitative policy data from Boise WUI stakeholders using explanatory sequential design (ESD). ESD begins with the collection of quantitative data, followed by the collection of qualitative data, where the quantitative results to inform the qualitative sampling (Figure 2). ESD is designed for qualitative data to explain the quantitative results (Creswell, 2015). We began this study by collecting all of the current wildfire policies in place by each stakeholder in the Boise WUI policy community. We then performed a content analysis of the collected policies to assess and interpret different themes among the wildfire policies. The resulting themes were coded into distinct categories to quantify and compare the policy themes of each stakeholder. Subsequently, we interviewed managers representing each Boise WUI stakeholder qualify the results of the coding. We further explain the quantitative and qualitative methods in the following two methods subsections.

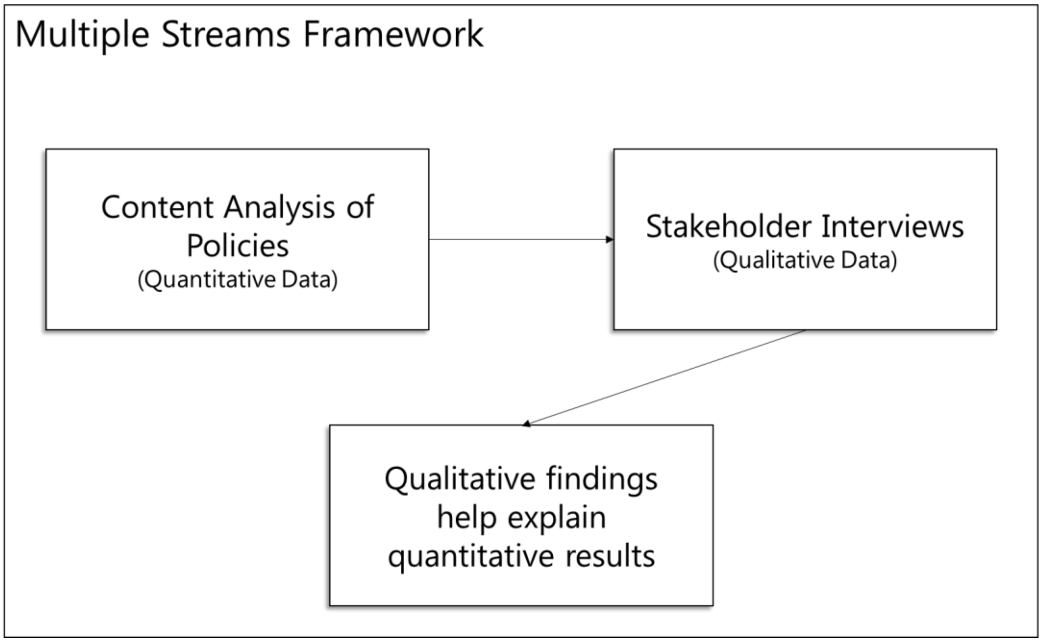

Figure 4.2 Explanatory Sequential Design, framed within Multiple Streams Framework, modified from Creswell, 2015.

Quantitative analysis

We collected the wildfire policies of land and hazard managers who participate in wildfire management at the Boise WUI, including the BLM, IDL, City of Boise, IOEM and ACEM. We excluded land management policies of Ada County from this study, as the primary use of land owned by Ada County is as a landfill. We acquired policies from stakeholder websites. Policies of each stakeholder range from ordinance, codes and statutes to mandates, goals and objectives (see Table 1). From these policy documents, we identified policies that address wildfire hazards, including wildfire prevention, wildfire response, wildfire mitigation, and secondary wildfire hazards (i.e. flooding and erosion). We assessed all policies that tied directly wildfire management within Boise's WUI land, excluding, for example, policies that addressed wildfire starts within logging areas. We did not code policies that were associated specifically with structure fires or with no possible connection to wildfire hazards (e.g. sprinkler and smoke detector codes).

The resulting list of policies were placed into an excel sheet with key descriptive data, such as what document the policy came from, for content analysis.

Table 4.1 Policy documents of Boise WUI stakeholders considered in this study

Stakeholder	**Policy Documents**
City of Boise	Boise City Code, Comprehensive Parks and Recreation Plan
Bureau of Land Management	Manual Transmittal Sheets: Fire Program Management, Fire Planning, Land Health, Integrated Vegetation and Management, Land Use Planning, Burn Area Emergency Stabilization and Rehabilitation
Idaho Department of Lands	Idaho Statutes
Ada County of Emergency Management	Ada County All Hazards Mitigation Plan
Idaho Office of Emergency Management	Idaho Hazard Mitigation Plan

We completed content analysis on the final list of policies to analyze differences in the ways in which policies address wildfire problems. We measured the latent content (underlying meaning) of the policies and identified themes of how a policy can address a wildfire hazard problem. It was important that the themes, which we would use to code all wildfire policies, were both simple and exhaustive. We required themes that succinctly describe the way each stakeholder defines wildfire problems, thus informing the problem stream of MSF.

Once we established our codes, we assigned a code to each policy. Policies that fit under more than one theme were given multiple codes. After assigning codes, we counted the number of policies under each coded theme for each stakeholder. We calculated the percentage of policies that fell under each code for each stakeholder, which provided a means to compare how stakeholders address wildfire problems by comparing differences in the dominant policy codes.

Qualitative interviews

We had learned from content analysis that the wildfire policies of stakeholders fall under key themes. We interviewed land and hazard managers within the Boise WUI policy community to elaborate on how managers use science to make wildfire policy decisions. We sought to confirm whether or not these themes would be reflected during interviews, where we asked wildfire managers questions about wildfire problems, wildfire policies and how wildfire science informed problems and policies. Individual interviewees were selected based upon our knowledge of wildfire manager representing different stakeholders within the Boise WUI policy community. Other managers were recommended to us during the initial set of interviews in a quasi-snowball sampling method. Before commencing interviews, final interview questions were written into an interview protocol and approved by Boise State University's Internal Review Board (IRB) (See Appendix D). Under IRB protocol we informed interviewers of the anonymity of their interview responses in the event of dissemination of any publications.

Our semi-structured interview script was designed to acquire information about individual managers' experiences with wildfire science and policies at the Boise WUI. We divided the semi-structured interviews into four sections (1) background questions about the managers, (2) stakeholder interaction questions, (3) wildfire problems and policies and, (4) use of science by managers. Background questions were intended identify the managers' unique role in the Boise WUI and to compare their role to other managers within the Boise WUI policy community. ‘Stakeholder interaction’ questions further developed the manager’s role within the Boise WUI stakeholder group by asking questioned designed to identifying key collaborators and partnerships within the WUI stakeholder group. ‘Problems and policies’ questions were designed to link interviews into MSF and the results of the quantitative analysis. This was done by asking questions that identify what wildfire problems managers currently face, how they define those problems, and discuss current and potential policy solutions to those policy problems. ‘Use of science’ questions were designed to discuss wildfire science in particular, and to glean information as to how different stakeholders and individual managers access, analyze and use science to make policies and policy decisions. Interview questions were also designed to link into MSF, by asking ‘use of science’ questions directly related to each managers’ responses to the ‘problems and policies’ interview questions. By asking the same core questions of every manager (Table 2), we were able to compare the responses by stakeholders in tandem with quantitative results of the policy coding assessment.

Table 4.2 Common interview questions asked of manager interviewees.

Interview section	Sample questions
Background	How long have you been in your current working position
	Describe your job
Stakeholder interaction	Who are the main stakeholders you interact with at the WUI
	Who do you interact with most frequently
Use of science	How do you use science
	What makes science helpful

problems and policies	What are the top wildfire problems you see in the Boise WUI
	How does science help you address those problems

Results

Quantitative data

Stakeholders of the Boise WUI policy community have a combined 164 policies that address wildfire hazards at the WUI (Table 3). A complete list of annotated policies for each stakeholder is found in APPENDIX D. The City of Boise had the most (68) WUI wildfire fire policies while the Idaho Office of Emergency Management had the least (13). The dominant coded wildfire policies were distinct among Boise WUI stakeholders (see Figure 3).

To code these policies, we adopted themes used in the Ada County Hazards Assessment to describe wildfire policies (*Ada County All Hazard Assessment*, 2013). We found that the themes inclusive of all policies. The four themes used for coding are (1) manipulate, (2) reduce exposure, (3) reduce vulnerability and (4) increase ability to respond to a wildfire hazard. Manipulation was coded for policies that address controlling or altering a wildfire hazard. Examples under this code included landscaping requirements (e.g. specific vegetation not allowed to be planted because it’s highly flammable) and building standards (e.g. foundation fill must be as compact as undisturbed hillside). Reducing exposure to a hazard was coded for policies that prevent intersection with the wildfire hazards in the first place. For example, there are City zoning codes that prevent development from taking place on slopes greater than 25% grade, and IBHS attempts to purchase landslide-prone lands to prevent developers from building on them. Policies were coded as reducing vulnerability if the policy attempts to increase the ability of the item in question to withstand a wildfire hazard. An example of this is the City policy that requires new homes constructed within the WUI to use fire resistant products on exterior walls. A policy was coded to increase the ability to respond to a hazard when the policy increased access for emergency response (e.g. fire trucks) or when the policy's goal was to educate citizens and managers about wildfire hazards. Examples of policies that increase the ability to respond include mandating all homes in the WUI to have turn-around access for fire trucks, but also include goal –oriented policies like increasing collaboration among stakeholders, or providing public outreach.

At the State and Federal level of management, policies frequently focus on manipulating and reducing exposure to wildfire hazards. The Idaho Office of Emergency Management has an even distribution wildfire policies, while the policies of Ada County Emergency Management policies most frequently address reducing resident's vulnerability to wildfire hazards and to increase the ability of both citizens and emergency personnel to respond to a hazard. The City of Boise's WUI wildfire policies focus primarily on manipulating and reducing vulnerability to wildfire hazards, though most of Parks and Recreation's polices address increasing the ability to respond to the hazard. Many of Parks and Recreation's policies focus on educating the public. Boise City Planning and Zoning focuses heavily on policies that manipulate wildfire hazards or reduce the vulnerability of homes to those hazards. Boise City Fire codes often work to reduce the vulnerability of homes to a hazard.

Table 4.3 Count of policies within four policy themes for each stakeholder in the Boise WUI.

Stakeholder	Manipulate	Reduce exposure	Reduce vulnerability	Increase ability to respond	Total
City of Boise	25	14	28	15	68
Boise City Fire	8	7	12	6	27
Boise City Zoning	16	7	14	2	32
Boise City Parks and Recreation	1	0	2	7	9
Ada County Emergency Management	3	4	10	11	22
Idaho Office of Emergency Management	4	6	5	6	13
Idaho Department of Lands	8	15	5	6	19
Bureau of Land Management	16	10	5	12	42

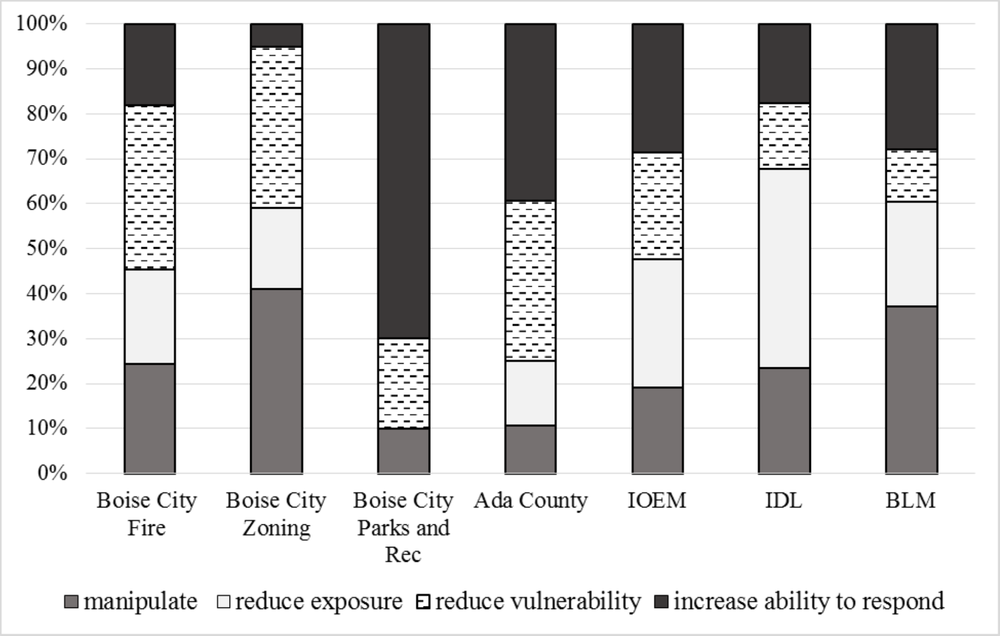

Figure 4.3 The dominant coded wildfire policies were distinct among Boise WUI stakeholders.

We also coded each policy for who is considered responsible for implementing the policy, and included (1) an individual, (2) a group of people, or (3) the government. The individual refers to a homeowner, landowner or business owner. The group may refer to a subdivision developer, advocacy group, or Firewise community. The government refers to the local, state or federal government that enforces the policy. Responsibility was not always made clear in the policy, we interpreted the most appropriate and logical responsibility for each policy. In many cases, multiple parties were interpreted to be considered responsible. These results are displayed in Table 4 and the relative amount responsibility placed by each stakeholder displayed in Figure 4.

Table 4.4 Count of responsibility of each stakeholder in the Boise WUI.

Stakeholder	Individual	Group of people	Government	Total policies
City of Boise	25	43	11	68
Boise City Fire	19	7	1	27
Boise City Zoning	5	31	2	32
Boise City Parks and Recreation	1	5	8	9
Ada County Emergency Management	3	19	7	22
Idaho Office of Emergency Management	2	5	13	13
Idaho Department of Lands	7	8	8	19
Bureau of Land Management	6	11	42	42

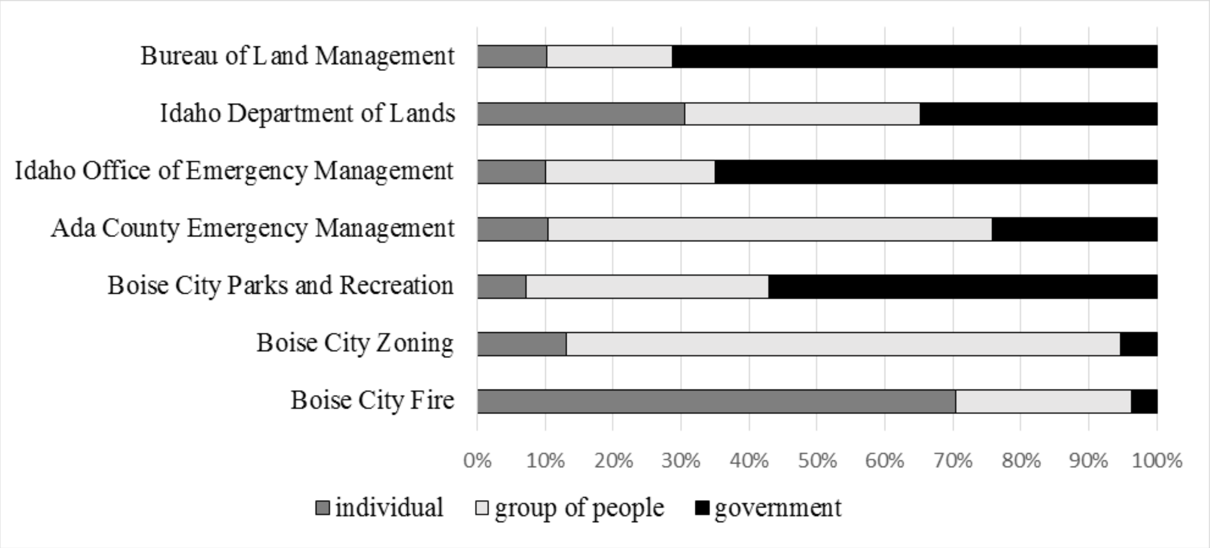

Figure 4.4 The relative amount responsibility placed by each stakeholder policy in the Boise WUI.

Qualitative results

We interviewed seven managers representing the land and hazard managers of the Boise WUI. We interviewed at least one member of every land and hazard management agency within the Boise WUI. Interviews lasted approximately one hour and were conducted in person or over the phone. Interviews focused heavily on the problem and policy streams of MSF. We sought to have WUI managers describe the wildfire problems they commonly face at the Boise WUI. We also asked mangers to describe potential policy solutions to the wildfire problems they had provided in the previous response. In this way, we were able to determine if how a manager discusses wildfire problems and their policy solutions aligned with the policy coding that current policies of each agency already had in play.

Problems and policies

Managers we interviewed identified several wildfire problems at the Boise WUI. Managers frequently described development in the foothills as a major current problem. ACEM, BLM, and IOEM noted that continued development into the Boise Foothills and toward hazardous areas was one of the top wildfire problems that they will face in the coming years. IDL also noted that a lack of planning codes that considered wildfire hazards was a problem at the WUI in general. Another frequent wildfire problem identified through interviews was humans causing their own wildfire hazards. The BLM, City, IOEM and IDL all discussed the presence of wildfire hazards that are caused by people living in the WUI. Examples of this problem included human-caused ignitions, flammable vegetation in close proximity to homes and people having an “it’s not going to be me” mentality. Other recurring wildfire problems brought up by managers included dense, flammable vegetation in occluded areas and flammable non-native grasses. Secondary hazards (i.e. post-fire flooding) was only mentioned once, by IOEM, as a wildfire problem. A complete list of WUI problems identified by managers can be found in Table 5.

Table 4.5 Complete list of WUI problems defined by managers during interviews.

Interviewer	**Problem definition**
ACEM	Economic loss from disasters
	Development in foothills
	Flooding
BLM	Getting people to actually prevent wildfire
	Preventing fire long enough to restore a landscape
	Development in hazardous areas
	Bulldozers making fuel breaks - hard to turn around
	Number of recreationists in foothills that would need to get out if a fire took place
	Lack of anchor points for combating fire
IOEM	Where hazards intersect homes
	Where hazards are highest
City Fire	Amount of hazardous vegetation in proximity to homes
	Lack of defensible space
	Lack of fuel breaks between homes and open space
	Occluded areas (e.g. open space) with dense vegetation near homes
IOEM 2	Development at the WUI

	Drought
	Human impacts - native and non-native species, ignitions
IDL	Public complacency
	Inadequate resources in government
	Lack of planning and building codes

We asked interviewees to describe potential policy solutions to the problems that they each identified. Some managers had unique solutions for each wildfire problem they identified, while other managers described one policy solution for multiple problems. For example, managers at the BLM had unique policy solution ideas for each of the problems they identified; the problem of developments in hazardous wildfire areas could be solved with a policy that encourages fuel breaks around those developments, while the problem of having a lack of anchor points within WUI developments (tactical locations to combat fire) could be solved by creating a policy that requires anchor points in new developments. Conversely, the Boise Fire Department addressed the wildfire problems that they identified - a lack of defensible space around homes, occluded areas, a lack of fuel breaks, and dense vegetation near homes - with a single policy solution of increasing the capacity to get funding to take action on these problems. A complete list of policies that each interviewer supplied to address each of their wildfire problems can be found in Table 6.

Table 4.6 Complete list of policy solutions to wildfire problems as described by interviewed managers.

Interviewer	Policy solution
ACEM	ID hazard areas, collaborate with groups that can implement policies that can reduce economic loss
BLM	Create "accommodation space" from which "actual" change regarding wildfire protection can take place (people need to be eased into big changes)
	Create fuel breaks
	Fuel breaks
	None
	Create safety zones in foothills for recreationists to go in case of fire. Could double as site for education about wildfire
	Create hardscaping anchor points in new developments
IOEM	Allocate funding to ID those location, map, and understand those hazards
City Fire	Prioritize funding and get more funding to meet the problems that science addresses (e.g. informs location of prescribed fires)
IOEM 2	Always coordinate to protect life and property.
	Idaho Department of Water Resources responsibility
	Use native grasses and shrubs in slope stabilization projects. Aligning goals of road ignitions prevention with other agencies
IDL	Educate to reduce the "it's not going to be me" mentality. Rural communities are more accepting of wildfire than urban areas
	Move money/funding from on the ground to wildfire management
	Assist in moving legislation for building and zoning codes

How science is used

We asked managers how science could be used to help solve the problems they identified, and how science could assist in developing or informing policy solutions. If interviewees were unable to identify how science could be used to inform the problem or policy stream, we asked, in a more general sense, what made science useful to them when making decisions at the WUI. All responses to these questions are in Table 7.

Two themes regarding the use of science emerged from interviews. The first is that science is used to identify wildfire hazard locations or future project areas. ACEM, BLM, IOEM and the City of Boise all noted that science is used when making decisions regarding the spatial location or extent of a current or future project. The second theme was that science is useful when it is understood quickly. ACEM, the BLM and IOEM all discussed how science is most useful when it conveys information in an efficient way. The BLM noted that "a 700 page document is nothing compared to a map that can visualized and understood immediately", while the IOEM mentioned that science is useful when it tells a story. In contrast, the IDL discussed that science was not particularly useful as the made decisions, noting that "science doesn't influence decisions that have already been made." When asked what they used science for when making decisions, the IDL interviewer recalled one situation where wildfire behavior models were used to make a land use decision, but that such occasions were uncommon.

Table 4.7 Interview responses to being asked what makes wildfire science useful at the WUI.

Interviewer	What science is used for?	What makes science useful?
ACEM	Compile data	Makes maps and models better, personalized and local, easy to understand
	Increases collaboration	
	Layers of hazard assessment	
BLM	Visual tool of where fires have been and what vegetation is there	700 page document is nothing compared to a map that can be visualized and understood, quickly usable and understandable
IOEM	Identify hazard areas	Use maps to tell stories allocate funding
	Identify where hazards intersect homes to allocate funding	
City Fire	Use to educate the public	
	Prioritize funding and justify budget	
	Inform policy makers who can increase funding	
	Could inform locations of prescribed fires	
IOEM 2	Cyclically look for gaps in knowledge that science can fill	
	Landslide identification	
	Fills gaps in knowledge	
IDL	Model wildfire risk	Science didn't identify anything that changed decisions that were already being made

Discussion

We conducted this study in order to determine how science is used to make decisions at the Wildland Urban Interface. We hypothesized that how a stakeholder defined a problem would be reflected in their policy solutions to that problem, and because science informs and influences problems and policies, we could identify how different stakeholders use science at the Wildland Urban Interface. To test this hypothesis, we first coded policies of Boise WUI stakeholders and identified that different stakeholders address wildfire problems with unique policy solutions. Land managing stakeholders at the City level (i.e. Boise Fire Department and Boise Zoning) address wildfire problems with policies that manipulate and reduce vulnerability to wildfire hazards, while the Idaho Department of Lands more strongly addresses reducing exposure to wildfire hazards, and the Bureau of Land Management policy focuses on manipulating and increasing the ability to respond to wildfire hazards. Hazard managers at the county level (ACEM) have policies that work to decrease vulnerability and increase the ability to respond to wildfires while state hazard managers (IOEM) have evenly distributed policies that address wildfire hazards.

City-level policies are dominated by manipulating wildfire hazards and reducing vulnerability to wildfire hazards. This can be explained by the wildfire hazards they must manage for. The city must create policies that manage for homes that have already been built at the WUI. In order to combat wildfire hazards that threaten life and property, city-level managers must write ordinances that reduce the danger placed on humans. For homes already at the WUI, it is difficult to reduce exposure to the hazard – the homes have already been built. Because homes and neighborhoods have already been established in the Boise Foothills, it is not surprising to see that many wildfire policies are considered the responsibility of homeowners and neighborhoods to implement. For example, many City WUI codes prohibit certain flammable or untreated building materials to be used when constructing or repairing homes in the WUI, and require that certified flame-resistant materials be used instead. To reduce vulnerability to wildfire hazards, new homes constructed in WUI neighborhoods must have a defensible space, which is an area surrounding a home that has been designed to slow the intensity of advancing fire from which wildfire suppression can be anchored.

The Idaho Department of Lands policies frequently address reducing exposure to the hazard. Many of their policies involve reducing wildfire ignitions by prohibiting campfires during wildfire season and by requiring logging outfits to suppress fires that they start while cutting and removing forest products (i.e. trees) from the forest. This policy places the incentive on logging companies to reduce the cost of suppressing wildfire by not starting them in the first place.

Bureau of Land Management WUI policies focus on manipulating and increasing the ability to respond to wildfire hazards. The BLM is often the first to respond with engines and firefighters to wildfires within BLM land near the WUI, therefore it is not surprising that their policies focus on increasing the ability to respond to wildfire hazards. Additionally, several BLM policies are in place to coordinate efforts with other firefighting entities (i.e. Boise Fire Department, Forest Service) when fighting fires in order to ensure rapid fire response. The BLM also has numerous policies in place to manipulate wildfire hazards, especially secondary hazards like post-fire flooding. The Emergency Stabilization and Rehabilitation protocol of BLM contains policies that reduce the potential for post-fire erosion by funding soil stability projects in erosion-prone areas. Reseeding, straw bale installation and mulching projects often take place within sloped BLM land to reduce erosion and capture runoff after wildfire.

Ada County Emergency Management policies focus equally on reducing vulnerability and increasing the ability to respond to wildfire hazards. Their policies focus on the neighborhood level, and include that neighborhoods have available water and quick access by emergency response when a wildfire occurs. Additionally, ACEM encourages wildfire mitigation to be undertaken by the local government (e.g. City of Boise) that would minimize damage done by wildfire. Many of ACEM's policies work to increase the ability to respond to the fire through education of the public about potential hazards, including wildfire, and also encourage intense collaboration among different wildfire stakeholders. Increased communication equates to increased ability to respond when a wildfire occurs at the Boise WUI.

Idaho Office of Emergency Management policies are evenly distributed among manipulating, reducing exposure, reducing vulnerability and increasing ability to respond to hazards. This can likely be explained by the broadness of their hazard policies. IOEM manages for several hazards throughout the state of Idaho, of which wildfire is only one amongst earthquakes, avalanches, pandemics, landslides and others. As a result, while some of their policies pertain to wildfire at the WUI, IOEM policies are often all-encompassing, and less likely to be categorized into one of the four WUI codes. For example, IOEM's policy to 'improve land use planning' could be coded under reducing exposure, reducing vulnerability and increasing the ability to respond to a wildfire hazard, rather than fitting within one code alone.

While each of the stakeholders at the Boise WUI have different dominate policy types to address wildfire hazards, they commonly define their wildfire problems similarly. Continued development in the foothills is considered a top problem by stakeholders. ACEM, BLM, IOEM and IDL noted that continued development into the Boise Foothills and toward fire-prone areas is one of the top wildfire problems that they will face in the coming years. The Boise WUI is growing quickly. Within the past two years (2015-2017), the City and County have approved at least two major housing developments, within which ~2000 homes will be constructed within the WUI, adding to the number of homes threatened by wildfire. Because these housing developments have been approved in recent time, the salience of development in the WUI likely explains why it was a commonly noted problem in interviews. Additionally, firefighters used recently graded home foundations within the new Harris Ranch development in the foothills to combat a ~2600 acre fire. If homes had already been constructed upon those newly-dug foundations, it is possible that the wildfire would have burned down those homes.

The BLM, Boise Fire, IOEM and IDL all discussed the problem of human influence on wildfire hazards. These managers each discussed that human-caused ignitions, human-selected landscaping, or homeowners uninformed of the wildfire hazards they face increase wildfire hazards at the WUI. Eighty-six percent of wildfires at the Boise WUI are started by humans. Fireworks, landscaping equipment and vehicles caused three major wildfires within the Boise Foothills this year, which burned a combined ~7500 acres. Additionally, many homes within the Boise WUI, especially in older developments, are surrounded by dense, mature, flammable vegetation. Decorative junipers and pines are highly combustible, and create a serious hazard directly adjacent to homes. Many homeowners are simply unaware of the wildfire hazards they create for themselves. To combat this problem, the Boise Fire Department and BLM have strong education components to their wildfire mitigation efforts. Programs like Ready Set Go encourage homeowners to develop an evacuation plan with their families in the event of a wildfire. In the program homeowners are educated about preparing for wildfire door-to-door with information kits that provide succinct information about what is required to evacuate in the event of a wildfire. Additionally, the City of Boise offers an annual chipping program that allows homeowners to have their hazardous vegetation chipped and hauled away at no cost to the homeowner. Information regarding what vegetation is hazardous is provided door-to-door prior to the chipper's arrival, allowing homeowners to gauge the hazards their vegetation creates.

When asked how science is used to make decisions about these problems, stakeholders described two dominant themes. First, science is commonly used to draw boundaries. Boise Fire, ACEM, BLM and IOEM discussed that science is used to inform project locations, such as where vegetation thinning is most necessary or areas that are most suited to prescribed fires. Additionally, the IOEM also mentioned that visual tools are a good educational tool for telling stories, which is useful when conveying information to the public in a meaningful way. Secondly, many managers discussed that visual tools could help allocate where funding for projects is most necessary, such as areas where dense vegetation surrounding homes could most use a chipper or education and outreach. This result relates back to the findings of Machelis (2002) regarding how science is used to make decisions. Maps are succinct and tangible. When designed well, maps convey a great deal of information in a short period of time, and draw boundaries indicating where and where not hazards exist or money needs to be allocated. Wright (2010) and Hunter (2016) both mention that time constraints make science unusable. A BLM manager stated that “a 700 page document is nothing compared to a map that can be visualized and understood quickly”. Maps are certainly faster to read than a 700 page document that may convey the same scientific information in a non-visual manner. As a hypothetical example, there may be several reports about where herbicide treatment has and has not reduced flammable invasive grasses, but only a map displaying those locations of success and failure may help managers to tangibly understand whether or not that treatment should be prescribed on their own land. As such, a map would quickly help managers decide where to allocate funding for herbicide treatments.

We hypothesized that because different stakeholders at the WUI used different policies to address wildfire problems that each stakeholder would describe science as being useful for distinct reasons, thus fitting within the Multiple Streams Framework. Science flowing through the problems and policy streams of each stakeholder will be used differently, as each stakeholder has different policies to address problems. However, stakeholders described that science is useful for similar reasons: science draws boundaries and helps allocate funding. Interestingly, MSF can describe why science is not used uniquely among stakeholders. In the background section, we described fragmentation of policy communities. Fragmented policy communities often lead to fragmented polices over a given policy issue (Kingdon, 1995), leading to disconnect amongst solutions to a similar problem. Fragmentation is the result of low collaboration, communication and knowledge sharing. At the Boise WUI, however, knowledge sharing is high and fragmentation is low. ACEM encourages collaboration among City, State and Federal stakeholders. As such, it is not uncommon for the BLM to co-educate the public with the City Fire Department or for IDL to work with the County on Community Wildfire Protection Plans. Additionally, annual windows of opportunity (i.e. wildfires in the foothills) create situations where stakeholders at the Boise WUI work together on the same wildfire problem, because wildfires frequently cross jurisdictional boundaries. The 2016 Table Rock Fire, for example, burned within City, State and Federal land, creating the opportunity to collaborate on rehabilitation projects. Because fragmentation is low amongst stakeholders, it is possible that managers at the Boise WUI, representing City, State and Federal land and hazard stakeholders, can be treated as one large stakeholder group. Within a spatially confined location (i.e. the Boise WUI), these stakeholders must address the same wildfire problems regardless of their differences in policies. This may explain why science considered to be useful for the same reasons across stakeholders. What is useful for a federal stakeholder (i.e. the BLM) at the local level (i.e. the Boise WUI) may not be what is useful throughout the land that the BLM manages.

Science must also address the right people in order to be usable (Figure 4). City-level policy often relies on individuals (e.g. homeowners) to implement the policies set forth, while state (IOEM) and federal (BLM) policies are to be implemented within their own level of government, rather than being passed on to neighborhoods or individual business owners. Ultimately, in order for science to be used when pushing policies through the window of opportunity, it must be communicated to the right people, be it individual homeowners or federal level managers. This may be why visual tools, such as maps, are useful by all stakeholders. While most citizens or managers may not understand a piece of scientific literature, like a journal article, most citizens and managers are likely to understand a map containing boundaries and zones of information. This finding is important for producers of science to consider. At the local level, where home and business owners are the responsible for implementing policies such as thinning vegetation around their homes or cutting flammable grasses, science must be able to speak to the general public. At the state and federal level, managers can use maps to target areas to provide education and outreach to encourage the implementation of wildfire reduction policies. As such, one piece of science would be useful for all levels of decision-making.

The implications of this analysis for Boise, and potentially for other WUIs, is significant. The push and pull of science must be mutual between scientist and user; this is not a new finding (Dilling and Lemos, 2011; Palmer, 2012). However, this study adds to our knowledge of the pull on science by decision-makers at the WUI. When a WUI is comprised of an unfragmented policy community, the same scientific information may be useful for all stakeholders. If a piece of science draws boundaries, is quick to understand and helps allocate funds, it will likely be considered useful by many wildfire stakeholders. When science is presented in a manner that is tailored to the target audience(s) by recognizing which policy themes they are required to follow, science can be better used to identify problems and inform policies that maximizes the use of that science. Ultimately, the three streams will merge and pass through the window of opportunity to make new policy decisions. Science can act as an indicator to influence these streams, and inform policies that combat wildfire hazards. These policies can manipulate and reduce exposure to wildfire hazards, reduce vulnerability to wildfire hazards or increase the ability to respond to those hazards. It is a matter of producing science that is capable of informing these policies to the levels of government that needs the information. It may be important for scientists to tailor science to meet the needs of managers, and if not, may lead to a disconnect between science and decision maker. If a scientist learns something about a natural hazard but doesn't inform policy at a level that can use it, the scientific endeavor may not have been worthwhile. Conversely, these findings also indicate that it may be the responsibility of wildfire decision-makers within the WUI policy community to continually inform scientists what scientific information would be useful to them and what will make it useful. As such, the mutual push and pull of science by scientists and decision makers will maximize the utility and use of science, creating more informed, and better prepared and protected Wildland Urban Interface.

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APPENDIX A

A Comparison of Field, Lab and SSURGO Clay Content in the Boise Foothills

The model used to predict the probability of post-fire debris flows in Chapters III and IV require inputs of topographic, precipitation, fire severity and soil attributes. Clay content is one such required soil input, and markedly influences model predictions of post-fire debris flow probability; as the clay content of soil within a drainage basin increases, the predicted probability of a post-fire debris flow also increases. SSURGO provides high resolution soils data for the Boise foothills; however, it is unknown how accurate SSURGO modeled values of clay content are compared to what is actually found in the field. In the results of this appendix, we provide the results of a comparison of field and hydrometer soil textures of soil samples taken in the foothills above Harris Ranch subdivision. We compared the resulting ‘real world’ clay content values to those provided by SSURGO for the same sample locations. Results show that both field texture and SSURGO overestimate clay content compared to that measured by hydrometer analysis. SSURGO overestimates clay content sample sites by ~10%. Interestingly, many of these previously undisturbed sample sites have since been disturbed in the construction of an extension of Harris Ranch subdivision, adding value to these findings. These results emphasize the need to field verify soil textures provided in regional and national soils maps (i.e. STATSGO and SSURGO) when calculating post-fire debris flow activity.

Study Area

The Harris Ranch subdivision is located at the eastern extent of the city of Boise, Idaho, at the boundary between the Boise River floodplain and the Idaho Batholith. Harris Ranch sits at the outlet of Squaw Creek, one of several ephemeral drainages that flow into the Boise metropolitan area. Incised portions of the outlet of this drainage reveal that Squaw Creek has deposited fire-induced, as well as at least one fire-related debris flow event, as indicated by charcoal within both deposits. The eight soil samples for this study were acquired from six hillside sites that drain into Squaw Creek within ~0.5 miles from the outlet from the Boise Foothills to the Boise River floodplain. Samples were taken from hillslopes 875-920 m above sea level. Samples were acquired from both north and south facing slopes which consist of sparsely vegetated south facing slopes and sagebrush dominated north facing slopes. However, vegetation in this area has been altered by human activity; grazing in the early 1900s led to the removal of native vegetation and introduction of cheatgrass and medusahead rye.

Methods

The top 30 cm of soil were collected from each site. Samples below 30 cm was collected when possible. Cobbles prevented soil from being acquired past 20 cm at site 1. Sites 2, 5 and 6 were sampled from soil profiles that were either naturally or anthropogenically exposed. Equal volumes of soil were acquired from each site. Samples were placed in Ziploc plastic bags. The bags were opened and left to dry in the Surface Processes lab for approximately 2 weeks. Each sample was weighed and sent through a 2 mm sieve and material >2 mm removed. The remaining samples underwent field texture analysis to estimate clay content as outlined by the USDA’s flowchart (*Soil Survey Field and Survey Methods Manual*). Field texture analysis measures clay content for each sample within 15-20%. Each sample was then tested using the hydrometer methods using instructions provided by the USDA (*Soil Survey Field and Survey Methods Manual*).

Results

Harris Ranch Study Site

				SSURGO	Texture by feel		**Hydrometer**
Site	date	aspect	depth range (cm)	Clay Content %	resulting texture	**Clay content range (%)**	**Clay content %**
1	1	S	0-20	11.1	SCL	20-35	10
2	2	N	0-20	16.7	SCL	20-35	14
2b	3	N	20-49	30.6	SC	35-55	16
3	4	SW	0-21	30.9	SC	35-55	12
4	5	W	0-30	34.4	SC	35-55	16
5	6	N	0-30	34.4	SC	35-55	31
5b	7	N	30-60	45.3	SC	35-55	28
6	8	S	0-34	35.3	C	55-100	50

The lowest clay content was sampled from site 1, the base of a south-facing slope comprised of lacustrine sediment outcrops and angular cobble and boulder-sized clasts.

7 of the 8 soil samples measured by the hydrometer yielded values lower than those provided by SSURGO. Hydrometer clay content for samples were, on average, 22.5% lower in clay content than the median value estimated by field methods. Field texture, however, overestimates the clay content in 7 out of 8 samples as compared to the SSURGO. The clay content of each sample measured using the hydrometer methods falls completely out of range of clay content estimated by field texture.

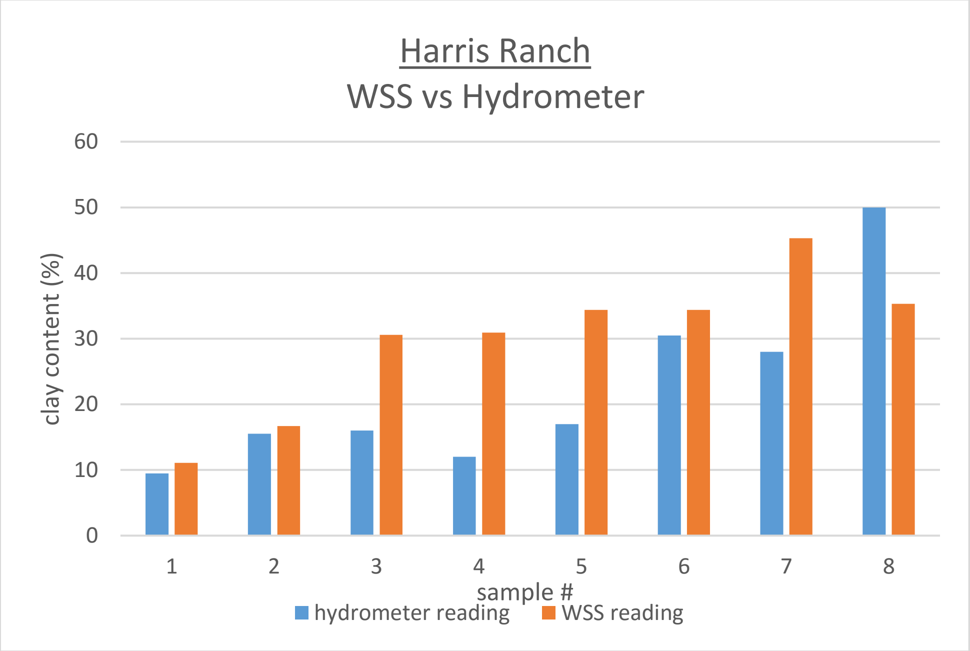


Figure A.1 Comparison of clay content of samples from Harris Ranch study site to clay content displayed on WSS at sample site location. Average overestimation was 10.7% clay content. For sample 8, WSS underestimates clay content by 14.7%

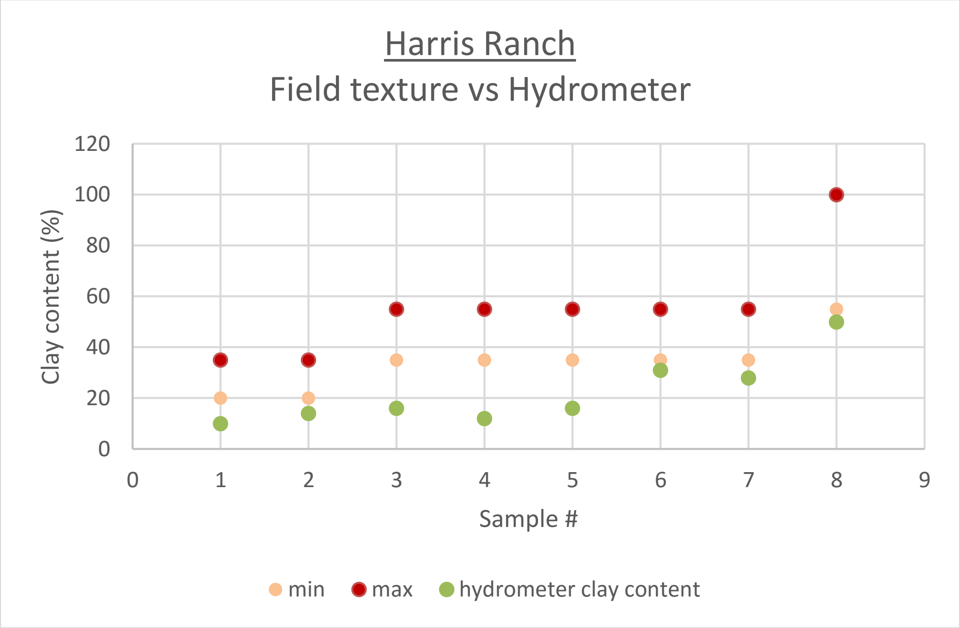


Figure A.2 Comparison of texture by feel field clay content of Harris Ranch sites to resulting hydrometer analysis clay content of each sample. Note that each sample's hydrometer clay content falls completely outside the range of that determined using texture by feel analysis (range indicated by green and red points).

APPENDIX B

Pairing USGS Post-fire Debris Flow Volume Model Estimates with LAHZRZ Depositional Extent to Estimate Post-fire Debris Flow Depositional Extent into Boise, Idaho

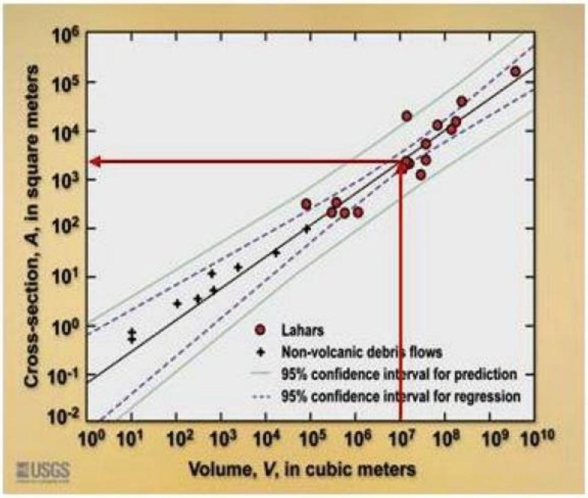
The objective of this exercise was to apply USGS post-fire debris flow model estimates of debris flow volume (acquired in Chapter 3) to a model, LAHARZ, which predicts the runout extent. I compared LAHARZ predictions to a mapped mudflow event that occurred in Boise in 1959. I hypothesized that LAHARZ would underestimate the depositional extent of mudflow deposits sourced from the Boise Foothills study area; debris flows have higher viscosity than mudflow and sediment-laden flood events that historically typify the Boise Foothills. I found that the *debris flow* function in LAHARZ underestimates the runout extent of mudflows that have occurred in the 1959 mudflow events; modeled deposition often did not reach alluvial fans that are known to have received mudflow deposition. The *lahar* function in LAHARZ produces runout onto alluvial fans. These results indicate that LAHARZ is not suited to estimate debris flow extent for mudflow-type debris flow deposition seen in the Boise foothills, but that the *lahars* function may produce a more accurate estimate.

<u>Background</u>

When attempting to identify areas that may be threatened by debris flow deposition, one option is to identify and delineate alluvial fans. However, this method of hazard identification does not account for portions of alluvial fans that may be deposition alley inactive, and does not consider differences in depositional volume. LAHARZ estimates the depositional extent of lahars, debris flows, and rock avalanches of a given volume. Given a starting point of deposition and a DEM, LAHARZ routes the debris flow volume and delineates the aerial extent of the debris flow volume. LAHARZ is commonly used to identify the paths of volcanic lahars, but has functions to estimate debris flow extent (Magirl et al., 2010; Youberg, 2010).

Methods

LAHARZ is a toolbox designed to run within a GIS, and is compatible with ArcMap. The tool was originally designed to delineate areas inundated by a lahar of a given volume. The latest of LAHARZ is also capable of delineating inundation zones for debris flows and rock avalanches. Inundation zones are empirically derived from lahar, debris flow and rock avalanche measurement records (see Figure 2). Regression through these measurements create the equations from which LAHARZ calculates and maps cross-sectional and planimetric inundation zones upon the provided DEM, beginning at deposition a deposition apex selected by the user. Within the toolbox are seven scripts, coded in Python™ language. Only two scripts are required if the user is selecting their own deposition starting points. These scripts are 1) *create surface hydrology rasters*, and 3) *create debris flow distal zones*.



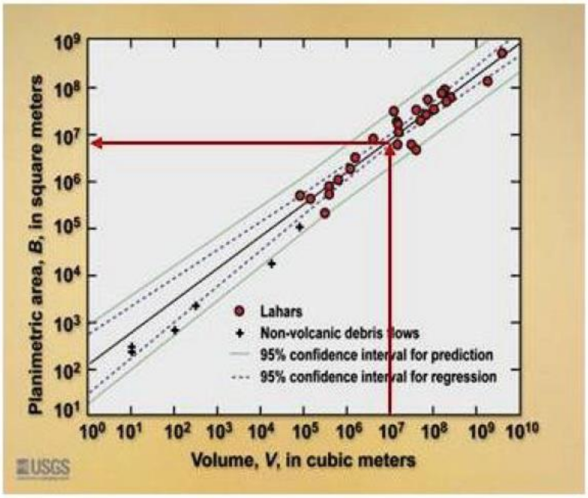


Figure A.3 Graphs depicting the relationship between lahar and debris flow volume to cross-section and planimetric area of deposition

To calculate debris flow extent using LAHARZ, I used modeled post-fire debris flow volume estimates from <0.5 km^2 basins calculated in Chapter 3, volume estimates of sediment from the 1959 mudflow event, and a 30 meter DEM of the 1959 burn area. Starting points of deposition were interpreted from aerial imagery. The selected starting locations for depositions were selected to be that of the apex of alluvial fans that deposit at the flanks of the Boise Front onto the Boise River plain. These data inputs were supplied to the LAHARZ scripts.

The first script, *Create Surface Hydrology Rasters* automates the process of filling sinks and generating flow direction, flow accumulation and stream rasters at a stream threshold specified by the user. The user then supplies volumes of debris flows to simulate. In this study, post-fire debris flow volume estimates were taken from both the USGS post-fire debris flow models and official reports regarding the 1959 mudflow events (Thomas, 1963). Once supplied volume estimates, LAHARZ iteratively “fills” each downhill pixel, using the empirical equations to determine inundation zone extent, until the entire input volume has been “deposited”. The output is a raster representing the deposition extent of the volumes provided by the user. For this study, this process was repeated for the *debris flows* and *lahar* functions to compare the deposition extents of the two deposit types, the workflow for which is depicted in Figure 3.

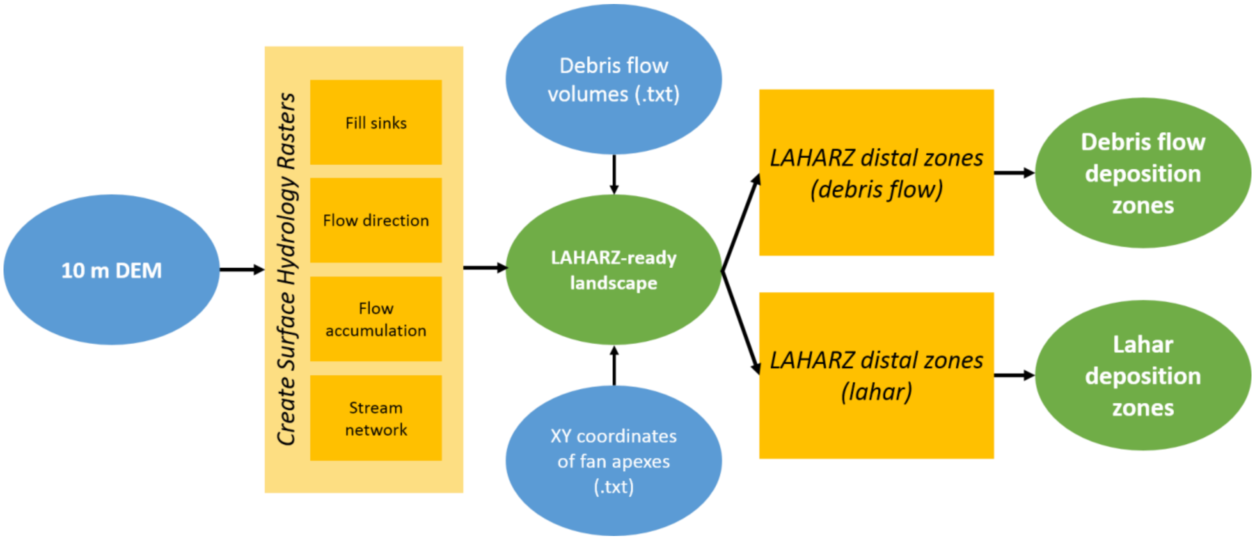
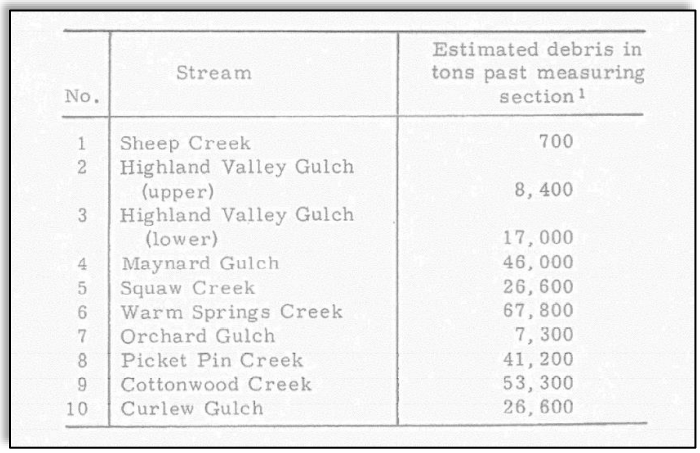


Figure A.4 Model builder-type work flow undertaken to produce debris flow extent for the Boise Foothills

The depositional extent of volume estimates of each sediment-producing stream outlet were modeled in LAHARZ. Cottonwood Creek, Warm Springs Creek, Squaw Creek, Maynard Gulch, and Highland Valley Gulch (Figure 4) deposited a field-estimated 219,100 tons of sediment and debris in the 1959 event (Table 1). LAHARZ requires volume input as m^3. The conversion from tons to cubic meters assumed a debris flow density of 2000 kg/m^3. We compare 1959 mudflow volumes to post-fire debris flow model estimates of the same fire perimeter over a range of fire severity scenarios. The model estimates of volume for each scenario are summarized in Table 3.



No.	Stream	Estimated debris in tons past measuring section[1]
1	Sheep Creek	700
2	Highland Valley Gulch (upper)	8, 400
3	Highland Valley Gulch (lower)	17, 000
4	Maynard Gulch	46, 000
5	Squaw Creek	26, 600
6	Warm Springs Creek	67, 800
7	Orchard Gulch	7, 300
8	Picket Pin Creek	41, 200
9	Cottonwood Creek	53, 300
10	Curlew Gulch	26, 600

Figure A.5 Original table from 1963 report (Thomas) of tons of debris from each stream in response to 1959 fire and rainstorm event.

Table A.1 Translating estimates of debris flow material in tons to volume in m^3. Density of debris flow material accounts for both the density of the granitic source (2650 kg/m^3) and less dense ash and soil, resulting in material approximately 2000 kg/m^3

Stream	Estimated debris (tons)	**tons to kg**	**density of material (kg/m^3)**	**volume (m^3)**
Highland Valley	25400	23042499	2000	11521.25
Maynard Gulch	46000	41730510	2000	20865.26
Squaw Creek	26500	24040402.5	2000	12020.2
Warm Springs Creek	67800	61507143	2000	30753.57
Picket Pin Creek	41000	37194585	2000	18597.29
Cottonwood Creek	53300	48352960.5	2000	24176.48

Table A.2 Post-fire debris flow model volume estimates for 1959 burn area over range of burn severities

	Volume (m^3) under different % moderate to high burn severity scenarios			
Drainage name	25%	50%	75%	100%
Highland Valley	6222	6871	7417	7913
Maynard Gulch	12710	14046	15174	16203
Squaw Creek	18777	21059	22595	23992
Warm Springs Creek	39690	44014	47682	51034
Picket Pin Creek	25382	27511	29291	30906
Cottonwood Creek	41333	44845	47778	50430

Results

Because Picket Pin and Cottonwood Creek merge to one outlet that flows into Boise, their volumes were summed for modeling in LAHARZ. A map comparing the *debris flow* function to the *lahars* function of LAHARZ is displayed below. The runout extents using the *debris flow* function for modeled and field measured volumes (from 1959 mudflow) do not deposit onto the Boise River plain, but remain within the confines of their stream valleys.

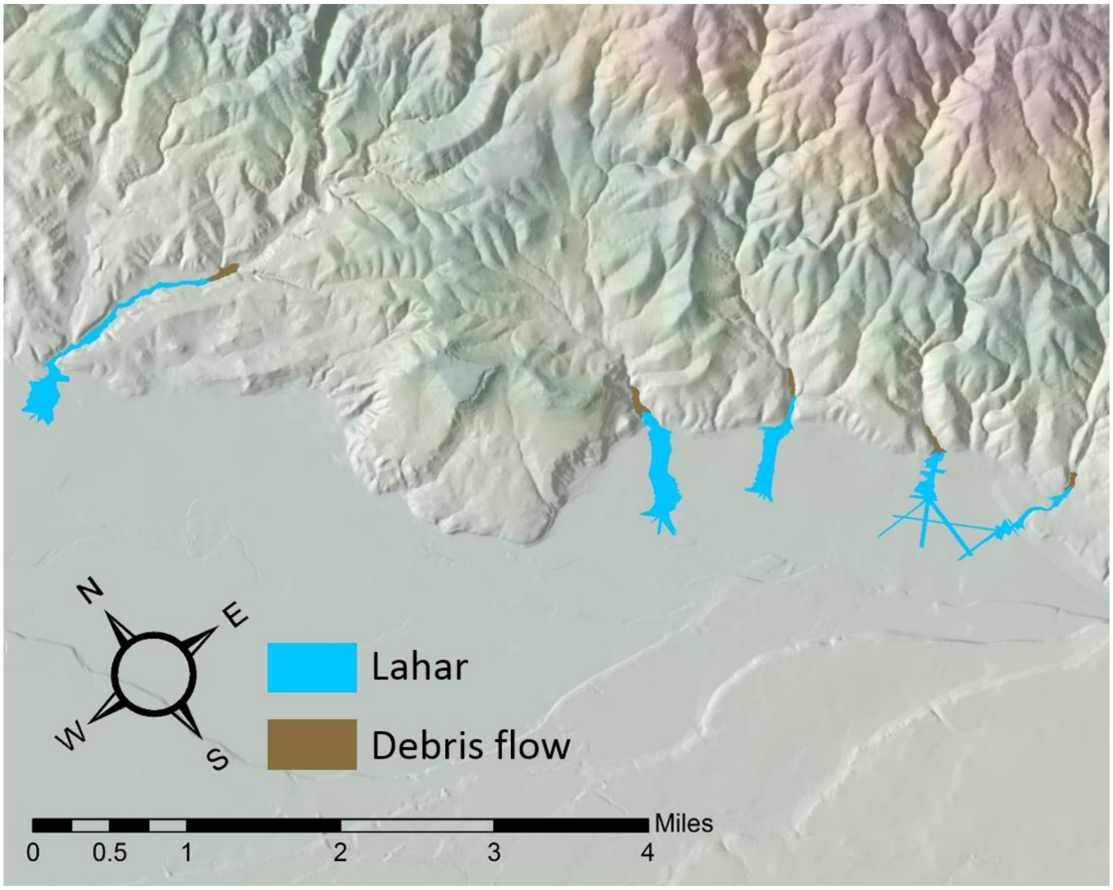


Figure A.6 Debris flow vs lahar deposition

Maps depicting the debris flow extent (via the *lahars* function) of 4 different burn scenarios (25%, 50%, 75% and 100% burned at moderate and high burn severity) are displayed below for each channel examined in this study. The ‘field estimate’ category refers to the estimates reported for the 1959 report.

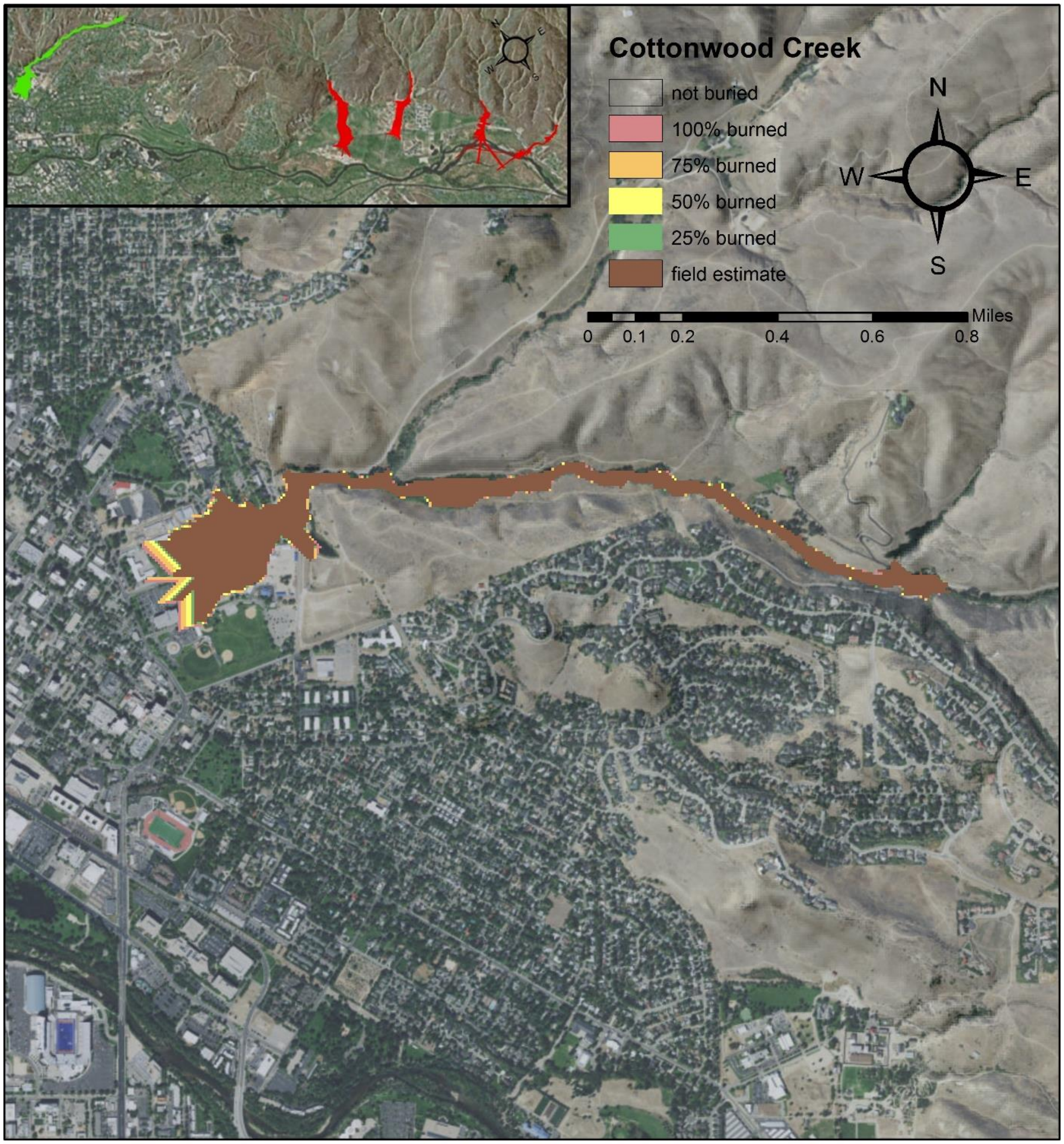


Figure A.7 Cottonwood Creek LAHARZ deposition extent using the lahar function. The resulting debris flow covers much of Military Reserve.

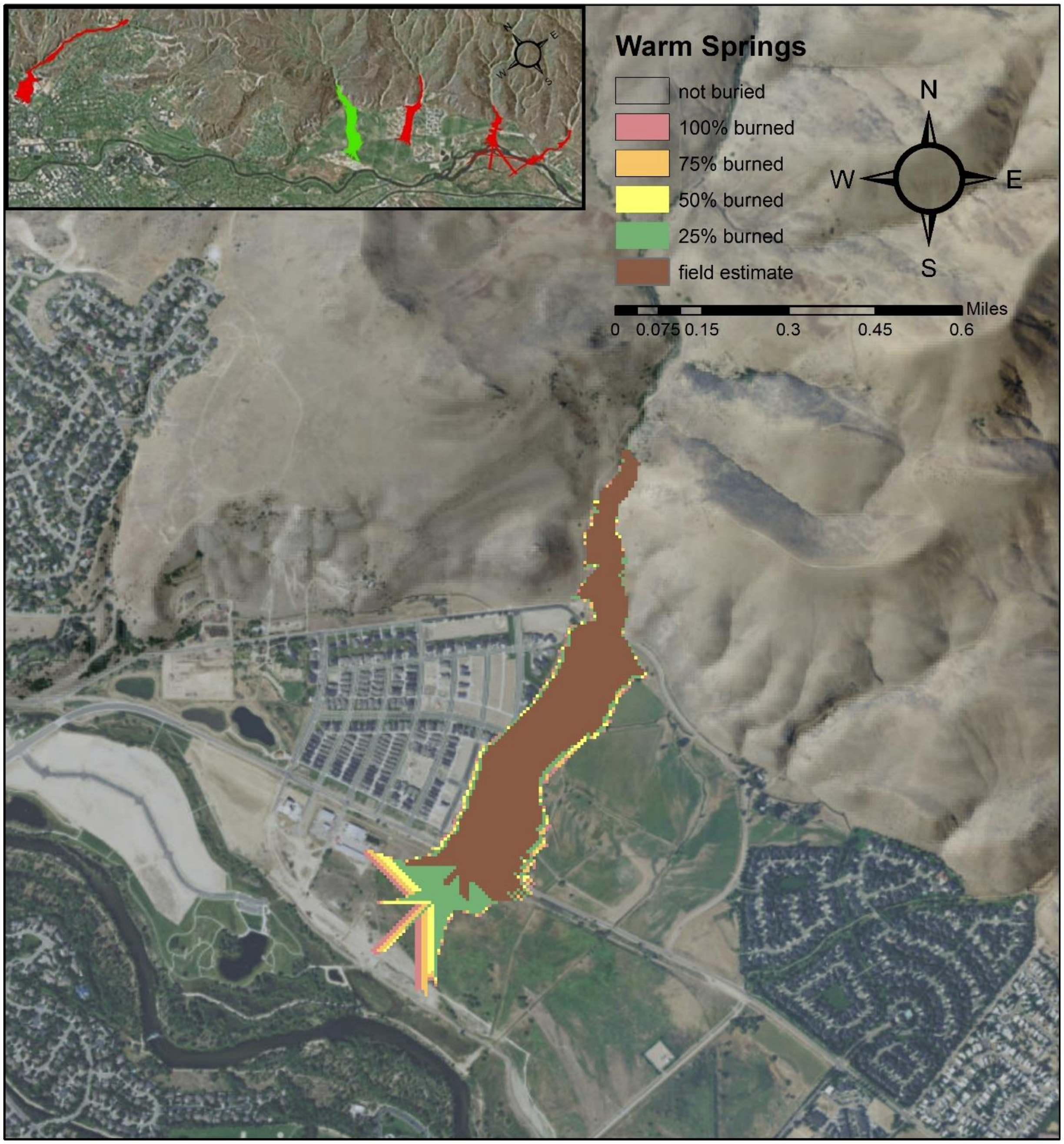


Figure A.8 Warm Springs LAHARZ deposition extent using the lahar function. The resulting debris deposits within the bounds of the Warm Springs alluvial fan.

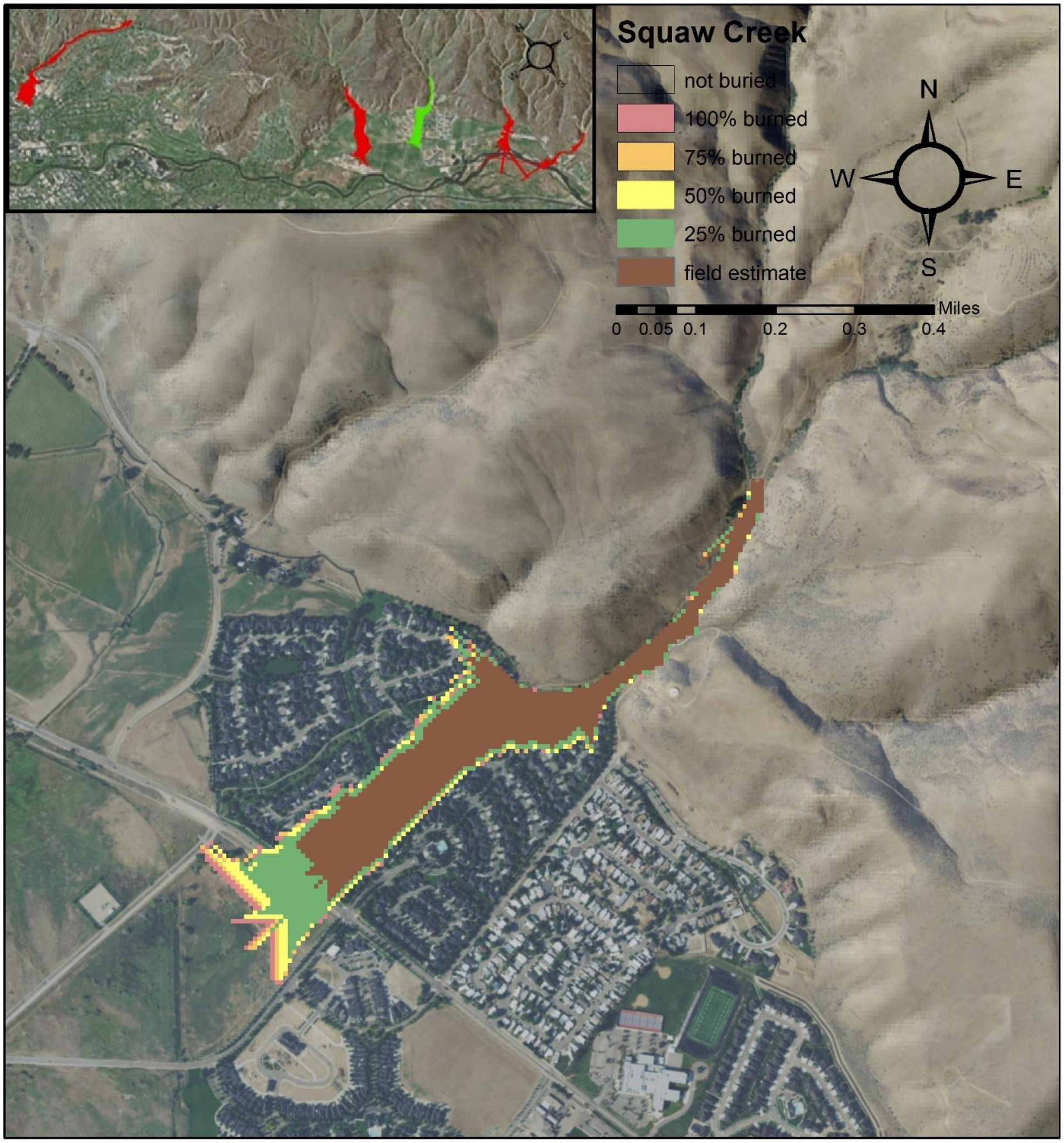


Figure A.9 Squaw Creek LAHARZ deposition extent using the lahar function. Note that the debris flow deposits toward the downstream direction (NW) of the Harris Ranch neighborhood.

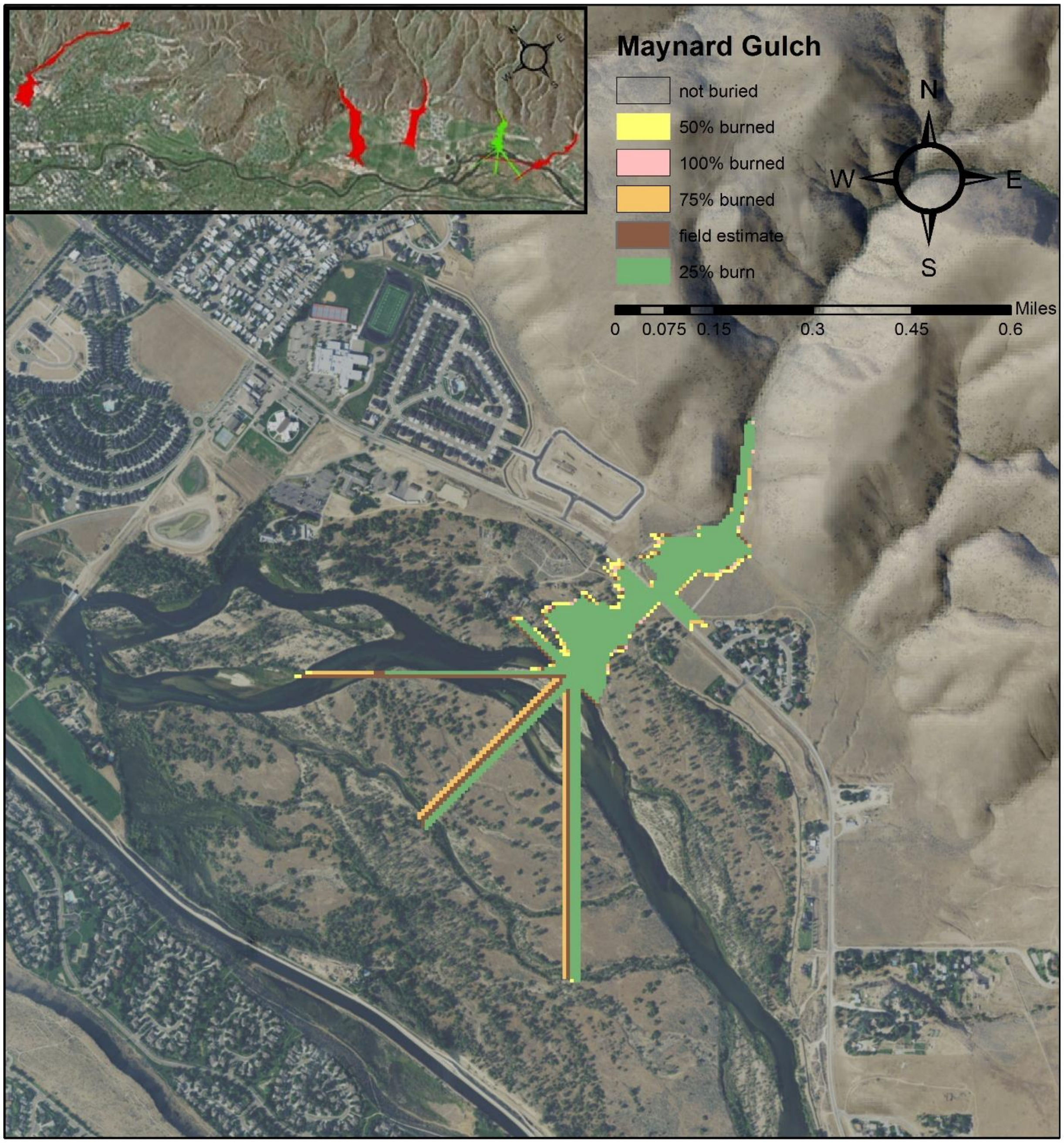


Figure A.10 Maynard Gulch LAHARZ deposition extent using the lahar function. Note that, upon reaching the Boise River, LAHARZ routes the remaining volume along one of the eight compass directions identified using the flow direction tool. Could be used as baseline estimate of how much sediment could enter the Boise River in event of post-fire debris flow.

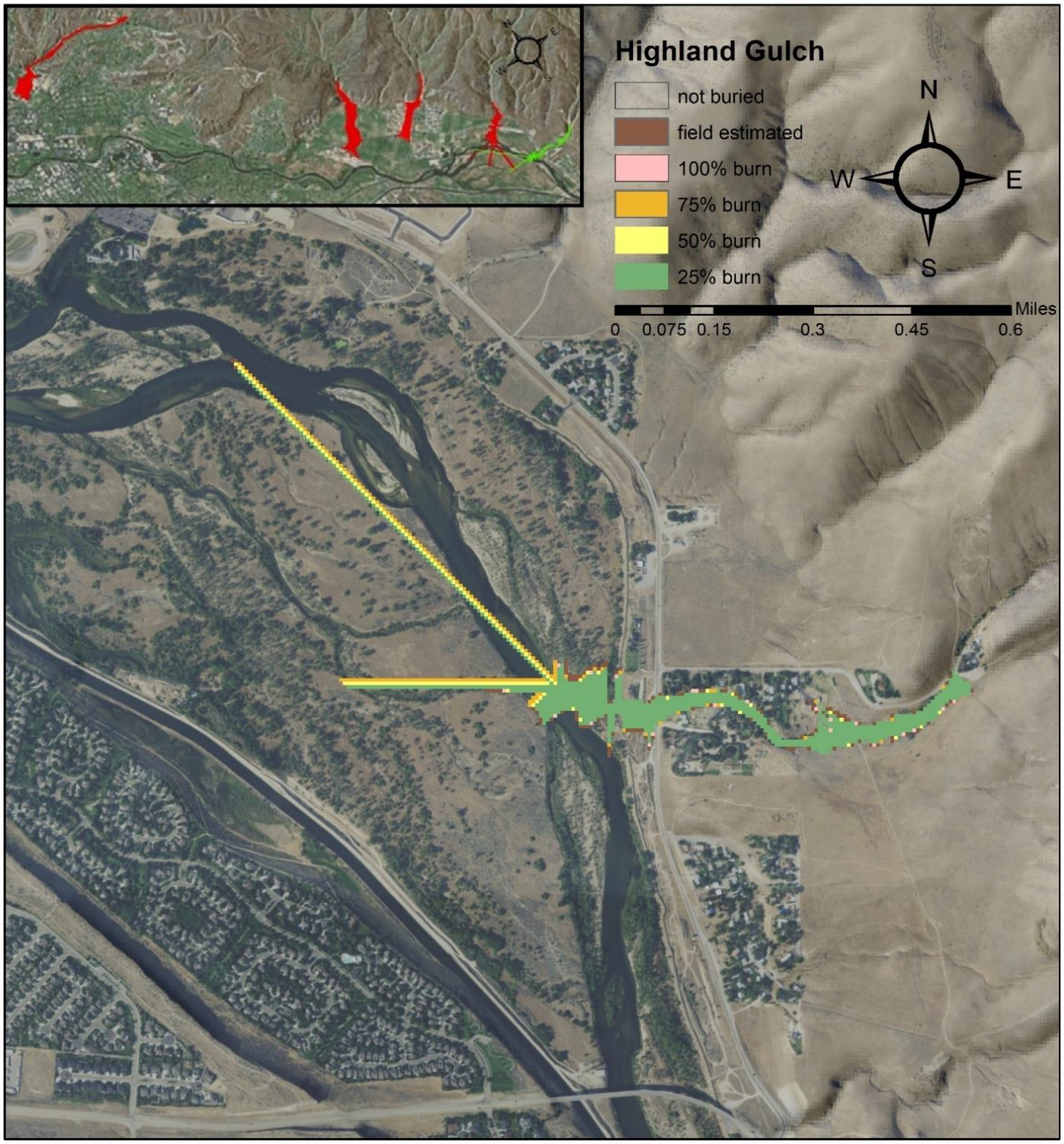


Figure A.11 Highland Gulch LAHARZ deposition extent using the lahar function. Note that, like Maynard Gulch, upon reaching the Boise River, LAHARZ routes the remaining volume along one of the eight compass directions identified using the flow direction tool.

Lastly, below is a map displaying both the mapped extent of mudflow deposition from the 1959 post-fire debris flow event in conjunction with LAHARZ estimated extent using

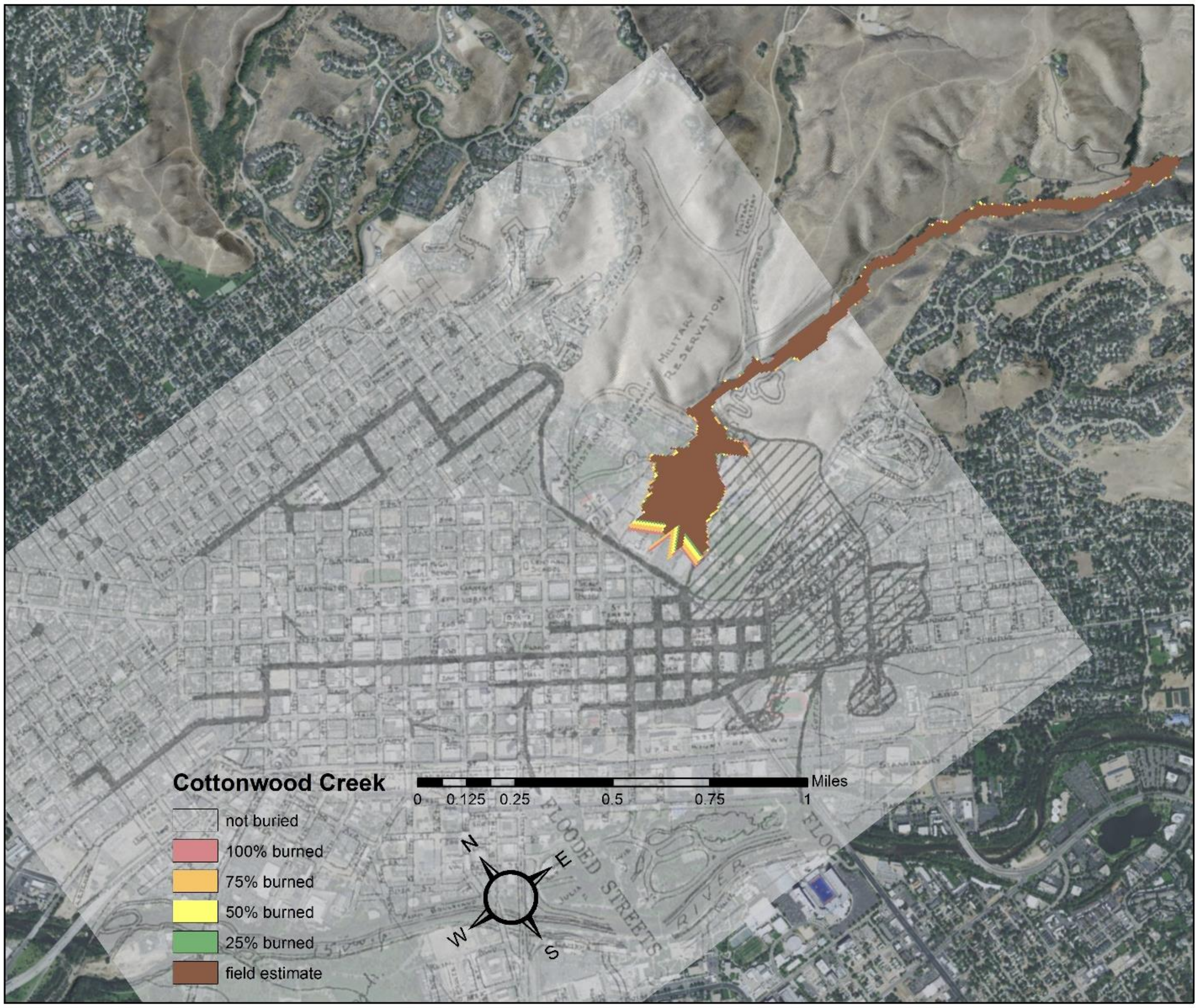
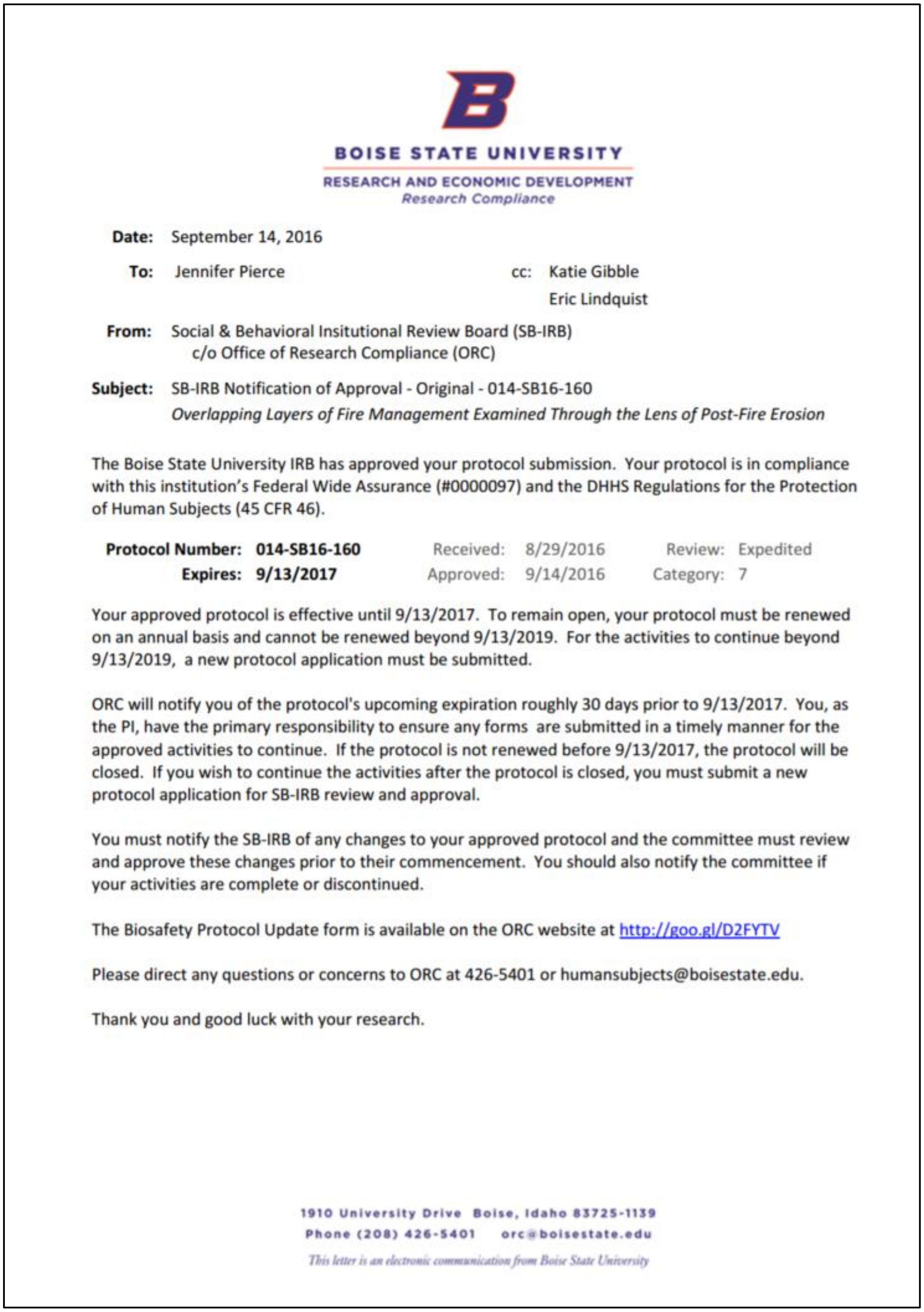


Figure A.12 Cottonwood Creek modeled vs. mapped deposition extent. Note how there are dissimilar debris flow extents and paths of deposition.

APPENDIX C

IRB Approval Form



BOISE STATE UNIVERSITY
RESEARCH AND ECONOMIC DEVELOPMENT
Research Compliance

Date: September 14, 2016

To: Jennifer Pierce

cc: Katie Gibble
Eric Lindquist

From: Social & Behavioral Insitutional Review Board (SB-IRB)
c/o Office of Research Compliance (ORC)

Subject: SB-IRB Notification of Approval - Original - 014-SB16-160
Overlapping Layers of Fire Management Examined Through the Lens of Post-Fire Erosion

The Boise State University IRB has approved your protocol submission. Your protocol is in compliance with this institution's Federal Wide Assurance (#0000097) and the DHHS Regulations for the Protection of Human Subjects (45 CFR 46).

Protocol Number:	**014-SB16-160**	Received:	8/29/2016	Review:	Expedited
Expires:	**9/13/2017**	Approved:	9/14/2016	Category:	7

Your approved protocol is effective until 9/13/2017. To remain open, your protocol must be renewed on an annual basis and cannot be renewed beyond 9/13/2019. For the activities to continue beyond 9/13/2019, a new protocol application must be submitted.

ORC will notify you of the protocol's upcoming expiration roughly 30 days prior to 9/13/2017. You, as the PI, have the primary responsibility to ensure any forms are submitted in a timely manner for the approved activities to continue. If the protocol is not renewed before 9/13/2017, the protocol will be closed. If you wish to continue the activities after the protocol is closed, you must submit a new protocol application for SB-IRB review and approval.

You must notify the SB-IRB of any changes to your approved protocol and the committee must review and approve these changes prior to their commencement. You should also notify the committee if your activities are complete or discontinued.

The Biosafety Protocol Update form is available on the ORC website at http://goo.gl/D2FYTV

Please direct any questions or concerns to ORC at 426-5401 or humansubjects@boisestate.edu.

Thank you and good luck with your research.

1910 University Drive Boise, Idaho 83725-1139
Phone (208) 426-5401 orc@boisestate.edu

This letter is an electronic communication from Boise State University

APPENDIX D

Annotated Policies of Stakeholders at the Boise Wildland Urban Interface

This table lists the abbreviated policies that were coded in Chapter 4. The complete excel dataset of policies can be found under G:\Geomorph\Katie Gibble\Thesis\Policies. Websites containing the location of these policies are listed within each Agency's individual workbook tab.

Managing Agency	**Policy**
Boise City Fire	Weed and grass mitigation
	Open burning permit
	Illegal fires
	Turning radius
	Fireworks
	Foothills roof cover
	Foothills defensible space
	Foothills appeals
	Foothills fireworks and open flame
	WUI designated zones
	WUI authority
	WUI appeal
	WUI building regulations
	WUI general
	WUI roof cover
	WUI roof replacement
	WUI siding
	WUI eaves

	WUI exterior walls
	WUI unenclosed underfloor
	WUI appendages
	WUI exterior glazing
	WUI exterior doors
	WUI vents
	WUI detached structure
	WUI emergency vehicle access
	WUI safety plan
Boise City Zoning	Hillslope permits over 15%
	Hillslope permits public hearing
	Hillslope permit must meet requirements
	Hillslope development avoid scarps
	Hillslope development avoid faults
	Hillslope development avoid collapsible soils
	Hillslope development avoid slopes >25%
	Hillslope development avoid high water table
	Hillslope must account for geology, vegetation
	Development must use minimal grading
	Development innovative methods of stabilization
	Development access by fire department possible
	Development pedestrian access possible
	Development grading cannot exceed a given amount
	Development max vegetation clearance

	Fill removal if not conducive to stability
	Retaining wall max
	Re-compaction minimum
	Cut-slope maximum
	Fill-slope maximum
	Subsurface stability standards
	Cut and fill set back from property
	Erosion prevention onto adjacent properties
	Interception ditches above cut and fill
	Curbs designed to prevent erosion
	Natural stream stabilization
	Runoff must be conserved on site
	Drainage must accommodate 100 year flood
	Sediment collection/retention ponds
	Nothing near street can hinder flood flow
	Roads designed to minimize disturbance
	Established deep rooted veg must be preserved
Boise Parks & Rec	Promote public education and awareness
	Erosion, protect river banks through programs
	Host Firewise seminars
	Team with other departments on educating about Firewise
	Partner with other departments to map fire hazards at WUI
	Work with planning on WUI fuels project
	Seek funding to restore and mitigate

	Provide education and awareness in addressing WUI issues
Ada County Emergency Management	Neighborhood must have available water
	Neighborhood must be in proximity of fire services
	Neighborhood must have emergency vehicle access
	Neighborhood must have site planning?
	Neighborhood must have noncombustible construction materials
	Neighborhood must have landscaping and fuel modification maintenance and management
	Must complete local hazard mitigation plan
	Mitigation protect lives and reduce hazard related injuries
	Minimize damage from natural hazards to properties
	Encourage development of long term mitigation projects
	Maintain natural environments capacity to deal with impacts of natural hazards
	Improve emergency preparedness and collaboration
	Minimize disruption to communities
	Use best available science and continually improve understanding of hazards
	Encourage retrofit purchase or relocation of property based on level of exposure and repetitive damage
	Strengthen codes and enforcement to insure communities can withstand impacts of hazards
	Integrate hazard mitigation policies into local government plans that protect and maintain resilience of landscape
	Develop new and improve early warning protocols
	Educate public on area's potential hazards
	Establish partnerships with stakeholders

	Increase resilience of facilities
	Determine ways to integrate requirements of mitigation plan into local government
IBHS	Save lives, and reduce exposure to risk from hazards
	Reduce and prevent damage
	Enhance coordination
	Reduce adverse environmental, natural resources
	Enhance vulnerability assessments through collection of data
	Prioritize mitigation based off VAs
	Reduce fuel loads in critical areas
	Publish maps identifying areas with high wildland fire probability
	Increase public awareness of financial consequences of building homes in hazard zones
	Improve land use planning
	Add incentives for counties to do cost sharing
	Purchase fire-prone lands
	Establish mitigation actions to promote fire adapted communities
IDL	38.104
	38.104B
	38.111
	38.113
	38.115
	38.116
	38.117
	38.118

	38.119
	38.12
	38.121
	38.122
	38.123
	38.124
	38.125
	Chapter 4 - Fire Hazard Reduction Programs
	38.405
	Chapter 5 - Seeding of burn areas
	38.502
	Chapter 6 - Forest insects, pests and disease
	Chapter 13 - Forest practices act
	Chapter 16 - Interstate Forest Fire suppression compact
	38.1201
BLM	Price match for mapping WUI hazards
	Monitor to ensure progress is made
	Involve public, local stakeholders in collection and monitoring
	Report findings
	Implement programs through soil water and riparian programs
	Implement wildfire management through wildfire management program
	Monitor veg after disturbance
	Data gathering to determine whether meeting objectives
	Use biological control to alter wildfire

	Use plantings/seeds after fire
	Protection of firefighters first
	Who's in charge in event/coordination
	Fire planning safety first
	Risk assessment to understand uncertainty
	Communicate uncertainty
	Based off best available science
	Interagency coordination is essential
	Emergency Stabilization and Recovery (ESR) stabilization of soil
	ESR human life and property
	ESR monitoring for success
	ESR rehabilitation evaluation
	ESR if land unlikely to recover
	ESR rehab weed treatment
	ESR rehab tree planting
	ESR repair facilities
	Reduce human caused fires through aggressive trespass program in concert with a high visibility prevention program
	Closures of access points to burn area
	Contour fell logging
	Culverts and rolling dips
	Early warning flood evacuation
	Protective fences
	Forest treatments (seeding)
	Hazard tree removal

	Log erosion barriers
	Mulching
	Recreation
	Revegetation
	Road stabilization
	Safety and public heath
	Soil stabilizations
	Straw bales
	Trails

APPENDIX E

Check list for Comparing 1959 Boise Mudbath to 2016 Updated Post-fire Debris Flow Models

In Chapter 3, we compared recorded sediment yields of post-fire debris flows in the 1959 Boise Mudbath to 2010 post-fire debris flow models (Cannon et al., 2010). Post-fire debris flow models were updated in 2016 (Staley et al., 2016) but were not used in this thesis. This appendix includes a checklist of items to compare the 2016 model predictions to 1959 sediment yields and the original 2010 post-fire debris flow model.

Preparation

__ confirm 2016 model maximum basin size (below 10 km^2)

__ decide how to split up basins that are >10 km^2 (Cottonwood and Warm Springs)

__ acquire 15 min peak storm rainfall accumulation (in mm) for 1959 storm in Boise Foothills. 1959 storm was 0.4 inches in 9 minutes – how to back out for 15 minute intensity?

__ acquire soil KF-Factor map for Boise Foothills. See Web Soil Survey

Execution

__ once split, re-run 2010 models over newly split basins

__ use Statistics as Table tool to pull average KS-Factor for each drainage basin

__ run new debris flow models through the 1959 precipitation scenario under 4 NBR scenarios