# PREDICTING THE SPATIAL DISTRIBUTION OF POSTFIRE DEBRIS FLOWS AND POTENTIAL CONSEQUENCES TO NATIVE TROUT IN HEADWATER STREAM NETWORKS

by

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# DEDICATION

For my father, Dr. James R. Sedell (July 5, 1944 to August 18, 2012) for his incredible contributions to science and to his family.

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# ABSTRACT

Native trout populations have declined over the last century because of habitat fragmentation and degradation, and the introduction/invasion of nonnative species. Now, many native species of salmonids exist in reduced ranges, primarily residing in headwater stream systems. Negative effects of predicted climate change, including increased water temperature, reduced precipitation, and increased risk of wildland fire may further jeopardize persistence of native trout populations. Headwater streams may be especially susceptible to disturbances such as debris flows. Because the probability of debris flow increases in landscapes that have recently burned, identifying susceptible areas before the occurrence of wildfire may provide information necessary to protect remnant headwater populations. Predicting the timing, extent, and severity of wildfires and subsequent precipitation and runoff events is difficult; however, it is possible to identify channels in stream networks that may be prone to debris flows. Here I present a fine-scale spatial analysis of debris flow potential in 11 high-elevation stream networks of the Colorado Rocky Mountains occupied by isolated populations of Colorado River cutthroat trout. I identified stream channels at high risk of debris flow events using models based on storm and burn scenarios, and data from geographic information systems (GIS) describing topographic, soil, and vegetation characteristics, and assessed the potential for catastrophic population disturbance given a variety of wildfire and post-wildfire storm scenarios. Results from GIS models suggest that populations in many of the study watersheds occupy areas with a high probability of experiencing post-wildfire debris flows, but the extent of their distribution and location within the stream network may provide sufficient refuge to prevent local extirpation. This method couples the spatially continuous distribution of fish and their habitat with a debris flow risk assessment model that accounts for the spatially variable properties within a watershed. Applying the risk assessment along the stream network, rather than to an entire watershed, provides a risk assessment that identifies the potential impacts of postfire debris flows within channels occupied by native fishes and other aquatic biota.

# 1. INTRODUCTION

Throughout the intermountain west, cutthroat trout *Oncorhynchus clarki* have experienced declines in distribution and abundance due to habitat fragmentation, habitat degradation, and interactions with nonnative species (Gresswell 1988; Behnke 1992). Extant cutthroat trout populations are generally confined to mid- to high-elevation streams (> 2,500 m) with high gradients (Gresswell 1988) and are often isolated by natural or anthropogenic barriers (Kruse et al. 2001; Shepard et al. 2005). Large-scale patterns of habitat occupancy are believed to result from the incursion of non-native fish species along with water development in downstream portions of occupied watersheds (Young 2008). Occupied streams are located disproportionately on public lands; particularly Forest Service lands (Rieman et al. 2003; Hirsch et al. 2006). In the upper Colorado River basin, occupied by Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*), a wide variety of land management practices have affected the population, including overgrazing, heavy metal pollution, and water depletion and diversion (CRCT Coordination Team 2006). Some of these practices have served to isolate upstream populations of cutthroat trout, thereby protecting them from invasion by non-native salmonids and disease (Harig and Fausch 2002). Fragmented streams however, restrict movement between formerly connected populations, leaving small isolated populations vulnerable to extinction.

Spatially isolated populations have a greater risk of extirpation because of stochastic or environmental events (Hilderbrand and Kershner 2000; Peterson et al. 2008; Fausch et al. 2009). For example, debris flows can scour stream channels, potentially extirpating or severely reducing populations of stream fishes, especially in headwater habitats (Roghair et al. 2002; Propst and Stefferud 1997; Brown et al. 2001). In isolated populations, resistance to extirpation and subsequent recolonization after stochastic disturbance are dependent upon the degree of watershed complexity and the ability of individuals in the population to move within the watershed (Guy et al. 2008; Neville et al. 2009).

In fragmented systems, fire may exacerbate extirpation risk either directly (e.g., due to temperature) or indirectly (e.g., due to postfire debris flows) (Gresswell 1999). Changes in water temperature or water chemistry associated with severe fire have led to direct mortality of trout (Howell 2006). Many populations have endured such fires with few or no ill effects or showed only temporary declines (Rieman and Clayton 1997; Gresswell 1999; Sestrich et al. 2011). More problematic may be postfire floods and debris torrents triggered by summer thunderstorms that have reduced or eliminated salmonid populations (Bozek and Young 1994; Gresswell 1999). Postfire flood events are especially common in the Southwest where fires burn prior to the onset of the monsoon season (Rinne 1996). Cannon et al. (2001) observed that in portions of the Rocky Mountains, the probability of some form of postfire debris flow was about one in three, and occurrence was largely dependent on storm events in which rainfall intensity exceeded soil infiltration capacity. Nevertheless, the majority of debris flows are in small ($< 2.6$ km$^2$), steep ($> 20$ %) basins (Parrett et al. 2003) and usually would not threaten entire populations (Rieman and Clayton 1997).

Debris flows are important disturbance events for creating and maintaining a mosaic of habitats that form the physical template of stream systems. In the Pacific Northwest, landslides and debris flows are common processes that affect habitat for stream dwelling organisms, especially headwater fishes (Reeves et al. 1995). For example, mass wasting events are responsible for sediment and wood input to stream channels that provide habitat structure for stream fishes (Benda and Dunne 1997; May and Gresswell 2004); furthermore, these stochastic events can create refugia at multiple spatial and temporal scales (Sedell et al. 1990). However, postfire debris flows can potentially extirpate, or severely reduce local fish populations and/or connectivity among subpopulations (Gresswell 1999).

Although some of the physical factors that trigger debris flows in a postfire environment are understood, little is known about how these factors may interact and influence the overall risk of debris flows in particular systems. Moreover, it is unclear how risk of debris flows corresponds to the overall probability of persistence for isolated populations of cutthroat trout in high-elevation systems.

Cannon et al. (2010), developed empirical models that provide estimates of the probability of postfire debris flow to assess hazards from recently burned drainages throughout the intermountain western USA. These multivariate models estimate probabilities of debris flows using combinations of predictive variable that describe the extent and severity of fire within a drainage basin, the drainage basin morphology and soil characteristics, and storm rainfall characteristics. These models are specific to particular geographic regions, and fire regimes are used to estimate debris flow susceptibility within the first few years following a fire (Gartner et al. 2008; Cannon et al. 2009; Cannon et al. 2010).

Debris flow susceptibility models are currently implemented in a geographic information system (GIS) by identifying specific drainage basin outlets, and then extracting the measurements of the model input variables for the drainage basin areas upstream from the drainage basin outlets. These measurements, along with specified rainfall conditions, are then used to estimate the probability of a debris flow for each identified drainage basin outlet. Although this approach can be used to identify debris-flow susceptibility for specific locations, it provides only a single estimate for each drainage basin, and does not reflect the range of debris flow hazards that may exist upstream of the drainage basin outlet. Debris-flow effects in a drainage basin will be greatest in the channels through which a debris flow travels, eroding and depositing material, and on the fan below the drainage basin outlet where material is deposited. Furthermore, if assessments of debris flow probability are needed for multiple locations along a stream channel, then the process of identifying each drainage basin outlet, delineating drainage basins, and obtaining measures for the input variables used in the models is labor intensive and time consuming.

## Objectives and Approach

Previous studies that modeled debris flows were mainly focused in the Pacific Northwest, where rain saturated soils along with steep hillsides are most commonly implicated in causing hill-slope failure and debris flows (Wondzell and King, 2003).

Benda and Cundy (1990) developed an early empirical model that identified channel slope and tributary junctions as critical components to the onset of debris flow deposition. Currently, there has been an increased interest in developing spatially explicit debris flow susceptibility models to identify hazardous areas that would impact human infrastructure and lives, particularly in postfire environments (Benda et al. 2007; Cannon et al. 2009; Gartner et al. 2011). However, few studies have closely examined the possible effects of postfire debris flows to aquatic organisms in a spatially continuous fashion both across the landscape and at the stream channel scale to identify both potential areas of refugia as well as risk of local extirpation (Rosenberger et al. 2011; Sestrich et al. 2011, May and Lisle, 2012).

In this study, I describe a model for assessing potential effects of debris flows on isolated populations of Colorado River cutthroat trout in 11 high-elevation headwater stream networks in the upper Colorado River Basin in the Colorado Rocky Mountains. In addition, I present a new method for assessing the probability of debris flow that characterizes the potential hazards within recently burned areas better than the present watershed-scale approach. Although prediction of the timing, extent, and severity of future fires, and subsequent precipitation and runoff events is uncertain because of the complex array of variables that influence such events, it is possible to identify geomorphological sections of stream channels that may be susceptible to debris flows. With this reach-scale debris flow risk assessment model, I used a set of geomorphological characteristics developed from digital elevation models that largely influence the initiation, propagation, and depositions of postfire debris flows and subsequent effects on isolated headwater populations of trout and associated habitat within drainage networks.

Application of the reach-scale debris flow risk assessment model within a drainage network provides a spatially specific estimate of potential risk of postfire debris flows. Maps developed from this process can be used to identify locations within the drainage network where the probability of debris flows is the greatest; moreover, model results may be useful for guiding postfire debris flow mitigation plans.

The first objective was to identify watersheds across the upper Colorado River basin that currently support isolated populations of cutthroat trout and have the greatest probability of experiencing a postfire debris flow. The second objective was to identify geomorphologically distinct sections of the occupied stream channel that have the greatest risk of experiencing a debris flow. The third objective was to identify the spatial distribution and abundance of both Colorado River cutthroat trout and their habitat within the drainage network and to develop maps of where the greatest risk of debris flows are in relation to the current occupancy of cutthroat trout and habitat.

# 2. STUDY AREA

In 2006, the U.S. Geological Survey initiated the Fire Science Thrust Project in response to concerns about the widespread infestation of the mountain pine beetle (*Dendroctonus ponderosae*) that has infested the lodgepole pine (*Pinus contorta*) forests in the southern Rocky Mountains. The objective of this project was to use a multidisciplinary approach to evaluate fire and postfire hazards in the Three Lakes Watershed in Grand County, Colorado, with the primary goal of developing tools that would help Federal, State, and local agencies identify areas at risk and take steps to minimize those risks. USGS Rocky Mountain Science Center initiated efforts on the inventory and assessment of the current state of the ecosystem, including fire fuels, tree mortality due to insect infestation, susceptibility to erosion and other postfire effects, the distribution of the Wildland-Urban Interface and native biota at risk in the demonstration area.

The study area in north central Colorado encompasses the Colorado River upstream from Glenwood Springs, Colorado and includes major tributaries of the Eagle River and the Blue River (Figure 1). Headwater streams in the upper Colorado River basin experience warm, dry summers, and most of the precipitation occurs during the winter as snow; annual precipitation ranges from 48 to 100 cm. Most of the tributary watersheds are comprised of small, first and second order montane streams primarily located on public lands administered by the U. S. Forest Service and the National Park Service. Stream channels alternate between unconstrained meadow segments with channel gradients of 1-2 % and constrained segments where gradients can exceed 5 %.

Mean elevation of watersheds in the area range between 2,300 m and 4,000 m, and the extent of perennial streams vary from 3 km to 9 km.

Riparian vegetation in the meadow segments is dominated by sedges (Carex sp.) and willow (*Salix* sp.), and in the steeper forested segments, there are mixed stands of lodgepole pine, subalpine fir (*Abies lasioicarpa*), Engelmann spruce (*Picea engelmannii*), and aspen (*Populus tremuloides*). Recently, many of the mature lodgepole stands in the study area have been infested with mountain pine beetle. The resulting landscape is characterized by acres of standing dead trees, and a dense understory of lodgepole seedlings.

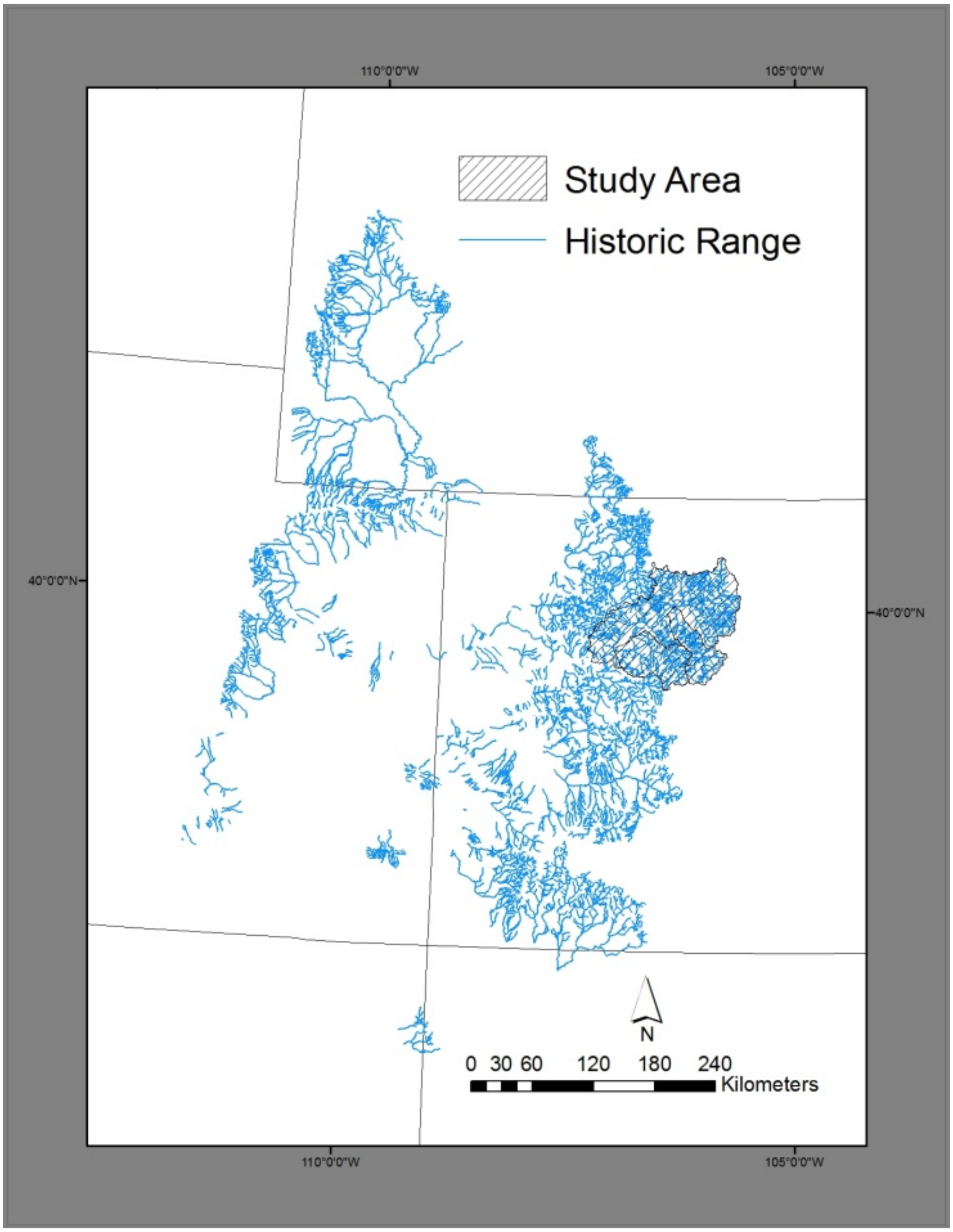

Figure 1. Study area in the upper Colorado River basin, Colorado, USA, and historic distribution of Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*).

# 3. METHODS

## Sample Design

Because I desired to infer results of the study to headwater drainages across the upper Colorado River basin with populations of Colorado River cutthroat trout, the sample unit was defined as a watershed (Gresswell et al. 2004). The sampling frame consisted of 53 headwater drainages (approximately second order, drainage area = 3-20 $km^2$) that supported genetically-unaltered populations of Colorado River cutthroat trout isolated by natural or anthropogenic barriers to upstream migration (cascades, waterfalls, culverts, and water diversions) located on federal lands. Because forest type, geology, and elevation were expected to influence the spatial distribution of fish and postfire debris flows in the region, four sampling strata were created by integrating the watersheds with GIS coverages of level IV ecoregions from the Southern Rocky Mountains (Alpine, Crystalline subalpine, Sedimentary subalpine, and Volcanic subalpine zones; U.S. Environmental Protection Agency, 2005; 1:250,000 level IV ecoregion coverage). Twelve watersheds were randomly selected for study in proportion to the number of watersheds in each stratum. Because brook trout *Salvelinus fontinalis* had displaced native cutthroat trout in one of the selected watersheds, it was excluded from further analysis, leaving 11 watersheds for analysis (Figure 2; Table 1).

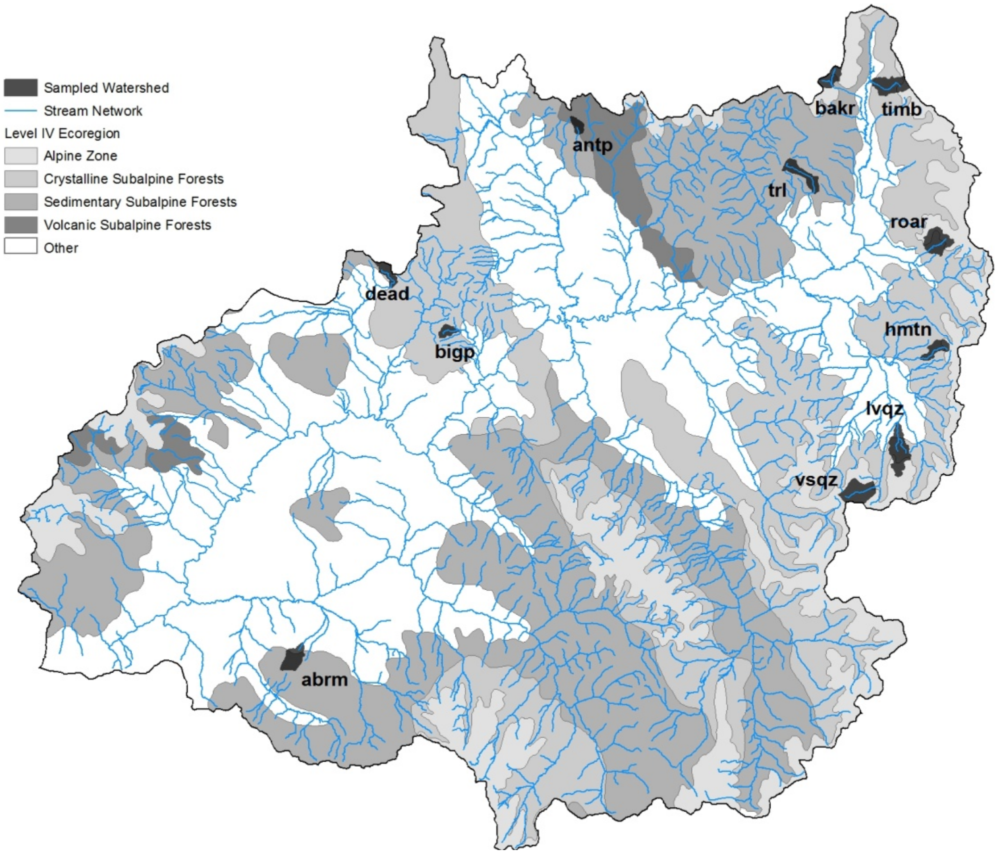

Figure 2. Distribution of sampled watersheds, which are currently occupied by Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) in the upper Colorado River basin, based on level IV ecoregions boundaries. For creek name codes, see Table 1.

Table 1. Physical characteristics and trout of 11 watersheds sampled in the headwaters of the Colorado River, 2008-2009.

| Watershed | Level IV ecoregion | Watershed area (km$^2$) | Mean elevation (m) | Stream length (km) |
|---|---|---|---|---|
| Baker Gulch | Alpine | 7.10 | 3505 | 5.62 |
| Roaring Fork | Alpine | 11.86 | 3350 | 4.28 |
| Vasquez Creek | Alpine | 13.21 | 3534 | 7.81 |
| Big Park Creek | Crystalline Subalpine | 3.29 | 2799 | 3.44 |
| Hamilton Creek | Crystalline Subalpine | 5.59 | 3253 | 6.81 |
| Little Vasquez | Crystalline Subalpine | 14.48 | 3202 | 6.12 |
| Timber Creek | Crystalline Subalpine | 11.14 | 3316 | 5.81 |
| Abrams Creek | Sedimentary Subalpine | 8.94 | 2834 | 8.11 |
| Deadman Gulch | Sedimentary Subalpine | 5.13 | 2824 | 5.18 |
| Trail Creek | Sedimentary Subalpine | 8.52 | 3125 | 7.45 |
| Antelope Creek | Volcanic Subalpine | 2.95 | 3068 | 3.27 |

## Objective 1: Watershed-Scale Debris Flow Probability Model

The probability of debris flow occurrence was calculated for each of the 11 sampled watersheds. The regression equation of debris flow probability is based on empirical data described by Cannon et al. (2010). The equation is:

$$P = \frac{e^x}{\left(1 + e^x\right)},$$

$$x = -0.7 + 0.03(A) - 1.6(R) + 0.06(B) + 0.07(I) + 0.2(C) - 0.4(LL),$$

where P is the probability of debris flow occurrence; *A* is the percentage of the watershed area with slopes greater than or equal to 30 %; *R* is basin ruggedness, the change in watershed elevation (meters) divided by the square root of the basin area (square meters) (Melton 1965); *B* is the percentage of the watershed area which could or has burned at high and moderate severity; *I* is average storm rainfall intensity (in millimeters per hour); *C* is clay content of the soil (in percent); and *LL* is the liquid limit of soil (% of soil moisture by weight), which is the water content at which a soil changes from a plastic to a liquid state (Table 2).

In order to estimate debris flow probability, it was assumed that all of the forested portions of the watershed (defined using the National Land Cover Database; U.S. Geological Survey 1992) would burn at moderate- to high-burn severity. Although this assumption may characterize only very large fires, it provides a consistent basis for comparison of debris flow risk among watersheds in the upper Colorado River basin and provides a likely scenario for debris flow occurrence.

Table 2. Physical variables for 11 watersheds of the upper Colorado River basin obtained from geographical information system (GIS; ESRI 2008) and field surveys.

| Variable (source) | Method of estimation |
|---|---|
| Basin ruggedness (GIS) | Change in basin elevation divided by the square root of the basin area (Cannon et al. 2010). |
| Channel slope (field) | Gradient of water surface, expressed as the percent change in elevation over the length of stream reach and estimated with a clinometer (Moore et al. 2007). |
| Clay content (GIS) | Raw data for soil properties were compiled from the State Soil Geographic (STATSGO) database which was processed by Schwartz and Alexander (1995) to obtain clay content. |
| Drainage basin size (GIS) | StreamStats (Capesius and Stephens 2009). |
| Ecoregion, level IV (GIS) | U.S. EPA (2005) |
| Hillslope (GIS) | Hillslope gradient > 30 percent derived from 10-m DEM. |
| Land cover (GIS) | National Land Cover Survey (USGS 1992). |
| Liquid limit (GIS) | Raw data for soil properties were compiled from the State Soil Geographic (STATSGO) database; data were processed Schwartz and Alexander (1995) to obtain liquid limit. |
| Valley width index, VWI (field) | Ratio of the width of the active stream channel to the width of the valley floor (Moore et al. 2007). |

The subalpine forest fire regime of Rocky Mountains in Colorado is dominated by infrequent, extensive, stand-replacing fire events (300 to 400 years), whereas surface fires affected only 1–3% of the forested area (Sibold et al. 2006). High burn severity is defined as the complete consumption of the forest litter and duff and combustion of all fine fuels in the canopy Lindsey (2002). A deep ash layer may be present on the forest floor, and the top layer of the mineral soil may be changed in color due to substantial soil heating where large-diameter fuels were consumed. Moderate-burn severity is defined as the consumption of forest litter and duff in discontinuous patches Lindsey (2002). Leaves or needles, although scorched, may remain on trees. Foliage and twigs on the forest floor are consumed, and some heating of mineral soils may occur where the soil organic layer was thin.

Rainfall is an essential element in the generation of postfire debris flows. In the Intermountain West, a great majority of debris flow events occur in response to low-recurrence (2 - 10 years) and low-duration (< 1 h) consecutive thunderstorms (Cannon and Gartner 2005). For comparative purposes, the storm intensity used in the equation was a 5-year recurrence-interval event (19 mm/h rainstorm for this area Miller et al. 1973) that occurred uniformly over each watershed. A 5-year rainfall event has a 20 % probability of occurring in any given year. It is estimated that burned watersheds are the most vulnerable to extensive erosion and potential debris flows for a period of 4-6 years following a wildfire (Cannon et al. 2008; Wondzell and King 2003); thus, the 5-year rainfall event is reasonably likely to occur while the burned area is most vulnerable, but does not approach a worst-case scenario. Furthermore, I looked at a combination of different rainfall intensities and percent area burned to see how sensitive the model was to various burn and subsequent rainfall scenarios.

The watershed areas and percentage of the watershed with 30 % or greater slopes were determined using ArcMap with 10-m digital elevation models (DEM). Clay content and liquid limit were estimated by Schwartz and Alexander (1995) using the State Soil Geographic (STATSGO) database.

As a final step, estimated debris flow probabilities were grouped into four different categories of class 1 (probability of debris flow risk < 25%), class 2 (probability of debris flow risk 26 - 50%), class 3 (probability of debris flow risk 51 - 75%), and class

4 (probability of debris flow risk 76 - 100%). Cannon et al. (2010) recommended such categorization because of uncertainties associated with the debris flow probability estimates.

## Objective 2: Reach-Scale Debris Flow Risk Assessment Model

To determine the relative probability of debris flows within individual reaches within each watershed, I developed a qualitative model based on the presence (or absence) of four primary initiating and transport factors: hill slope gradient, flow accumulation pathways, steep channel gradient, and confined valleys (Benda and Dunne 1997; Wondzell and King 2003). Hill-slope gradient and flow accumulation pathways that contribute to the initiation and transport of debris flows were determined from 10-meter DEM using GIS, and channel gradient and valley confinement were measured from field surveys. To compare the debris flow probability ranking from the empirical model with the aggregate of reach level rankings, I developed a weighted average of the reach rankings by multiplying the ranking score for a reach by the reach length, summing all reaches in the watershed, and dividing by the total length of stream surveyed.

The reach-scale debris flow risk assessment model incorporated a set of empirical rules for identifying initiation sites and transport distances of debris flows in the upper Colorado River headwater streams. The potential for debris flows was evaluated using GIS-based analysis of hill slope and channel characteristics. Debris flows initiate on hill slopes and are transported downstream by steep and confined stream channels. Probable initiation sites were identified using a 10-meter DEM, and hill slope characteristics suitable for debris flow initiation were evaluated for each 10-m pixel of first-order watersheds in the DEM. I restricted the evaluation of debris flow initiation areas to first-order watersheds because the hill slope characteristics of higher order watersheds are not typically conducive to debris flow initiation (Benda and Cundy 1990; Benda et al. 2005).

Debris flows that initiate when water flowing overland acquires enough sediment and energy must move over a threshold distance to become a “bulking” debris flow. Bulking debris flow initiation sites were defined by a linear cluster of at least nine 10-m pixels (90 m distance on long axis) having a minimum of 30 % slope. For pixel clusters that met these criteria, I conducted a flow accumulation analysis to determine the flow direction and accumulation in each pixel.

Identification of initiating cells for landslide-initiated debris flows was based on similar analysis of hill slope characteristics in first-order watersheds. Unlike bulking debris flows, landslide-initiated debris flows can originate in a single pixel. Pixels were classified as initiating cells for landslide debris flows if the slope is > 30 %. The entire drainage area of a stream reach was classified as an initiating area for bulking and landslide initiated debris flows if at least one initiating cell was present within the watershed.

Extent of downstream movement of debris flows was estimated using the following rules: 1) an initiating cell was present in the contributing area of the stream reach, 2) the reach had an average gradient > 7 %, and 3) the reach was classified as confined, with a valley width index of < 2.5. The modeled debris flow path was assumed to continue downstream until it reached a stream segment that did not meet these criteria, or until it merged with a reach that had a 10 times greater drainage area. Delineating channels at > 7 % slope is useful because most reaches meeting this criterion are in the debris flow propagation domain.

This information was summarized and incorporated into the reach-scale debris flow model with each characteristic assigned a (+) if the feature supported initiation or propagation of a debris flow or a (-) if the feature supported the onset of deposition or the feature was absent. Positive notations were summed to determine the probability ranking on a scale of one to four (low to high). To compare the watershed-scale debris flow probability ranking with the weighted average of the reach-scale debris flow risk assessment rankings, weighted ranks were rounded to the nearest whole number (for rankings with decimal fraction of 0.5, even numbers rounded up and odd numbers rounded down).

All 11 watersheds were mapped in ArcGIS 9.3 3D Spatial Analyst (ESRI, 2008). Stream network reaches were dynamically segmented and displayed according to debris flow risk rankings and color coded from blue (risk rank of 1) to red (risk rank of 4).

### Objective 3: Spatial Distribution and Abundance of Cutthroat Trout, Physical Habitat, and Debris Flow Risk

In order to assess how the distribution of cutthroat trout and physical habitat compare with estimates of debris flow risk, I conducted continuous fish and habitat surveys in all occupied stream channels within each watershed. Prior to field surveys, the channel network of each watershed was divided into stream segments (Frissell et al. 1986; Moore et al. 2007) using information from topographic and geologic maps, aerial photographs, and field reconnaissance to identify tributary junctions and barriers to fish movement (Gresswell et al. 2006). In the field, segments were divided into geomorphic reach types based on substrate, gradient, bed morphology, and pool spacing (Montgomery and Buffington 1997), and in each reach, channel-unit types were classified using criteria of Bisson et al. (1982). Physical variables that described channel-unit size, substrate class, valley segment type, and channel type were recorded for each channel unit (Gresswell et al. 2006).

Physical habitat surveys were conducted when water levels were near base flow (June through August). Channel-unit types of pools, fast-water (rapids, cascades), and steps were classified according to criteria developed by Bisson et al. (1982). Length and width of every pool was measured (nearest 0.1 m). Maximum depth was measured in each pool to the nearest 0.1 m. The height of each vertical step > 0.5 m was measured (nearest 0.1 m). Substrate class was made by ocular estimates (+/- 10 %) of the dominant substrate type. Substrate types included bedrock, boulder, cobble, gravel, and fines (sand, silt, and organics). Channel slope (percent gradient of sampled reaches) was measured using a clinometer and was averaged for each reach. Valley width index (VWI), the ratio of the width of the active stream channel to the width of the valley floor, was estimated for the reach by dividing the average valley floor width by the average active channel width (Moore et al. 2007). Geomorphic reaches were designated as pool-riffle, plain-bed, step-pool, or cascade (Montgomery and Buffington 1997).

In order to develop a spatially explicit representation of trout abundance and distribution in the isolated channel networks (Gresswell et al. 2006), fish were collected in all pools using single-pass electrofishing technique starting in the lowest portion of each watershed and continuing upstream (Bateman et al. 2005). To identify the upstream extent of fish distribution, the mainstem and tributaries were sampled for 50–300 m (approximately 10–40 individual pool sample units) beyond the point at which no more fish were detected. Captured fish > 70 mm (total length) were held in a holding net that was secured in the stream. During processing, a fish was placed into a water bath of anesthetic, (MS-222; concentration = 125 mg/L), until it began to lose equilibrium or did not respond to a slight squeeze of the tail. Anesthetized fish were measured (total length to the nearest 1 mm). After processing, the fish were placed into a recovery tank in slow water and monitored for recovery.

In each watershed, fish and pool abundance was spatially arranged over the stream reaches designated with the debris flow risk rank to create a map that highlights areas of high debris flow risk. Lastly, all 11 watersheds illustrating the location of cutthroat trout were mapped and displayed in ArcGIS 9.3 3D Spatial Analyst package (ESRI, 2008) by spatially referenced numbers of cutthroat trout and pool depth (which represents pool habitat quality).

# 4. RESULTS

## Objective 1: Watershed-Scale Debris Flow Probability Model

The estimated probabilities from the watershed-scale model in the 11 sampled watersheds in the upper Colorado River basin varied from 32 to 71 % probability of experiencing postfire debris flows within 1-2 years following a fire (Table 3; Figure 3). All watersheds in the Alpine zone (Baker Gulch, Roaring Fork, and Vasquez Creek) had 71 % probability of a debris flow occurring in the watershed. Probabilities were mixed in sedimentary subalpine and crystalline subalpine zones, with the lowest in Big Park Creek (crystalline subalpine zone, 32 %) and Deadman Gulch (sedimentary subalpine zone, 37 %). Probability of debris flows was almost twice as high in Timber Creek (crystalline subalpine zone, 70 %) and Abrams Creek (sedimentary subalpine zone; 63 %). Hamilton Creek and Little Vasquez, both of which are in the crystalline subalpine zone, had a 50 % probability of a debris flow occurrence. The only watershed in the volcanic subalpine zone was Antelope Creek, and it had a 55 % probability of a postfire debris flow. The debris flow probability ranking for all watersheds was either a 2 or 3 (Table 3).

Table 3. Probability of postfire debris flow for 11 watersheds sampled in the upper Colorado River basin, 2008-2009. Watershed-scale probability of a debris flow and probability ranking were estimated with the model developed by Cannon et al. (2010). The weighted reach-scale relative probability of debris flow ranking is derived by multiplying the ranking score (where 1 is a low probability ranking and 4 is a high probability ranking) for a reach by the reach length, summing all reaches in the watershed, and dividing by the total length of stream surveyed.

| Watershed | Level IV ecoregion | Watershed-scale probability of debris flow (%) | Watershed-scale probability of debris flow ranking | Weighted reach-scale relative probability of debris flow ranking | Percent of stream with a 3-4 reach-scale ranking (%) | Percent of fish-bearing reaches with a 3-4 reach-scale ranking (%) |
|---|---|---|---|---|---|---|
| Baker Gulch | Alpine | 66 | 3 | 2.8 | 70 | 43 |
| Roaring Fork | Alpine | 66 | 3 | 2.5 | 52 | 26 |
| Vasquez Creek | Alpine | 66 | 3 | 3.0 | 78 | 69 |
| Big Park Creek | Crystalline Subalpine | 32 | 2 | 2.1 | 40 | 83 |
| Hamilton Creek | Crystalline Subalpine | 51 | 3 | 1.9 | 28 | 23 |
| Little Vasquez | Crystalline Subalpine | 51 | 3 | 2.4 | 28 | 48 |
| Timber Creek | Crystalline Subalpine | 60 | 3 | 3.0 | 75 | 68 |
| Abrams Creek | Sedimentary Subalpine | 63 | 3 | 2.9 | 63 | 48 |
| Deadman Gulch | Sedimentary Subalpine | 37 | 2 | 1.5 | 0 | 0 |
| Trail Creek | Sedimentary Subalpine | 43 | 2 | 1.9 | 25 | 29 |
| Antelope Creek | Volcanic Subalpine | 55 | 3 | 1.8 | 0 | 0 |

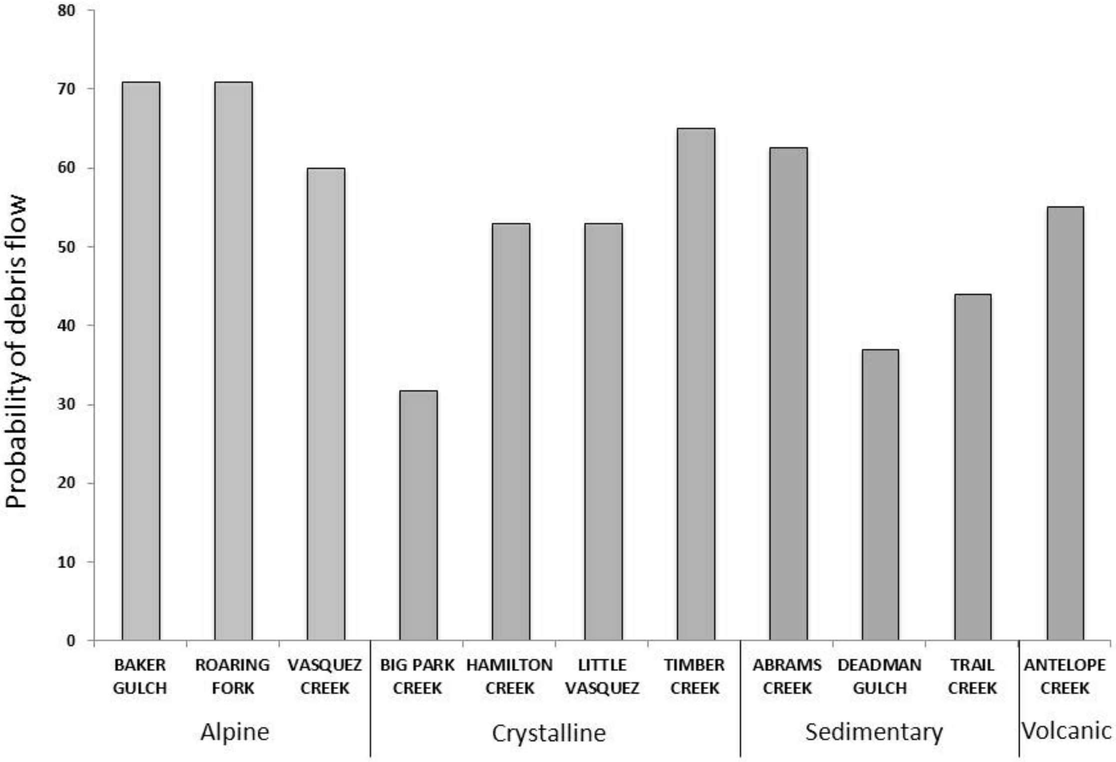

Figure 3. Probability of debris flow occurrence for watersheds in the upper Colorado River basin from a hypothetical high burn severity fire and subsequent rainfall event (cf. Table 3).

## Objective 2: Reach-Scale Debris Flow Risk Assessment Model

At the reach-scale, six watersheds Abrams Creek (Figure 4), Baker Gulch (Figure 5), Hamilton Creek (Figure 6), Little Vasquez Creek (Figure 7), Timber Creek (Figure 8), and Vasquez Creek (Figure 9) had at least one reach with all four topographic characteristics associated with debris flow initiation and transport (Table 4). Three was the highest rating for reaches in Big Park Creek (Figure 10), Roaring Fork (Figure 11), and Trail Creek (Figure 12), and in Antelope Creek (Figure 13) and Deadman Gulch

(Figure 14), the highest rating was two (Table 4). In most cases, reaches ranked 4 were found in the lower portions of the watershed. This is due to the S-shaped longitudinal profile of the stream channel, where the headwaters in many of these high elevation streams begin in low gradient meadows and then rapidly descend before leveling out towards the downstream end near major tributary junctions. However, there were exceptions. For example, reaches in the middle of the Timber Creek stream network were ranked at 4 (Figure 8), and in Abrams Creek, the mainstem and a tributary in the upper portion of the watershed ranked 4 (Figure 4). A tributary to the upper mainstem of Baker Gulch was also ranked 4 (Figure 5).

The probability of postfire debris flows at the watershed-scale were comparable for 10 watersheds, and the one exception, Deadman Gulch, had a watershed-scale risk ranking of 2 and a weighted reach-scale ranking of 1.5. In watersheds with a ranking of ≥ 3, there was a moderate to high reach-level debris flow probability ranking (i.e., 3 or 4) for ≥ 50 % of the stream reaches. All of the Alpine zone watersheds (Baker Gulch, Roaring Fork, and Vasquez Creek), Timber Creek, and Abrams Creek were ranked 3 and 4, and the greatest proportion of stream with highest risk of debris flow was found in Timber Creek and Vasquez Creek (75 and 78 % respectively).

Table 4. Reach-level characteristics that influence postfire debris flows in 11 watersheds sampled in the upper Colorado River basin, 2008-2009. A plus (+) represents a positive contribution to the propagation of debris flow and negative (-) represents that the parameter does not contribute to debris flow but potentially enhances onset of deposition. Rank is determined by the sum of (+) for a given reach.

| Watershed | Reach | Bulking and landslide potential | Hill slope gradient (>30 %) | Valley Width Index (< 2.5) | Channel gradient (> 7 %) | Risk ranking |
|---|---|---|---|---|---|---|
| Abrams Creek | 1 | + | + | + | - | 3 |
| | 2 | - | + | + | - | 2 |
| | 3 | + | + | + | + | 4 |
| | 4 | + | - | + | + | 3 |
| Antelope Creek | 1 | + | - | + | - | 2 |
| | 2 | + | - | + | - | 2 |
| | 3 | - | - | - | + | 1 |
| Baker Gulch | 1 | + | - | + | + | 3 |
| | 2 | - | - | + | + | 2 |
| | 3 | + | - | - | - | 1 |
| | 4 | + | - | + | + | 3 |
| | 5 | - | - | + | + | 2 |
| | 6 | + | - | + | + | 3 |
| | 7 | + | - | + | + | 3 |
| | 8 | + | + | + | + | 4 |
| | 9 | + | - | + | + | 3 |
| Big Park Creek | 1 | + | + | + | - | 3 |
| | 2 | + | - | + | - | 2 |
| | 3 | + | - | - | - | 1 |
| Deadman Gulch | 1 | - | - | - | - | 1 |
| | 2 | + | + | - | - | 2 |
| | 3 | + | - | + | - | 2 |
| | 4 | + | - | - | - | 1 |

Table 4. Continued

| | | | | | | |
|---|---|---|---|---|---|---|
| Hamilton Creek | 1 | + | + | + | + | 4 |
| | 2 | - | - | - | - | 1 |
| | 3 | - | - | + | - | 1 |
| | 4 | + | - | - | - | 1 |
| | 5 | - | - | + | - | 1 |
| | 6 | - | - | + | - | 1 |
| | 7 | - | - | + | + | 2 |
| Little Vasquez | 1 | + | + | + | + | 4 |
| | 2 | - | - | + | - | 1 |
| | 3 | - | + | + | + | 3 |
| Roaring Fork | 1 | - | + | + | - | 2 |
| | 2 | + | + | - | - | 2 |
| | 3 | - | + | + | + | 3 |
| | 4 | + | + | + | + | 3 |
| | 5 | - | + | - | - | 2 |
| | 6 | - | + | + | + | 3 |
| Timber Creek | 1 | - | - | - | - | 1 |
| | 2 | - | + | + | + | 3 |
| | 3 | + | + | + | + | 4 |
| | 4 | + | + | + | + | 4 |
| | 5 | + | + | + | + | 4 |
| | 6 | - | - | - | - | 1 |
| Trail Creek | 1 | - | + | + | - | 2 |
| | 2 | - | + | + | + | 3 |
| | 3 | - | + | - | - | 1 |
| | 4 | - | + | + | - | 2 |
| | 5 | - | - | + | + | 2 |
| | 1 | + | + | + | + | 4 |

Table 4. Continued

| | | | | | | |
|---|---|---|---|---|---|---|
| Vasquez Creek | | | | | | |
| | 2 | + | + | + | + | 4 |
| | 3 | + | - | + | + | 3 |
| | 4 | + | - | - | - | 1 |
| | 5 | + | - | + | + | 3 |
| | 6 | + | - | + | + | 3 |
| | 7 | + | + | - | - | 2 |
| | 8 | + | - | + | + | 3 |

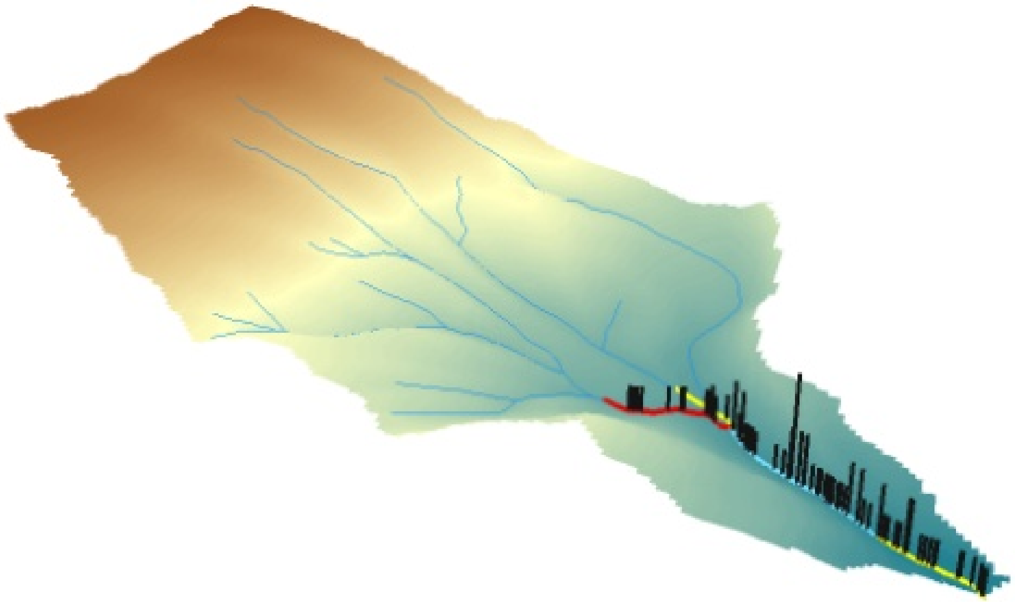

Figure 4. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70 mm) along with risk of debris flow delineated along streams reaches in Abrams Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations. Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

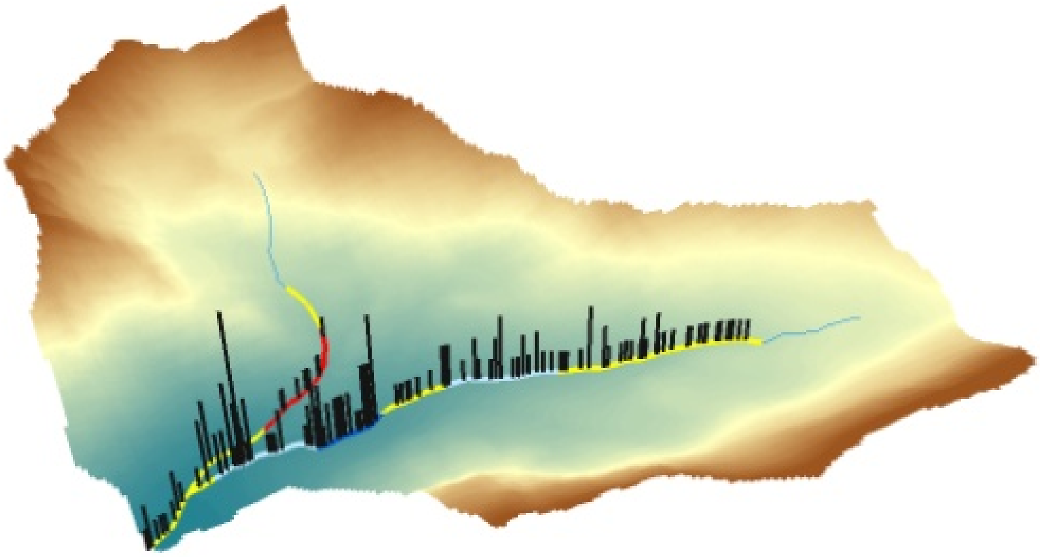

Figure 5. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70  mm) along with risk of debris flow delineated along streams reaches in Baker Gulch. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations.  Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

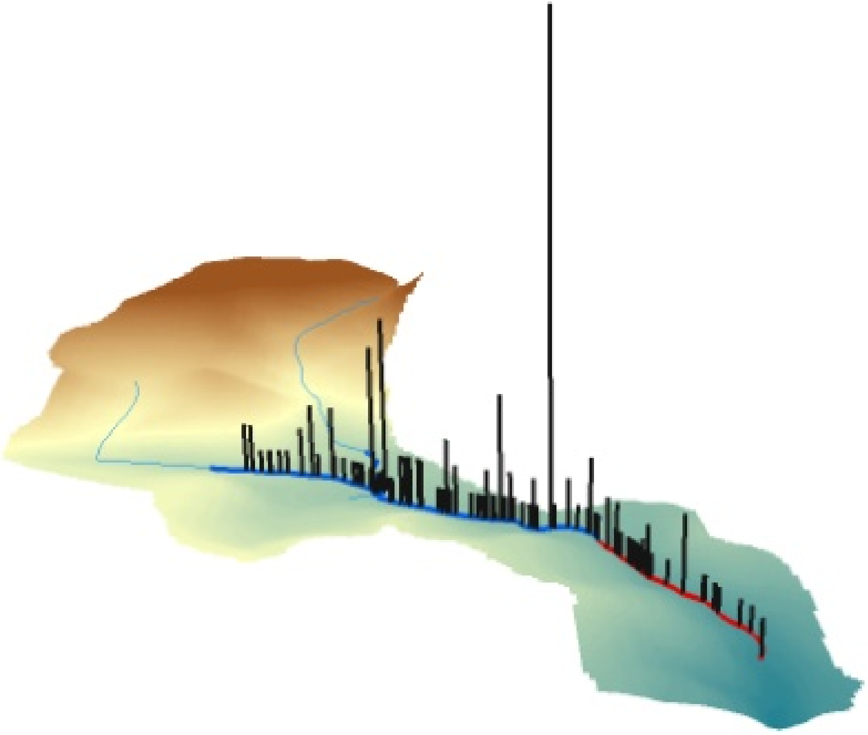

Figure 6. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70  mm) along with risk of debris flow delineated along streams reaches in Hamilton Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations.  Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

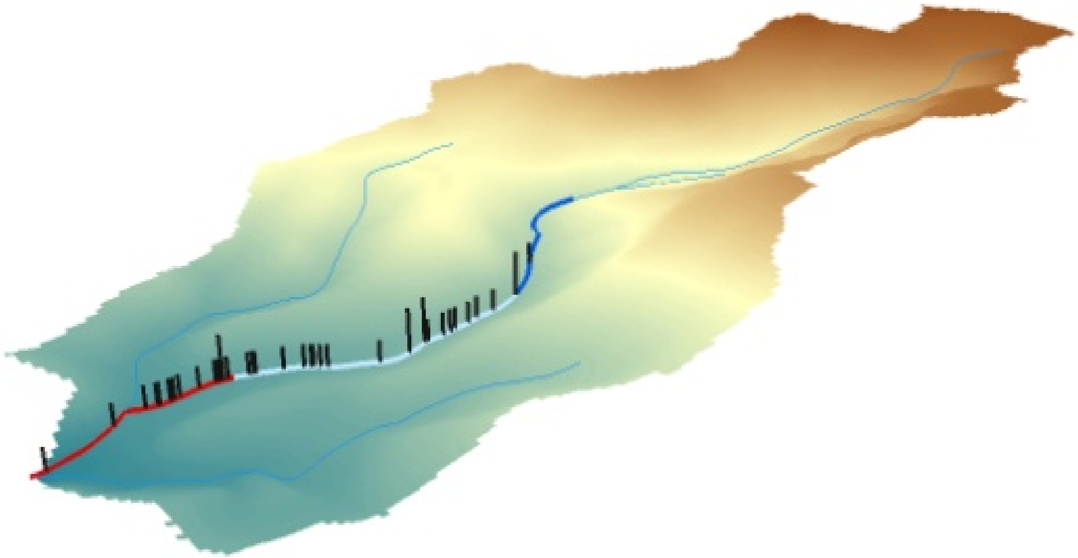

Figure 7. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70  mm) along with risk of debris flow delineated along streams reaches in Little Vasquez Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations. Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

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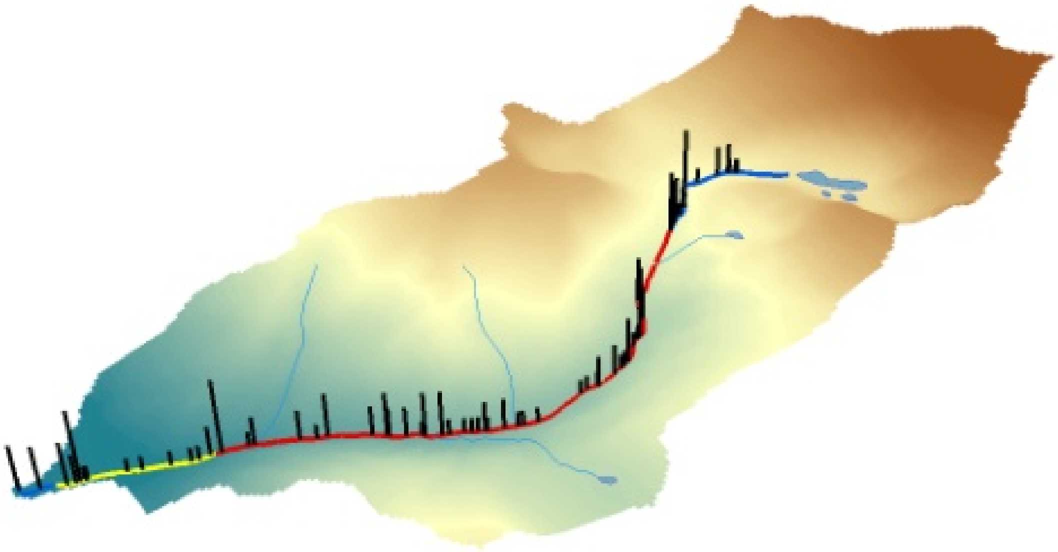

Figure 8. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70  mm) along with risk of debris flow delineated along streams reaches in Timber Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations.  Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

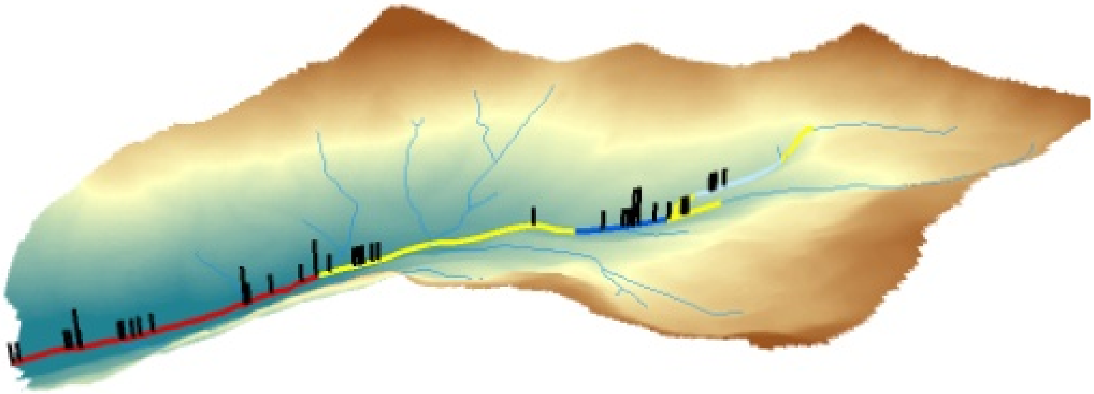

Figure 9. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70 mm) along with risk of debris flow delineated along streams reaches in Vasquez Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations. Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

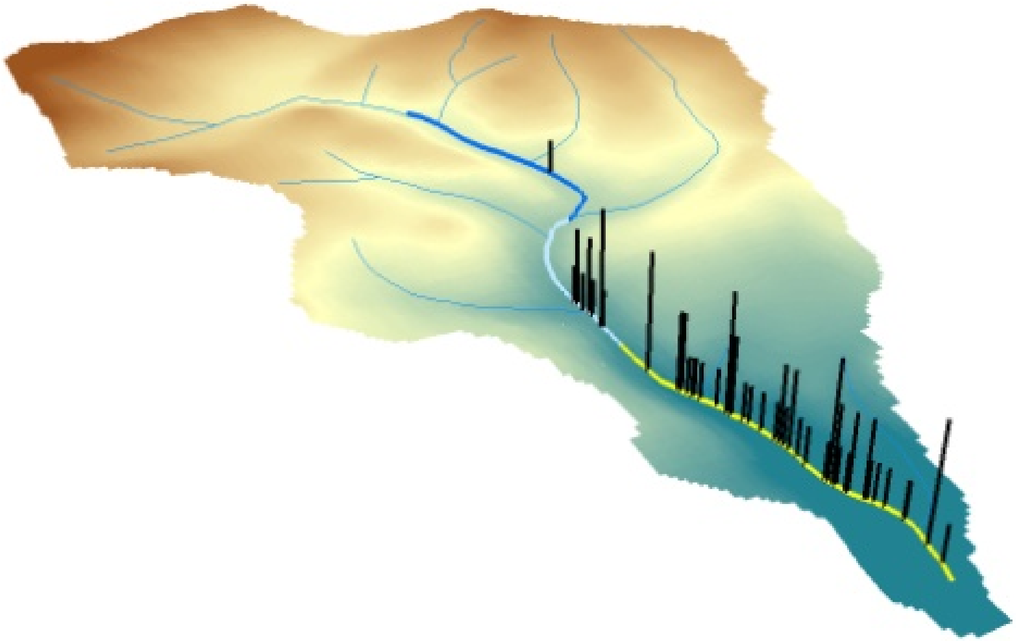

Figure 10. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70 mm) along with risk of debris flow delineated along streams reaches in Big Park Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations. Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

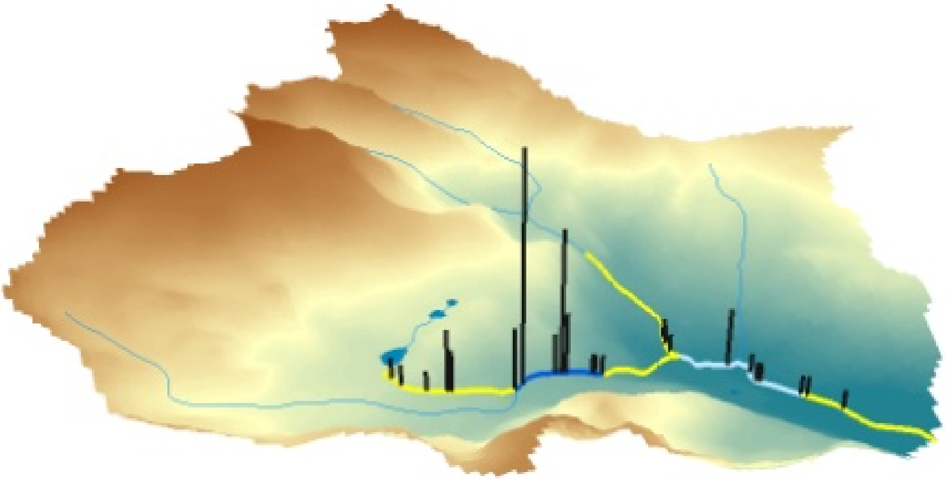

Figure 11. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70  mm) along with risk of debris flow delineated along streams reaches in Roaring Fork. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations.  Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

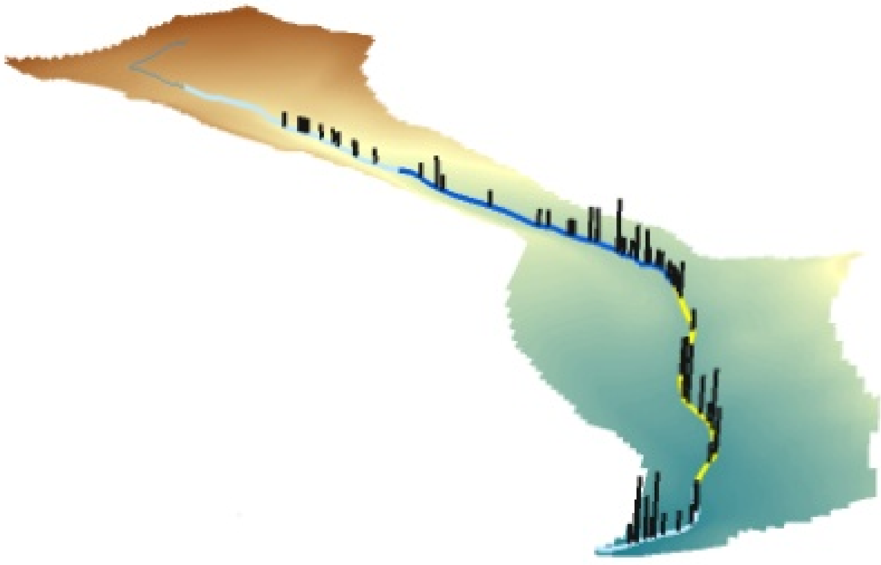

Figure 12. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70 mm) along with risk of debris flow delineated along streams reaches in Trail Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations. Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

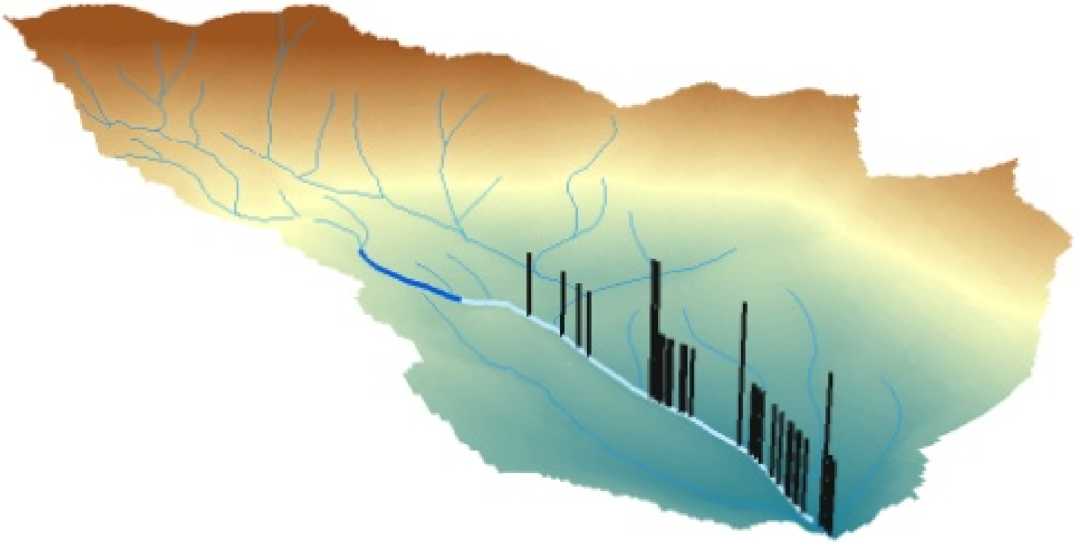

Figure 13. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70  mm) along with risk of debris flow delineated along streams reaches in Antelope Creek. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations.  Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

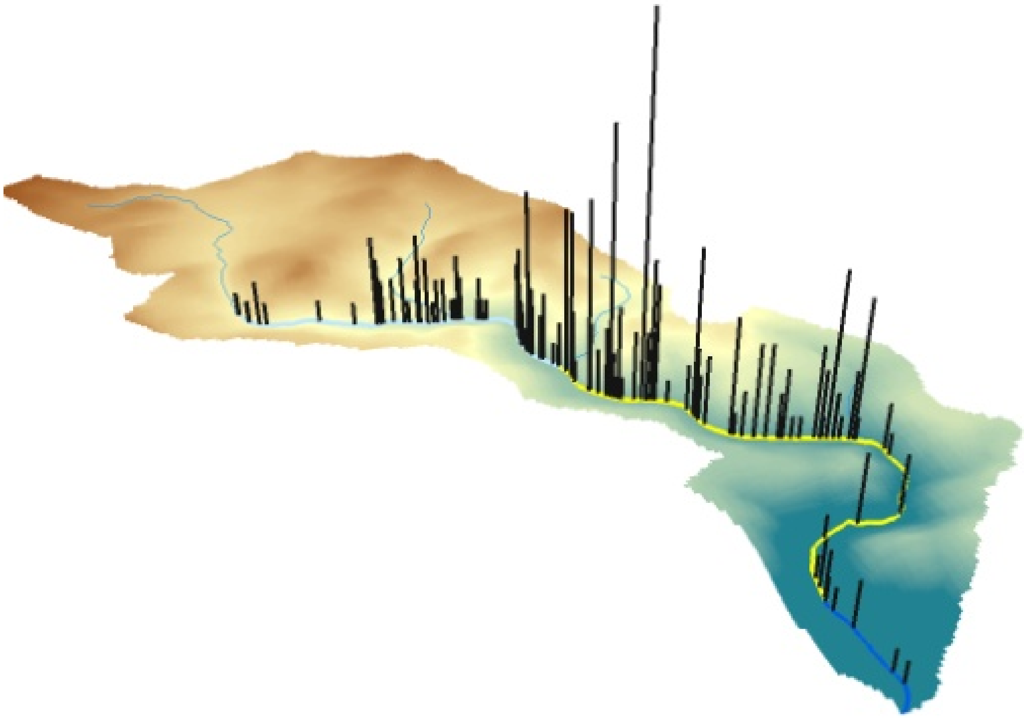

Figure 14. Spatial variation in the distribution and abundance of Colorado River cutthroat trout (length > 70 mm) along with risk of debris flow delineated along streams reaches in Deadman Gulch. Vertical bars indicate the relative abundance of cutthroat trout sampled in pools with single-pass electrofishing in three-dimensional representations. Debris flow risk assessment rank by stream reach is color-coded from low risk as coded by dark blue to high risk, denoted by red of a postfire debris flow.

## Objective 3: Spatial Distribution and Abundance of Cutthroat Trout, Physical Habitat, and Debris Flow Risk

The greatest proportion of pool habitat with high risk (reach-scale risk ranking of 3 and 4) of debris flow (equal to or greater than 70 %) occurred in Abrams Creek, Timber Creek, and Vasquez Creek (Table 5). However, the proportion of fish residing in pools within the high probability zone was less than 70 %, and only 48 % of fish sampled in Abrams Creek fish were in areas of high probability of debris flows (Table 6). Although only 40 % of Big Park Creek had a high probability of debris flow, 83 % of the fish captured in the stream network were found in these high-risk areas (Table 6). The only watersheds where potential for debris flows to negatively affect available pool habitat and present fish was zero were Antelope Creek and Deadman Gulch (Tables 5 and 6). In all other watersheds, there was moderate probability of negative effects to available pool habitat (32 to 69 %) and fish (23 to 69 %) from postfire debris flows.

Proportions of fish and available pool habitat that were located in areas with a high probability of debris flows seem to be evenly distributed among level IV ecoregion types (alpine zone, crystalline, sedimentary, and volcanic subalpine zones). However, geomorphic bedform was also closely linked to the likelihood of postfire debris flows. Reaches that have a higher channel gradient (e.g., cascade, plain-bed, and step-pools reaches) are more susceptible to debris flows than those with low gradient bedforms, such as meadow trenches and pool-riffle reaches (Figure 15).

Table 5. The percentage of pools in each reach-scale debris flow risk ranking category (on a scale of 1-low to 4-high) for watersheds in the upper Colorado River basin. High risk includes risk ranking 3 and 4.

| | Risk rank | | | | |
|---|---|---|---|---|---|
| Watershed | 1 | 2 | 3 | 4 | Percentage of pools at high risk |
| Abrams Creek | 0 | 29 | 39 | 32 | 71 |
| Antelope Creek | 13 | 87 | 0 | 0 | 0 |
| Baker Gulch | 11 | 20 | 55 | 14 | 69 |
| Big Park Creek | 24 | 16 | 60 | 0 | 60 |
| Deadman Gulch | 55 | 45 | 0 | 0 | 0 |
| Hamilton Creek | 65 | 3 | 0 | 32 | 32 |
| Little Vasquez Cr | 48 | 0 | 16 | 36 | 52 |
| Roaring Fork | 0 | 68 | 32 | 0 | 32 |
| Timber Creek | 25 | 0 | 15 | 60 | 75 |
| Trail Creek | 40 | 33 | 27 | 0 | 27 |
| Vasquez Creek | 9 | 21 | 38 | 32 | 70 |

Table 6. The percentage of Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) in each reach-scale debris flow probability ranking category (on a scale of 1-low to 4-high) for watersheds in the upper Colorado River basin. High risk includes risk ranking 3 and 4.

| | Risk Rank | | | | |
|---|---|---|---|---|---|
| Watershed | 1 | 2 | 3 | 4 | Percentage of fish at high risk |
| Abrams Creek | 0 | 52 | 30 | 18 | 48 |
| Antelope Creek | 0 | 100 | 0 | 0 | 0 |
| Baker Gulch | 24 | 33 | 38 | 5 | 43 |
| Big Park Creek | 1 | 16 | 83 | 0 | 83 |
| Deadman Gulch | 37 | 63 | 0 | 0 | 0 |
| Hamilton Creek | 76 | 1 | 0 | 23 | 23 |
| Little Vasquez Cr | 52 | 0 | 8 | 40 | 48 |
| Roaring Fork | 0 | 74 | 26 | 0 | 26 |
| Timber Creek | 32 | 0 | 15 | 53 | 68 |
| Trail Creek | 37 | 35 | 29 | 0 | 29 |
| Vasquez Creek | 22 | 9 | 24 | 44 | 68 |

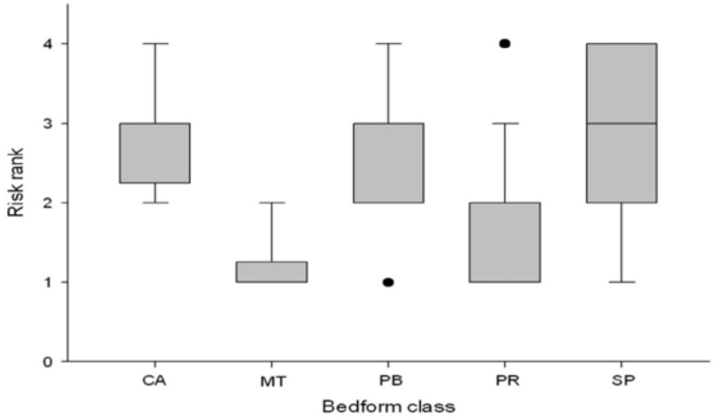

Figure 15. Reach-scale debris flow probability ranking (1-4; low to high) for sampled stream reaches in each geomorphic bedform class. CA = Cascade, MT = Meadow trench, PB = Plain bed, PR = Pool riffle, and SP = Step pool; based on methods from Montgomery and Buffington 1997

# 5. DISCUSSION

In this study, I compared watershed-scale debris flow probability and reach-scale debris flow risk assessment models to examine the probability and extent of debris flows within and across drainage basins. Subsequently, results from the reach-scale debris-flow risk model were integrated with the distribution of Colorado River cutthroat trout and physical habitat in order to assess the potential consequences of postfire debris flows in the upper Colorado River stream ecosystems. The reach-scale debris flow risk assessment model provides a direct process linkage between hillslopes and stream channel networks as it identifies debris-flow source areas and links them to the specific channel reaches that could be affected. The model can graphically display reaches that have the highest probability of being affected by debris flows, thus predicting how much available aquatic habitat will be influenced by potential postfire debris flows. Ultimately, understanding debris flow susceptibility should improve the ability to predict habitat types, disturbance regimes, and the associated distribution of species assemblages and abundance over entire channel networks.

At the watershed-scale, probability of postfire debris flow varied from 32 % to 71 % across the 11 watersheds in this study. Thresholds for postfire debris flow initiation are often based on slope angle, rainfall amount, and duration (Cannon et al. 2001; Cannon et al. 2008). All of the sampled watersheds were susceptible to debris flow, irrespective of prevailing climate, geology, and topography (Wondzell and King 2003). Abundance of cutthroat trout in watersheds with high probability of debris flow and high proportion of affected stream length would be predicted to fluctuate substantially (Reeves et al. 1995; Dare et al. *in review*), as it would affect a variety of habitat that crucial to all life history stages (Guy et al. 2008; Hilderbrand and Kershner 2000; Lake 2000). These populations may be at greatest risk of extirpation, especially where tributaries are too steep to provide habitat, and fish are confined to the mainstem channel (Guy et al. 2008; May and Lisle 2012). In contrast, in watersheds with a broader spatial distribution of salmonid habitat and lower extent and severity of debris flows may experience less extreme fluctuations in fish abundance because populations are less likely to be affected by damaging debris flows (Gresswell 1999; Guy et al. 2008; May and Lisle 2012).

Watersheds located in alpine zones of the upper Colorado River basin exhibit a higher probability of postfire debris flows than those found in lower elevations. However, the models are limited to forested areas in these watersheds and do not include areas of tundra vegetation and exposed rock that typically occur in these high-elevation watersheds. Limiting the models to forested portions of a watershed reflects a realistic approach those areas where fire would have most impact on the landscape. Furthermore, alpine watersheds observed in this study tended to be more dendritic than watersheds at lower elevations, and there is commonly a greater proportion of the stream network that could be used as refugia (sensu Guy et al. 2008; Neville et al. 2009). When watersheds are located in the alpine zone, the possibility of debris flows usually increases in the lower portions of the watershed, primarily in steep and forested stretches of the stream channel. Although Colorado River cutthroat trout may be spatially distributed throughout these watersheds, even in locations that are highly likely to experience debris flows, fish were often found above reaches of debris flow initiation and transport (Figures 6, 7, 8, and 14) and located in high elevation meadow reaches and/or lakes.

Interestingly, debris flow probability was relatively sensitive to the percentage of forest area burned and storm rainfall intensity. If the percentage of forest area burned in each one of the watersheds was reduced to 75, 50, or 25 % and the other variables were held constant, the probability of a debris flow occurrence in all watersheds was less than 40 % (Figure 16a). Conversely, if storm rainfall intensity was increased to 25.4 mm/h, most watersheds with a 100 % burn scenario had a 50 % chance of experiencing a debris flow. This percentage increases as storm rainfall intensity increases (Figure 16b).

These results underscore the fact that all of the watersheds have some degree of risk of postfire debris flow, especially if the fire covers a large proportion of the watershed, but an increase in the postfire storm rainfall intensity also influences the likelihood of a debris flow occurrence. In fact, there is undoubtedly some risk of debris flow even in the absence of fire, and physical variables (e.g., hill slope and soil properties) are important predictors of debris flow potential. It is the interaction of these physical variables that determine the portion of the stream channel that is most vulnerable to debris flows, but the occurrence of debris flow in these vulnerable portions of the watershed ultimately depends on the burn pattern and the intensity and distribution of postfire precipitation (Gresswell 1999).

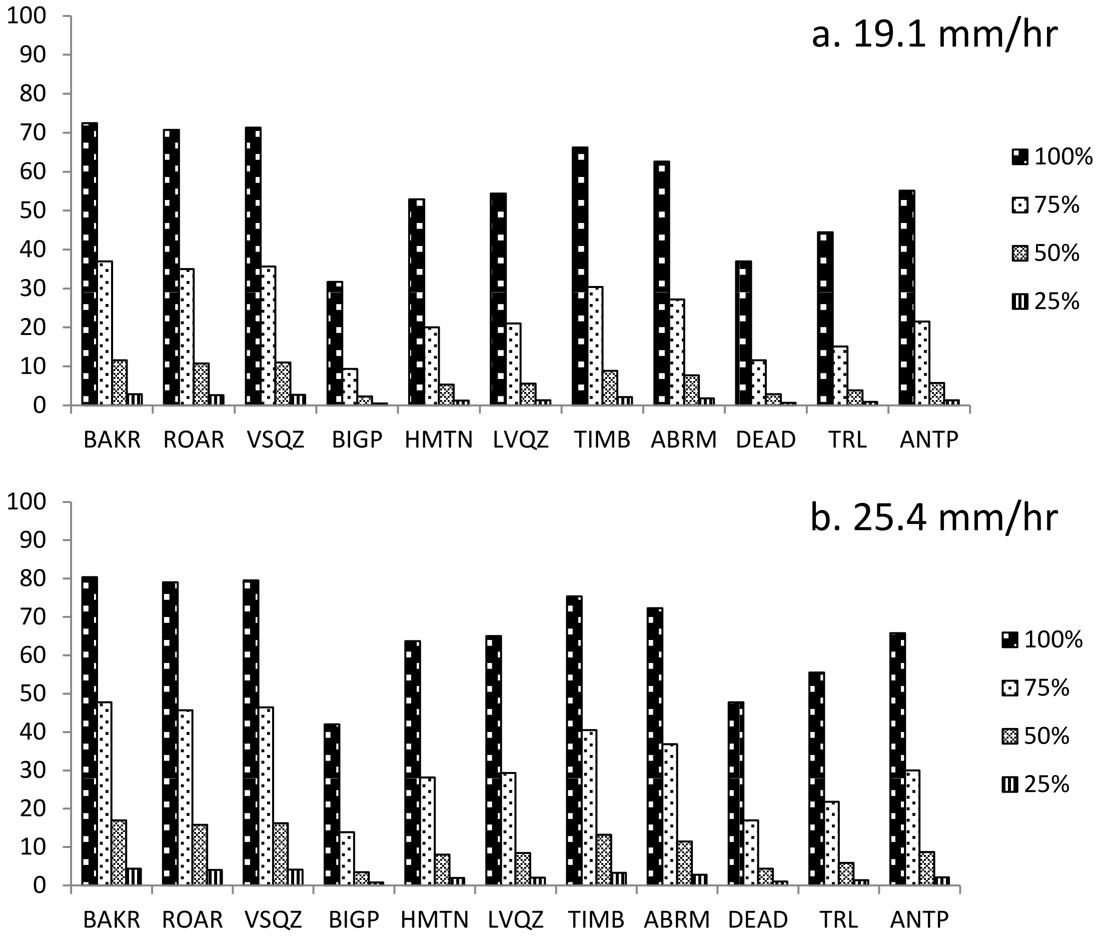

Figure 16. Probability of postfire debris flow under four different burn area and five storm rainfall intensity scenarios for eleven watersheds in the upper Colorado River basin. Four different categories of high severity burn scenarios that include 25, 50, 75, and 100 % of the watershed area; and two different storm rainfall intensity regimes at a.) 19.1 mm/h, and b.) 25.4 mm/h. BAKR = Baker Gulch, ROAR = Roaring Fork, VSQZ = Vasquez Creek, BIGP = Big Park Creek, HMTN = Hamilton Creek, LVQZ = Little Vasquez Creek, TIMB = Timber Creek, ABRM = Abrams Creek, DEAD = Deadman Gulch, TRL = Trail Creek, and ANTP = Antelope Creek.

One limitation of the watershed-scale empirical debris flow model (Cannon et al. 2010) is predictions are specific to the pour point of a watershed, (often delineated at road crossings or major tributary junctions). At the same time, it is not possible to determine where in the debris flows initiate, or where of deposition begins. Thus, the ability to quantify negative effects of hypothetical debris flow to aquatic habitat and to the abundance and distribution of fishes is severely constrained.

Another limitation of the watershed-scale debris flow model is the resolution of the data input. For example, available soils data were at a 1:500,000 resolution, and therefore, it was difficult to capture the heterogeneity of soil types, specifically clay content and liquid limit that strongly influence the occurrence of postfire debris flow. If the spatial resolution of the soils layer were 1:25,000 (i.e., the resolution of a 10-meter digital elevation model), then information derived from the soils layer would be more useful for the assessment of the reach-level debris flow model.

Results from the reach-scale debris flow risk assessment model suggest that postfire debris flows are potentially common among sample locations in the upper Colorado River basin, and at least some of the fish-bearing reaches in every watershed were likely to be affected. Debris flow potential was highest in the lower and middle reaches in most of the watersheds, even those in the alpine zone. Although Colorado River cutthroat trout occur in areas of high risk, distribution in all of the streams was patchy, and cutthroat trout were never restricted to the vulnerable areas.

Only Timber Creek (Figure 8) had the greatest extent of stream channel with a rank of 4 (> 5 km), and only about 2 km of stream was rated with a low probability of debris flow. If the remainder of Timber Creek was affected by debris flow, the remaining area is considerably less than 8 kilometers of stream length often cited for persistence of isolated populations of trout (Hilderbrand and Kershner 2000). Although isolated populations in small drainages may be vulnerable to loss of genetic variability and stochastic extirpation (Cook et al. 2010), evidence suggests that some may persist for decades or longer (Wofford et al. 2005; Guy et al. 2008; Cook et al. 2010). Furthermore, previous studies suggest that trout populations that are extirpated following postfire debris flow often return to prefire abundance and density if connectivity is maintained within the system.

As a consequence, a scenario of complete extirpation by postfire debris flows is not highly probable in any of the level IV ecoregion types sampled in this study. In fact, Colorado River cutthroat trout were distributed throughout the accessible portions of all watersheds, including headwater lakes and meadows, well above the topographical influences of a potential debris flow. Previous research suggests that trout in headwater lakes can rapidly colonize downstream in stream networks (Adams et al. 2001; Roghair et al. 2002). The effects of isolation are more pronounced in small linear networks because a loss of connectivity leaves small fragments of stream that may be too small to support trout over an extended period (Fagan 2002); however, for any given network size, dendritic topologies may provide more opportunities for refuge (Guy et al. 2008; Neville et al. 2009).

The main limitation to the reach-scale debris flow risk assessment model is the inability to provide quantitative debris flow estimates. This qualitative model can be used for identifying reaches that are susceptible to debris flows but cannot estimate the extent of associated effects. Many debris flows initiate in a contributing tributary or hollow and subsequently terminate upon entering the main channel, thus altering only a short section of the stream reach because the angle of the tributary is nearly perpendicular to the main channel (May and Gresswell 2004). In other scenarios, debris flows may propagate and continue into the main channel because the tributary junction entered at an acute angle (Benda and Cundy 1990). This model was not designed to assess magnitude or volume of sediment and wood entrained within debris flows, but it can be used to identify reaches of stream that are highly susceptible to debris flow effects.

The advantage of the reach-scale debris flow risk assessment model is that is easy to use and requires only readily available field and GIS derived variables. Although qualitative, it also provides context at a scale that is meaningful for fish and allows users to examine the entire watershed at a variety of spatial scales. In addition to predicting potential effect of debris flow on spatial distribution and abundance of fish, the model can be used to understand the potential spatial effects of debris flow to the riparian vegetation and channel morphology. These important stream characteristics in turn, can affect temperature and primary and secondary production (Rosenberger et al. 2011).

Parameters used in the reach-scale debris flow risk assessment model were identified by studying previous postfire debris flows in the Intermountain West, and therefore, it is potentially useful for the upper Colorado River Basin (Cannon et al. 2010). Furthermore, because primary assumptions of the model include the occurrence of high-severity fire and substantial postfire rainfall events, predictions are potentially positively biased. It is also important to remember that debris flows can occur after heavy rainstorms, even in unburned watersheds (Wondzell and King 2003). Although it is virtually impossible to predict the location and severity of wildfires and the intensity and duration of postfire precipitation events, hypothetical scenarios, such as those presented here, provide useful insights for planning and for conceptualizing potential fire effects (Rieman et al. 2003).

Additionally, the reach-scale debris flow risk assessment has substantial heuristic value. For example, by examining the watershed with high-resolution topographical information and stream channel characteristics in conjunction with spatially continuous fish abundance information, it is possible to assess effects of a postfire debris flow on isolated populations of native salmonids. Examining natural processes and physical characteristics of the watershed that contribute to postfire debris flows provide important insights for decision-support models that evaluate landscape resilience and long-term persistence of isolated populations in conjunction with available habitat, temperature, and connectivity (Williams et al. 2009; Dare et al. *In review*).

Emerging conceptual frameworks in riverine ecology emphasize the importance of habitat heterogeneity, stochastic disturbances, and scaling issues (Schlosser 1991; Fausch et al. 2002; Poole 2002). Concomitantly, these frameworks are hindered by insufficient understanding of the physical basis for predicting interactions between stochastic disturbances and the topology of channel networks, and the patterns of heterogeneity in the habitat and fish distribution that they generate (Benda et al. 2004; Ganio et al. 2004; Torgersen et al. 2006). In my study, data were collected in a spatially continuous manner throughout each watershed, and it was possible to collect biological and geographical information necessary to assess the interaction between potential effects of debris flows and the spatial distribution of cutthroat abundance. Results underscore the importance of heterogeneity of the physical habitat template at a variety of spatial scales.  In essence, this study provides the ability to explore the effects of spatially explicit phenomenon (e.g., debris flow) on the distribution and abundance of salmonids.

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