A RISK ASSESSMENT FOR HILLSLOPE EROSION FROM WILDFIRE AND IMPLICATIONS FOR WATER QUALITY AND WATERSHED ECOLOGY

by

Patrick Timothy McGunagle

A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

December 2019

ACKNOWLEDGEMENTS

I would like to thank the many professors that have worked with me to understand my own intrigue for land resources and environmental sciences. I thank Dr Otto Stein, Dr Joel Cahoon, and Dr Steve Perkins for working with me in the nebulous stages of this degree, Dr Tony Hartshorn for his inspiration and unlimited passion for teaching, and Dr Ann Bertagnolli for setting the rigorous tone of my academic years in Bozeman. I further thank my graduate committee, Dr Bob Peterson, Dr Scott Powell, and Dr Tracy Sterling, for guiding me through the curriculum and working with my eclectic background and curiosity.

I must acknowledge the United States Forest Service Rocky Mountain Research Station, especially William Elliot, Pete Robichaud, and Mary Miller, for providing open source modeling programs for land managers and citizen scientists to understand the natural phenomena occurring on our nation’s greatest asset, public lands. I acknowledge the Wildfire Risk Management Science Team, especially Joe Scott, Matthew Thompson, Mark Finney, and Dave Calkin, for their work towards quantified wildfire risk assessment. As a public lands owner, I thank the Joint Fire Science Program for continuing the rigorous interpretation of the processes affecting our open spaces. I must further thank the culture of Montana State University, for keeping me inquisitive and yet grounded to the incredible reality of Montana.

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

LIST OF TABLES

Table Page

LIST OF FIGURES

ABSTRACT

In the western United States, wildfire is a natural disturbance and regulatory mechanism by which vegetated watersheds reset the natural succession regime. Wildfire management by humans protect property, people's lives, and values such as freshwater provision or recreational opportunity. However, erosion is a natural process that is directly exacerbated by wildfire. Erosion as debris flows, mass-wasting, or increased sedimentation is a continual phenomenon augmented by natural disturbance; fire plays an important role in stream channel development and floodplain connectivity. Hillslopes are the flanks of a valley and the margins of the eroding uplands and they vary in form and are indicative of the local geology and soils. However, ground observations to determine hillslope characteristics is expensive and negates the positive benefit of risk assessment as a "fast, cheap, good" method for targeting areas to manage a watershed for erosion risk. Therefore, my paper presents a risk assessment demonstrating the knowledge gap that limits economical risk management decisions to a pre-disturbance environment. I discuss hillslope erosion as the primary disturbance effect that can be managed pre-fire by the characterization of risk through an integrated ecological risk assessment. A beneficial outcome of accurate ecological risk assessment is knowledgeable resource triage in emergency situations, as well as the ability to proactively and economically manage for anticipated ecological effects. In addition, incorporating ecological risk metrics to a pre-disturbance management plan allows for inherently ecologically-sound operational objectives. I explore the risk of hillslope erosion from wildfire and how erosion from wildfire affects water quality and watershed ecology. I review the current understanding of erosion potential and how to minimize wildfire impact. I then demonstrate how to use the Total Risk Quotient to manage for total risk. I find that risk assessment for hillslope erosion requires interpreting layers of risk established by the topography, the fire, the storm, and the timing of these events. I conclude that whenever multiple natural phenomena affect resources and value, economic analysis to understand the total risk and risk mitigation options is required.

INTRODUCTION

Wildfire is a natural disturbance that is inherent to the ecosystems of the western United States. As people interact with wild lands, we expose ourselves and our systems to risk from natural phenomena. Erosion is a natural process by which upland hillslopes weather. Wildfire effects augment erosional processes, altering ecosystem services provision. Wildfire may also impact human property.

Land managers have many models to predict wildfire probability and behavior; other models predict erosion. Erosion models for known fires aid in the prediction of hillslope erosion, but for a given watershed before a fire has occurred, few models and a still-nebulous risk assessment process predict erosion risk. Therefore, in this paper, I synthesize current knowledge and efforts to close this knowledge gap with an example case study and risk characterization tool. I present a risk assessment characterization tool to pinpoint areas for "fast, cheap, and good" risk mitigation in project management (Atkinson, 1999) (Figure 1).

Figure1: The project management conundrum redrawn from Atkinson (1999) to develop informed and efficient management decisions. Otherwise known as "fast, cheap, good," the manager may only manage for two conditions at once: all three is an impossibility.

In this paper, I explore the diagnosis of risk of hillslope erosion from wildfire within an unburned watershed, the Haskill Basin Watershed north of Whitefish, Montana, USA. I review the risk assessment techniques and consider gaps in the economics of risk development and realization. Finally, I show how risk characterization informs management strategy for proactive risk mitigation in a watershed of mixed value and services distribution.

Background

Erosion is a function of biological, climatic, geomorphic, and chemical factors. Within a natural system, erosion prediction is resolved into three components:

- The Watershed
- The Fire
- The Storm

These components define how severely erosion affects plant succession and timing, water quality, and human infrastructure (Byram, 1959; Pritchett and Fisher, 1979; Rust et al, 2018).

Current limitations in erosion risk assessment before fire include model validity, data scarcity, and internal watershed functions such as buffering capacity or runoff timing (Poff et al, 2010). A Fire Behavior Triangle defines instantaneous fire behavior (NWCG, 2014); I propose an Erosion Triangle to understand erosion as a process (Figure 2). The Erosion Triangle is important to discerning hazard influence, especially by independent events, through the risk assessment process.

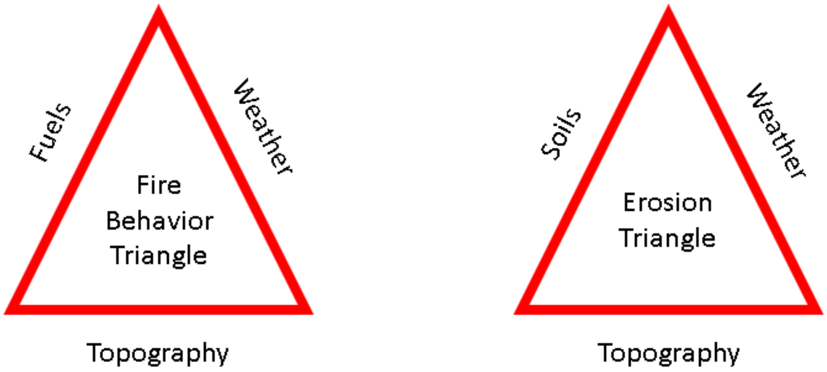


Figure 2: The Erosion Triangle informs understanding of erosional processes in a similar manner to the Fire Behavior Triangle for fire behavior. Each side of each triangle defines a system that may or may not be managed to mitigate risk (NWCG, 2014).

Risk Assessment

The risk assessment process for ecological hazards is an Ecological Risk Assessment (ERA). The ERA process is comprised of 1) Problem Formulation and Hazard Identification, 2) Effects Analysis and Response Relationships, and 3) Risk Characterization and Uncertainty Analysis (EPA, 1998). The ERA for hillslope erosion is an integration of qualitative and quantitative inputs relating ecological variables such as timing, succession, ecotoxicity limits, endangered species, and thresholds for human health (EPA, 1998; Young and Sanzone, 2002). Some variables may have mandated Levels of Concern (LOC), which are used to understand a Risk Quotient (Value ÷ LOC) for that variable (EPA, 1998; Phelan et al, 2015). A Total Risk Quotient, that is, a real-time aggregate of exposure, vulnerability, and manageable risk, is my solution to understanding risk at a point through time and in conjunction with management options.

Risk mitigation becomes an economics decision for land managers seeking to maximize risk mitigation with limited resources. The effective management of disturbance effects requires understanding of where and how ecosystem values and services are impacted (Finney, 2005). The understanding of risk by both wildfire and fire effects, such as erosion, is sourced from the evaluation of quality thresholds within the landscape, which may be a relative evaluation to a reference condition (Thompson et al, 2015). I present the concept of developing and mapping aggregate risk to spatially represent limiting thresholds among these many ecological variables.

Wildfire

Wildfire is a disturbance, but fire is usually natural within the ecosystem (Tedim et al, 2018). Fire effects are characterized by changes in redundancy within the system, recovery rates and resiliency, and added influence, such as climate change (Poff et al, 2010; Staley, 2010; Robichaud et al, 2010). Fire activity across a landscape is confined by topographic features that define fire behavior as well as the vegetation patterns that are fuel for wildfire(Byram, 1959; NWCG, 2014). Wildfire varies by intensity and behavior depending on the fuels available and the weather conditions of the burn period (NWCG, 2014). Wildfire effects are not evenly distributed, and the severity of these effects varies in conjunction with future events, such as erosion effects by fire and later precipitation events (DeBano, 1981; Ice, 2004; Cerda and Robichaud, 2009).

Hillslope Erosion

Erosion is a natural phenomenon and the effect of disturbance on erosional processes include the following study areas: debris flow analysis, sedimentation analysis, and succession disruption analysis. Risk assessment for each of these areas is not conducted with the same methodology; the method I present in this paper allows for fluidity between these different philosophies by understanding erosion effects on water quality and watershed ecology. For the total relative effects of erosion, the development of a Vulnerability Index identifies background erosion rates and pre-disturbance quality through the use of “measurable, comparable and consistent statistics” (EPA, 1998; Phelan et al, 2015). The concept of centers of risk-- that is, where risk from many sources compounds additively into distinct nexus within certain areas-- further balances these three varying erosion assessment paradigms; the limiting threshold for exposure informs my Total Risk Quotient development later in this paper.

A risk assessment for erosion to a single hillslope pre-fire is composed of many variables, none of which dominantly controls erosion prediction. Therefore, watershed-scale erosion risk assessment for thousands of hectares is extremely difficult. Current models assess for fire behavior and precipitation effects, however, natural stochasticity at this scale, coupled with other latent effects (such as climate change, or a century of fire exclusion on the landscape), combine to make rules-based models ineffective without case-by-case calibration by costly empirical verification. The literature suggests that for a known fire and known watershed, erosion risk assessment is a function of few geomorphic variables and a single probability distribution of the modeled precipitation “event set” of many hypothetical storms. Pre-fire, this distribution is compounded by myriad other conditions governing wildfire characteristics, diluting erosion predictive capacity and confidence. I will explore how the erosion focus areas of debris flow analysis, sedimentation analysis, and succession effects analysis combine to discern an aggregate erosion risk both pre-fire and, more confidently, post-fire.

Case Study

Haskill Basin, north of Whitefish, MT, is a 2,694-ha watershed (Hydrologic Unit Code(HUC10):1701021005) on the Flathead National Forest that provides approximately 70% of the municipal water for the City of Whitefish's 6,500residents (RDG, 2007). Conservation easements with Stoltze Lumber Company and the U.S. Forest Service create a perpetual use agreement of the watershed for municipal water provision. Erosion from wildfire threatens the quality of the water supplied to the City of Whitefish (RDG, 2007) (Figure 3).

Figure3: Haskill Basin Watershed, Whitefish, MT, HUC101701021005.

HAZARD IDENTIFICATION AND EFFECTS ASSESSMENT

What are the limits of our understanding for erosion risk from wildfire? Conceptualizing disturbance by wildfire and subsequent precipitation is not simple. The understanding of the hazard must come from understanding the relationships of the Watershed, the Fire, and the Storm.

Thompson and others (2013) defined a fireshed as a "biophysical area under which wildfire can occur and spread, loosely defined by natural containment [topographic features]." For a given fireshed, erosion risk is a function of distributions of multiple fire effects including Soil Burn Severity (SBS), location of threatened High Value Resources and Assets (HVRAs, usually the wildland urban interface),watershed properties and background erosion rates, and likely climate precipitation events, among others. Spatially, a raster of risk per unit area is used to diagnose aggregate risk at a point under many potential scenarios, possibly in real-time (Thompson et al, 2016). Thus, a unit-based total risk characterization for the landscape is created and evolves with changing conditions (Scott et al, 2013). These variables also inform a relative ERA of one watershed or portion of the fireshed against others, or to unburned portions of the single watershed. I used a given "severe" wildfire to complete a higher-tiered risk assessment but acknowledge that this adds a degree of conservatism to erosion prediction and risk.

The last decade of research has dramatically increased our understanding of erosion. Robichaud et al(2006) introduce the erosion prediction model used by Miller and Elliot (2011) to predict erosion rates post-wildfire across the Rocky Mountains. Ice (2004), Curran et al (2006), and Larsen et al (2009), used climate models and total exposed mineral soil as predictors for erosion rates in severely burned watersheds. Moody et al (2010) shows relationships of fire impacted soils and erosion processes for hydrologic fire effects mapping. Wilson et al (2018) quantified hydrologic response of hillslopes to modeled precipitation events after burning and demonstrates the "importance of functional connectivity when forecasting hydrologic and erosion responses to disturbances." Poff et al (2010) and Staley et al (2010) articulate Ecological Limits of Hydrologic Alteration (ELOHA) and rainfall thresholds for post-fire debris flow triggering, respectively. Silins et al (2009), Shakesby et al (2016), and Staley et al(2017) provide empirical validation to sediment production models of post-fire runoff, including debris flows.

Factors contributing to specific risk by water erosion for a burned area include hillslope length and steepness, remaining surface cover, and the amount and intensity of rainfall (Miller et al, 2011). An individual soil particle is eroded from place and transported in different ways according to variation in these properties: rainsplash, sheetwash, and rilling all contribute to particle transport downslope and into a sediment trap or receiving aquatic system (Pritchett and Fisher, 1979). The prediction of particle movement through this physical system is controlled by geomorphic factors for the design watershed and the design storm.

I develop the Erosion Risk Triangle and the Total Risk Quotient by demonstrating how the watershed, the fire, and the storm all contribute to identify the hazards by which deleterious erosion affects watershed functional value.

The Watershed

Watershed ecology is the study of the interaction of watershed organisms and the environment; although wildfire measurably affects watershed form, it does not equally affect watershed function (Ice, 2004; Mast et al, 2016; Tedim et al, 2018). It is important to understand that analyzing watershed ecology from the context of human use is a point of value system for form and not ecological function (EPA, 1998). Finney (2005) discusses that metrics for quantitative ecological effects are difficult to discern within the watershed. Rather, output conditions, such as water quality response, or faunal and floral response, such as mortality rates, provide better endpoints as required by the EPA (1998) for ERA. A partially burned watershed allows better understanding of fire behavior (e.g., why certain areas burned and others did not), than a completely burned watershed (Tedim et al, 2018).

Watershed initial condition is a function of use (mixed, resource-driven, recreational, etc.) and ecological health (Phelan et al, 2015). Fire history is an important diagnostic to understand susceptibility in any given year for a point within the watershed to fire and fire effects (Finney, 2005; Thompson et al, 2012). HVRAs are the most quantifiable, tangible and manageable risk metric within a landscape, and usually govern the societal expectation for risk management (Thompson et al, 2016). However, relating dollar value for a building is simpler than relating degrees of dollar damage to the timing and magnitude of runoff and sedimentation from a wildfire-impacted watershed (Finney, 2005; Scott et al, 2013). Ranking of HVRAs is critical to understanding human movement through the system and parameters by which ecosystem services are conveyed or consumed. For example, a low-intensity wildfire that does not consume HVRAs or impact stream crossings has a net benefit for the system by adding resiliency against catastrophic wildfire in the immediate future (Sun et al, 2019). Exposure assessment is more easily conducted for a single location than along a spatial distribution. Further, multiple independent variables combine to produce a dilution of precision for the integrated risk assessment (Burmaster and Harris, 1993; Cox et al, 2005; Hassenzahl, 2006)

Geomorphic Factors

Fire and water are both ecological forces. Topographic features limit fire to a fireplain, as defined by Scott et al (2015), which is not as easily visualized by form as a floodplain, though each disperses the force of fire and water, respectively, in a similar manner.

I define high-risk hillslopes by understanding the current state of knowledge for erosion processes. Significant rilling (water funneling and creating new micro channels), ravel (dry movement of particles on 60-80% slopes), and mass wasting by landslides or slumping occurs when planar slope length is greater than 60-m (Pritchett and Fisher, 1979; Bryan, 1979; Moody and Kinner, 2006). Planar hillslopes of slope angle greater than 10° are at risk for water erosion due to raindrop soil particle splash displacement and subsequent sheetwash transport under intense storm events (Miller et al, 2011). Hillslopes of slope angle 15-16° are prone to sheetflow erosion scour under such storm events (Wilson et al, 2018). Hillslopes of greater than 24° slope angle are likely to contribute to channelized overland flow (Bryan, 1979; Staley, 2010). Typically, very little ravel and mass wasting occurs on slopes with post-fire vegetation cover exceeding 50% (Robichaud et al, 2010). Burned slopes of 20° or more with vegetation canopy loss of greater than 70% cover are considered high risk for water erosion, because lack of needlecast and leaf litter does not buffer sheetflow erosion effects (Robichaud and Elliot, 2006). The hillslope relative vulnerability to erosion, as well as ecological relationships and values distribution approximated by slope angle, is described in Figure 4.

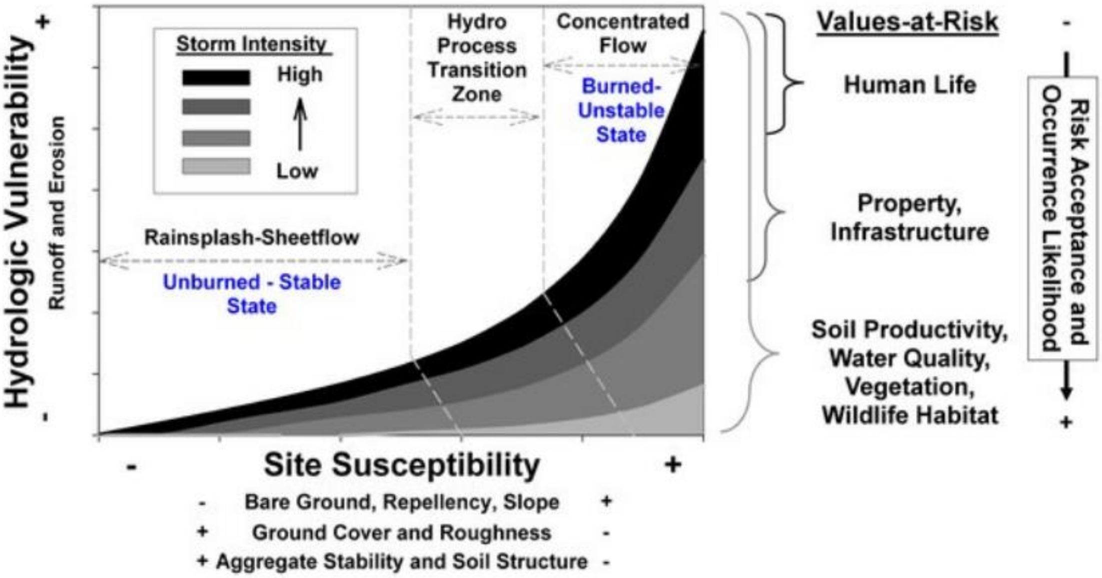


Figure 4: Representation of hillslope erosion and susceptibility to disturbance, including relative use assessments, relative ecological significance, erosion production relationships, and relative risk assessed from relative erosion vulnerability, from Williams (2016).

Longer hillslopes incur more channelization and gullying due to building momentum within the overland flow (Moody and Kinner, 2006; Moody and Ebel, 2014). Precipitation intensity controls erosion effects: variation in sediment production by aspect, ratio of head or toe of slope to midslope grade, or width do not govern erosion prediction (Staley et al, 2012; Sun et al, 2019).

I found strong consensus that any roughness element distributing flow or absorbing flow momentum along a hillslope mitigates erosion effects. Hillslope length and slope angle are the dominant parameters for erosion risk.

Debris Flows

Debris flows are the most visible form of post-fire runoff effects; debris flows are tremendously powerful mass wasting events and can scour away infrastructure or deposit extreme amounts of material on top of HVRAs. Soil saturation condition and debris flow triggering are weather dependent, and the U.S. Geological Survey Landslides program helps refine prediction in the western US (Staley, 2010; Staley et al, 2017). Debris flows as a fire effect occur generally in steep terrain and on unsupported slopes covered in light, flashy fuels (Curran et al, 2006; Moody and Martin, 2009). Debris flows are a function of burn severity, percentage of burned area with slope gradient greater than 30% and 50%, rainfall thresholds, and proximity to a receiving stream channel (Staley et al, 2017). Rainfall thresholds reflect case-specific infiltration rates for soil saturation critical points and are based on soil classification and single storm intensity or cumulative effects of multiple low-intensity storms (Moody and Martin, 2009; Moody and Ebel, 2014; Staley et al, 2017).

I contend that debris flow prediction uses a much deeper soil analysis, usually 5cm and deeper soil profiles, than succession-based or sedimentation erosion effects prediction. Haskill Basin is at low risk for debris flows due to high rock fragment content in soils and highly vegetated hillslopes supporting mature xeric forest.

Sedimentation

Stream sedimentation is the lesser component of post-fire runoff prediction dominated by the debris flow discussion. However, sedimentation has the greatest impact on water quality (Mast et al, 2016; Sankey et al, 2017; Hohner et al, 2019). Background sediment yield rates of 0.15t/ha/yr for the Rocky Mountains were established by Moody (2009) and Miller (2011). Sedimentation increases stream temperature and turbidity; increased organic matter has effects on dissolved oxygen demand (Tecle and Neary, 2015; Rust et al, 2018). Sediment production by fire also has a chemical signature; Rhoades et al (2019) shows that elevated nitrogen is present in streams at ten times the background rate for fire-impacted watersheds fourteen years post-fire. Similar quality effects can occur due to mobilized metals or nutrients in post-fire channel-altering flow regimes (Tecle and Neary, 2015; Wohl et al, 2015).

Stream sedimentation affects drinking water standards and must meet pre-finishing quality requirements. While erosion risk diminishes with vegetation succession (usually by year five after a wildfire), the sediment under transport within the stream channel can be mobile for 10-100 years (Moody and Kinner, 2006; Robichaud et al, 2010; Rhoades et al, 2018). Pre-finishing capabilities of the receiving municipal freshwater distribution network are at risk for impact by fine sedimentation; Haskill Basin is at risk for sediment production and sedimentation impacts to municipal water diversion infrastructure and reservoirs.

Stream Channel

The characteristics of the watershed’s transporting stream channel further define transmission of risk to downstream HVRAs. Terrain and weather dictate the occurrence of saturated soil conditions required to initiate a debris flow, whereas channel form allows the debris flow conveyance (Ice, 2004; Williams et al, 2016; Staley et al, 2017). Haskill Basin is a high-mountain stream of high gradient; such streams exhibit high debris flow potential post-fire (Staley, 2010). Identifying deposition zones for floodplain or debris flow sediment attenuation is important to understanding risk conveyance from the fireshed to downstream HVRAs, such as culverts and bridges.

Stream channels may restructure due to post-fire runoff events (Ice, 2004; Moody and Kinner, 2006; Rust, 2009; Poff et al, 2010; Wohl et. al., 2015). In a fire excluded landscape, the stream channel is more prone to incising and floodplain disconnection post-fire (Ice, 2004; Moody and Kinner, 2006; Hohner et al, 2019). Hydrograph routing will change: the same storm pre- and post-fire will exhibit higher amplitude and faster discharge for the burned area dependent on canopy loss (Sun et al, 2019). This direction of study may be the next step to discerning critical hydrologic alteration limits (potentially a risk assessment endpoint as required by EPA (1998) framework), and understanding fire ecology and watershed processes.

Succession

Forest soils are usually very poor (Byram, 1959; Pritchett and Fisher, 1979). Loss of the organic horizon by pyrolysis and erosion holds great effect on the timeline for forest succession (Cerda and Robichaud, 2009). Fire-impacted, eroded mineral soil landscapes can promote invasive species spread before recolonization by native species occurs (Allen et al, 2006). Erosion affects the ability for forest soils to aid in succession of plant and timber resources to support other ecosystem services and cultural use (Pritchett and Fisher, 1979). Succession is not investigated as an erosion control mechanism in this study, though successional changes in species composition affect erosion rates (Silins et al, 2009; Rust et al, 2018). Succession may be affected by trends such as climate change (Sankey et al, 2017).

Successional thresholds can be related to soil burn severity, hydrophobicity, and slope angle. Succession-altering ecological limits are similar to debris flow analysis, in that existing seed banks are often well-established to greater than 5-cm soil depth (Ice, 2004; Hohner et al, 2019). Haskill Basin is at low risk for succession impacts by erosion due to land cover being dominated by mature xeric forest with an inherent seedbank.

The Fire

The pre-fire ERA for hillslope erosion requires a predicted fire effects distribution. For the watershed, fireshed and storm, a design “severe” wildfire is also necessary. This fire occurs at Energy Release Component (ERC, a fuel combustibility measure) of 97th percentile and severe fire weather conditions, typical of a “Red Flag Warning” fire weather day (NWCG, 2014). The fire ignition location and Julian timing are added factors within the risk assessment (usually, a fire occurring in late August in the Rocky Mountains burns faster and larger than a fire starting in mid-June) (NWCG, 2014).

Wildfire point risk is a function of asset susceptibility to burning, the likelihood of a wildfire, and the intensity of wildfire and its first order effects (Scott et al, 2013). Fire severity is often measured by the extent to which foliage is stripped from the landscape, the extent to which litter on the forest floor is consumed, and the amount of mineral soil exposed to future precipitation events (NWCG, 2014; Sankey et al, 2016). On average, about 30% of a large wildfire area burns with severe intensity, defined as exposing mineral soil in over 70% of previously canopy-covered area (NWCG, 2014). This exposed mineral soil is at the highest risk for erosion due to removal of the intercepting canopy vegetation (Miller et al, 2011).

Ignition Location

Risk Assessment by Ignition Location (RAIL) is critical to understanding a fireshed development for a given ignition point (Thompson et al, 2015). For a zone defining expected ignition points (such as along an electrical network), Monte Carlo probability factoring of weather and fuels simulates many thousands of fires (Scott and Thompson, 2015). The effects for each of these fires are rank-ordered by magnitude (size and burn severity by area) and weighted by expected positive or negative effects to HVRAs and ecological values. RAIL is useful to assess relative risk to specific HVRAs in context to weather input in order to understand fire spread variation for the same ignition location (Scott et al, 2013; Scott and Thompson, 2015). For Haskill Basin, a typical at-risk ignition zone of 10-m from roads is appropriate for RAIL analysis, as well as 50-m on either side of ridgetops, which are prone to lightning (RDG, 2007; Thompson et al, 2012).

Soil Burn Severity

Soil burn severity (SBS) contributes to chemical changes in soils and how a soil particle interacts with water (Cerda and Robichaud, 2009). SBS cannot be accurately predicted pre-fire, yet is arguably the greatest indicator of soil property alteration leading to increased erosion risk and nutrient load supplied to the stream (Cerda and Robichaud, 2009; Larsen et al, 2009; Robichaud et al, 2010). Hydrophobicity effects are a function of vegetation, depth of a duff layer, burn intensity, and the parent material of the soil (and probability for chemical pyrolysis effects) (Debano, 1981; Curran et al, 2006; Moody and Kinner, 2006). Infrared heat maps of the fire add real-time calibration of SBS prediction equations. Patterns of hydrophobicity within a fireshed are not well understood though there is loose correlation between overall soil hydrophobicity, soil type and depth, initial soil moisture content, and overall fire intensity (Debano, 1981). SBS is also roughly incorporated into the pre-fire erosion risk assessment through spatial analysis of fuel load and ERC on at-risk hillslopes using LANDFIRE data, though pre-fire vegetation patterns are not indicative of post-fire SBS (Robichaud et al, 2010; Thompson et al, 2012).

I found that pre-fire SBS prediction is a very nebulous topic with low-confidence prediction capabilities by current modeling techniques. Once a fire has started, SBS assessment becomes much easier. Haskill Basin pre-fire SBS is developed using Mean Fireline Intensity (MFI- BTU/sec/ft) mapping for a direct relationship with SBS.

The Storm

A hypothetical storm using precipitation thresholds for erosion and local climate data is an added probability; storm timing post-fire is an added weight. The exceedance probability of this storm adds further risk interpretation (e.g., the ERA difference for a 50-yr storm occurring twenty days post-fire and a 100-yr storm occurring ten days post-fire is important). Annual timing of the storm is also important: erosion effects are most severe in years one and two, and by year five have often returned to pre-fire rates due to revegetation of exposed mineral soil areas (Robichaud and Elliot, 2006).

Ten-minute rainfall intensity (I_{10}) is the parameter for scour of unprotected soil (Robichaud et al, 2010). Regional variation in precipitation expectation and seasonality informs both fire behavior models and erosion prediction. A 50-yr storm event with I_{10} values of 35mm/hr marks the threshold for erosion response within a watershed in the northern Rocky Mountains (Miller et al, 1973). Erosion response further depends on geomorphology; erosion response is not a binary metric.

The storm is the critical driver for erosion prediction. For example, a hillslope in the Rocky Mountains 60-m long and 20° slope or greater with 70% canopy cover loss due to wildfire will produce large sediment yields from overland channeling when a 10-yr storm withI_{10} of greater than 44 mm/hr occurs (Miller et al, 1973; Miller et al, 2011; Staley et al, 2012; Moody and Martin, 2015; PRISM, 2019). A high SBS, clay-loam dominant hillslope of these characteristics and 40% rock fragment percentage by soil volume (a texture metric) exhibits a sediment yield of 15-23 t/ha/yr under unvegetated conditions and exposed to an annual precipitation regime including at least one such 10-yr storm (Miller et al, 2011; Sankey et al, 2016; Sankey, 2018).

Timing

The ERA must also reference the timing of exposure or threat potential (EPA, 1998; Thompson et al, 2012). Erosion risk is greatest immediately after wildfire and before plants establish in the burned areas; precipitation events initiate debris flows and significant stream channel morphological changes (Ice, 2004; Moody and Kinner, 2006; Robichaud and Elliot, 2006; Moench and Fusaro, 2008; Staley, 2010). Climate change affects regional fire regimes and successional processes (Lentile et al, 2007). Seasonal flow regimes or seasonally frozen ground alter water quality response to precipitation events (Poff et al, 2010; Rhoades, 2015).

EXPOSURE ASSESSMENT

Exposure assessment for an event set of possible outcomes is accomplished through modeling environmental phenomena. Models allow land managers to avoid costly ground-truthing to plan risk mitigation projects more economically. I use several models to interpret the Haskill Basin watershed for erosion-prone hillslopes and for fire effects. I use a modeled storm century to predict storm event likelihood on fire-impacted areas. I leave the erosion characterization of assessed spatial fire and storm risk open for interpretation, as would be presented to a land manager, though I present an example total risk analysis tool, the Total Risk Quotient (TRQ), for procedural purposes.

Models and Datasets

The U.S. Forest Service Rocky Mountain Research Station has created many models for fire behavior and erosion prediction. I used these models to provide an example erosion risk assessment for Haskill Basin. Input data sources for western United States hillslopes and watersheds include comprehensive LANDFIRE (LF, landfire.gov/) fuels assessment datasets of varying resolution, the National Land Cover Dataset (NLCD) (USGS, mrlc.gov) of sixteen land cover classes at 30-m resolution, SoilWeb (casoilresource.lawr.ucdavis.edu/gmap/) soil characterization at 30-m resolution, and

Parameter-elevation Regressions on Independent Slopes Model (PRISM, prism.oregonstate.edu/) climate data at 1.0-km resolution.

A pixel-based raster of fuels within a watershed, climate data, geomorphic factors, and fire behavior is accomplished using the framework that was developed for quantifying invasive species threat over spatially explicit extents (Allen et al., 2006). Assigning a value currency to HVRAs and their location within the raster set creates a spatial threat-value map (Thompson et al, 2012; Scott et al, 2015). Modeling expected scenarios for distribution of effects is accomplished by forcing of known (high confidence) behavior effects, such as crown fire, as well as likely ignition points (RAIL analysis). For example, human-caused fires tend to start along arteries of human movement, whereas naturally caused fires tend to start along lightning-prone ridgetops (Thompson et al, 2015). Scott et al (2015) introduces Monte Carlo tailoring for exposure analysis and exceedance probability ranking to tabulate risk within an event set of fires for a range of probable fire weather conditions. Tailoring may also be accomplished by designing a worst-case scenario wildfire and modeling the effects distribution. The event set of fires is layered with an event set of probable 10-yr precipitation events to understand distribution of erosion effects by fire (Miller et al, 2011; Thompson et al, 2012; Staley et al, 2017; Wilson et al, 2018).

Watershed

I ran the models for Haskill Basin. Characterized by the LANDFIRE data set, Haskill Basin is approximately 80% mature forest, 12% shrubland, 4% open grass, and 4% unburnable water/rock/road. Basin soils characteristics range from Cirqueland-Entic

Cryandepts to Andeptic Cryoboralfs, with some hard rock outcroppings. The Geographic Watershed Erosion Prediction Project (GeoWEPP) tool identifies 436 hillslopes greater than 0.25ha (Figure 5)and of these 167 are greater than 30% slope and support mature forest cover, thus increasing potential for severe soil burn severity by wildfire. Fire has been excluded in Haskill Basin since at least 1920 and the Flathead National Forest of which it is a part supports a 100- to 200-yr stand replacing fire regime, according to the LANDFIRE fire history data set. I determined that unburned Haskill Basin is at higher risk for fire than other recently burned basins. Stand replacing wildfire exhibits widespread severe fire effects (NWCG, 2014).

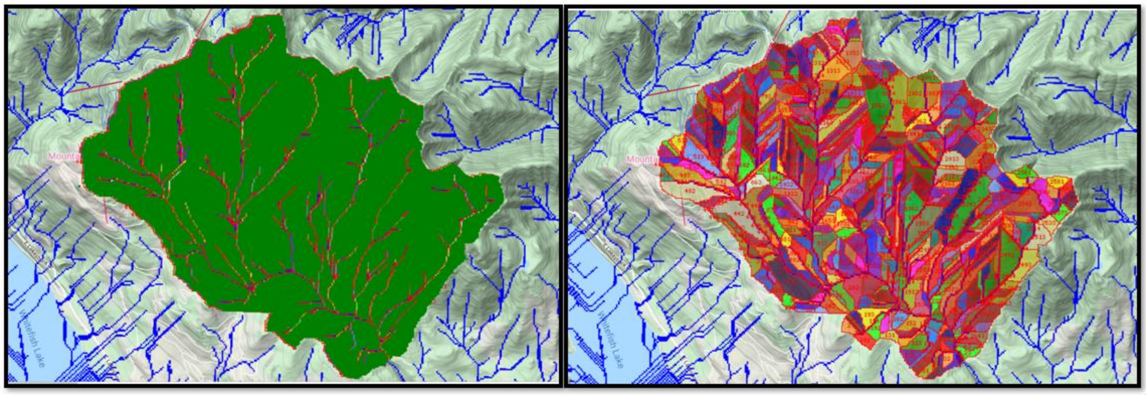


Figure5: GeoWEPP channel delineation for Haskill Basin (left) and GeoWEPP hillslope development for Haskill Basin (right) using 60m minimum slope length and 0.25ha minimum hillslope area.

My fire behavior investigation for Haskill Basin Watershed uses the 97thpercentile ERC values provided by National Wildfire Coordinating Group and InciWeb Fire Information System (Figure 6), Foliar Moisture Content of 85%, and likely wind inputs of 15mph from the southwest. These conditions define severe wildfire potential for the Flathead National Forest. Typical fuel conditioning includes1-hr fuel moistures of 15%, 10-hr fuel moistures of 30%, and 100-hr fuel moistures of 40%, all required inputs for fire behavior models. Regional ERC maps of the format from Figure 6 show Julian date of fire likelihood and duration of conditions for major fire spread, incorporating the timing variable missing in this risk assessment thus far. By Figure 6, this timing variable may be understood as the period from July 20 to August 10.

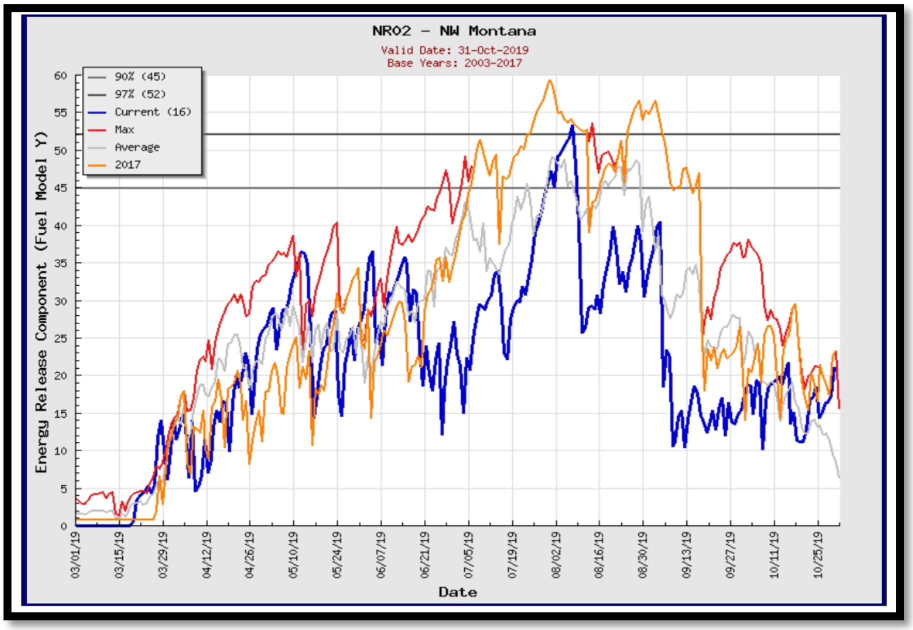


Figure6: ERC for 97th percentile MT-Flathead National Forest, showing fuel moisture conditioning and expected Julian date of fuels availability to large fire growth and behavior, and fuels conditions of extreme fire years, in this case 2017 (from InciWEB.gov and NWCG, 2014)

Fire

The Interagency Fuels Treatment Decision Support System Landscape Burn Probability (IFTDSS LBP) fire model I used predicts a maximum pixelated (30-m raster) burn probability in Haskill Basin of 0.0282, which is high relative to the national average of 0.015 (Scott and Thompson, 2015). Thus, these areas of Haskill Basin have about a

3% chance of burning in any given year. These areas are the eastern, heavily-timbered ridges of Haskill Basin and burn probability distribution is shown in Figure 7.

The LBP model creates many thousands of fires for the watershed. Scott et al. (2012) describe the least likely, highest magnitude (acres burned) fire by rank 1/*n* in the risk aggregation by event set. Fire behavior models, for a random ignition point within the watershed, suggest fire effects distribution for input weather forecasts, calculated on a pixel-based spread model. Such a raster is important for hydrograph routing; canopy-clearing, severe wildfire significantly alters the hydrology of a watershed (Silins et al, 2009). I did not add the additional models and uncertainty of hydrograph routing for a severely burned Haskill Basin watershed.

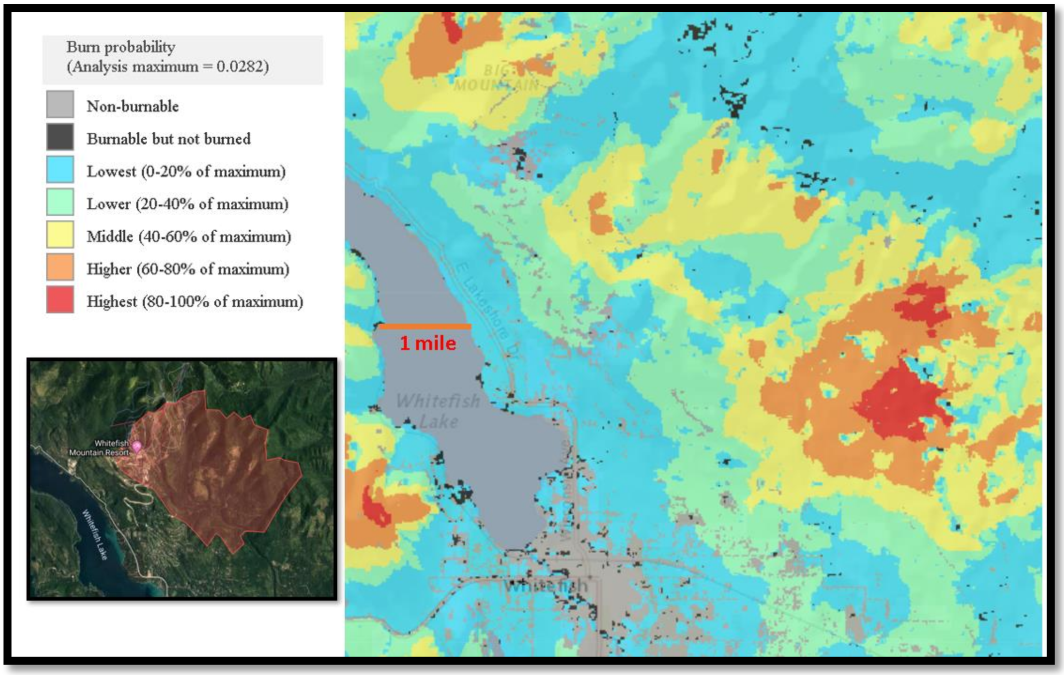


Figure7: Landscape Burn Probability for areas around Whitefish Lake, MT, and including Haskill Basin, MT. IFTDSS LBP graphic, maximum LBP = 0.0282.

Fire behavior models BehavePlus and FlamMap6.0 produce fire behavior predictions. Haskill Basin as modeled in FlamMap6.0 shows high Mean Fireline Intensity of over 5,000 BTU/ft-sec for most of the watershed. Modeled flame lengths are maximum 6-8ft within these same areas. Fire behavior models demonstrate the significance of certain input variables; for instance, crown fire likelihood is highly controlled by input wind direction.

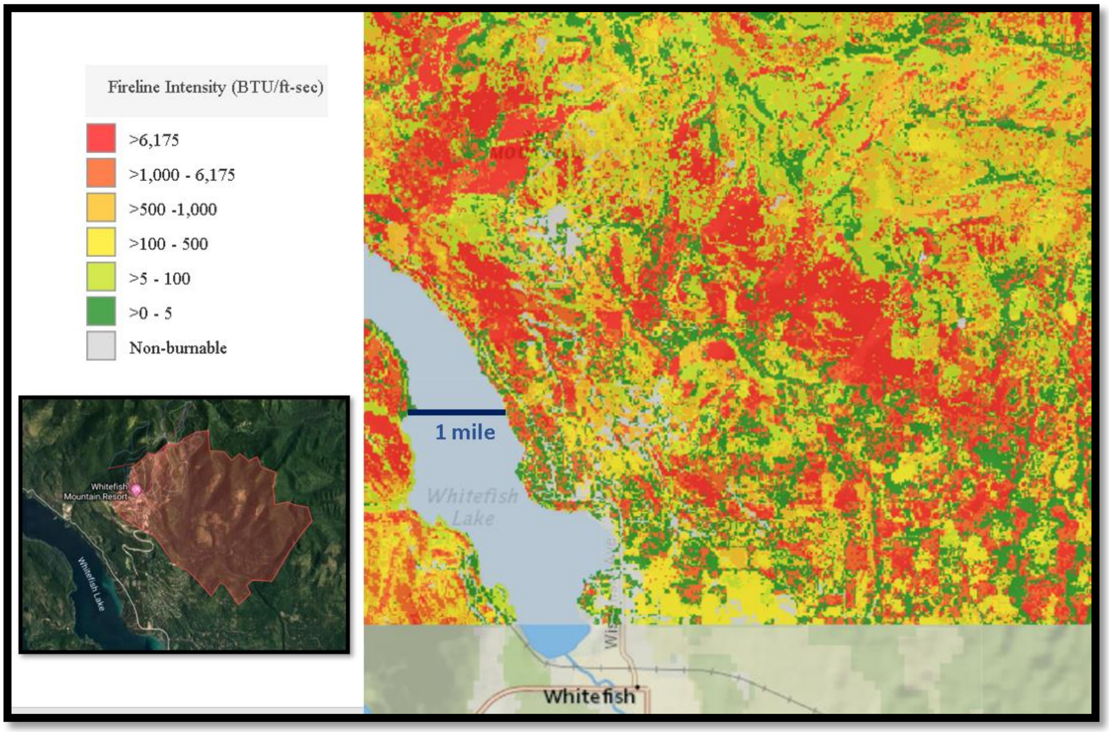


Figure 8: FlamMap6.0 graphic (ERC 97th percentile) Mean Fire Intensity (BTU/ft-sec) produced by Severe Fire Potential conditions and no prescribed management action in Haskill Basin Watershed. Mean Fireline Intensity may be a predictor for SBS.

Fire behavior is not directly related to burn probability (Figures78). The distribution for fire rate of spread has little correlation with burn probability. Mean Fireline Intensity is an estimation of SBS mapping post-fire using the assumption of a direct relationship with SBS. Fire behavior changes through the landscape with topography and fuels; several representative fire behavior examples are rate of spread, crown fire activity, heat per unit area, and fireline intensity (Figure 9).

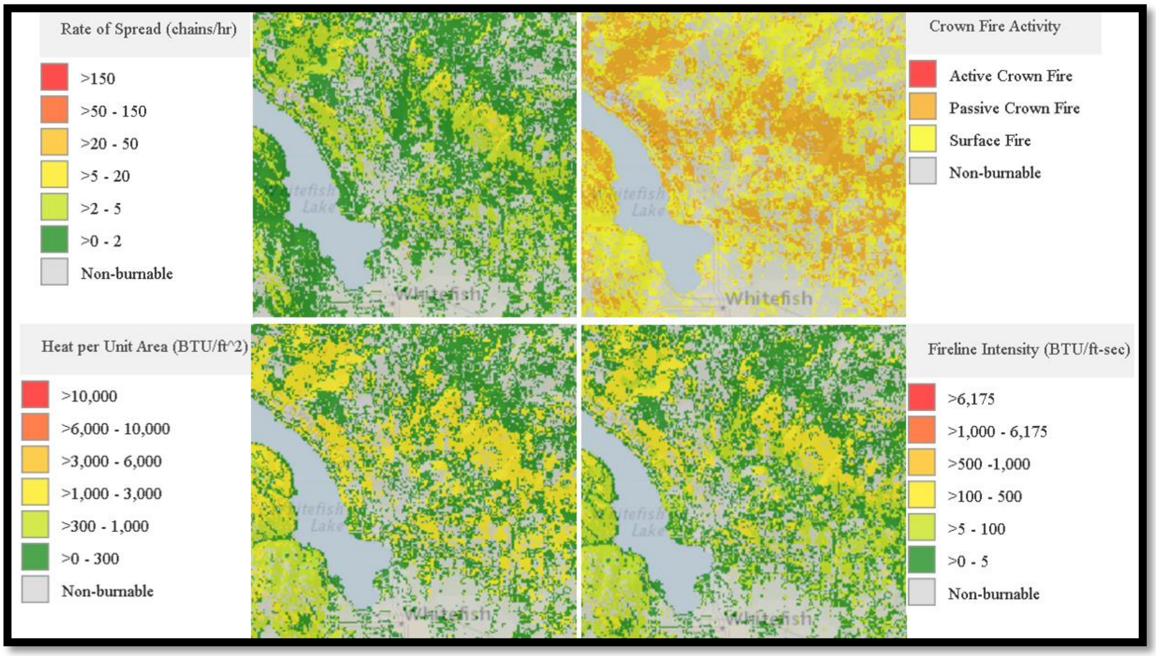


Figure 9: Composite output of Landscape Fire Behavior model provided by IFTDSS showing unique fire behavior metrics that inform fire effects distribution on the soils and hillslopes of the watershed. For ERC 97th percentile, Haskill Basin shows relatively low fire effects severity using the suggested severe fire and fuels model inputs.

Conditional flame length is a weather-dependent variable displaying fire response to fuel and topographical alignment. Conditional flame length for Haskill Basin for a typical southwest wind event day is displayed in Figure 10. Integrated risk by LBP is the composition of burn probability and conditional flame length, and the distribution of high-risk areas is important for RAIL analysis and HVRA susceptibility. Integrated risk mapping for Haskill Basin is displayed in Figure 11.

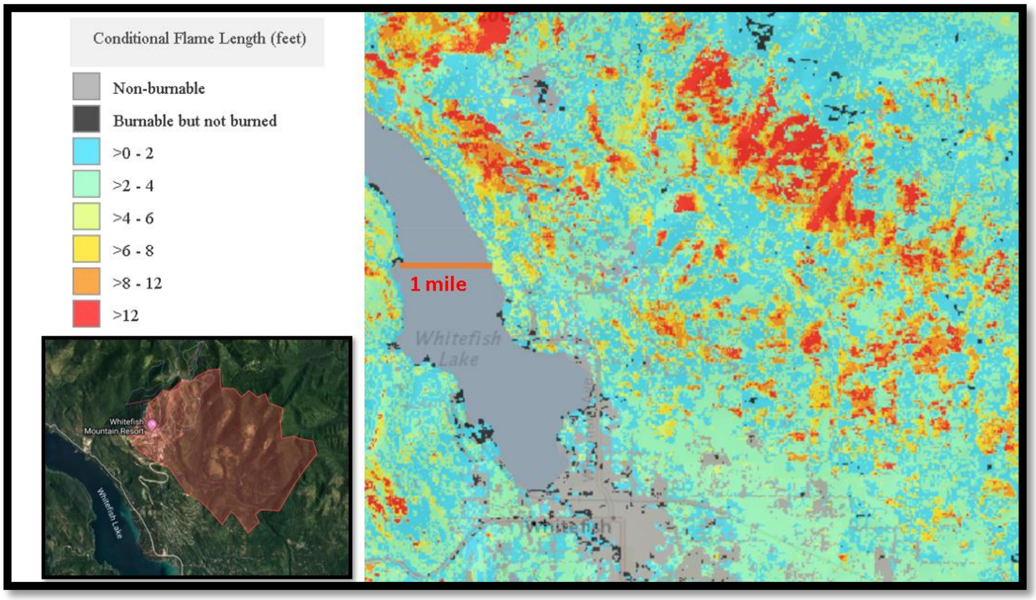


Figure 10: Landscape Burn Probability Model Conditional Flame Length output, informing a similar aggregate risk by fire effects distribution when layered with soil characteristics mapping and hillslope geomorphic factors.

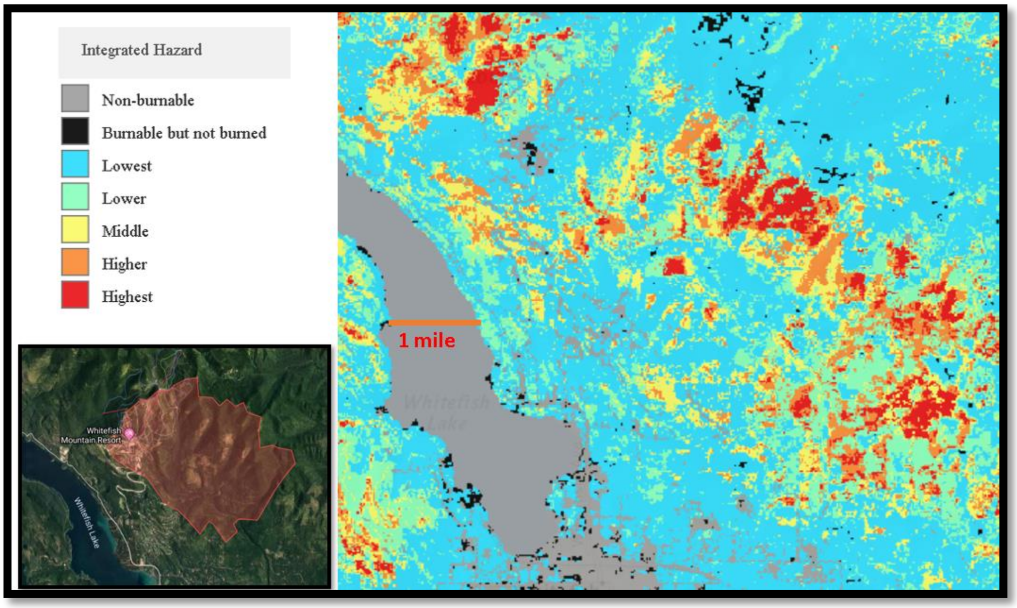
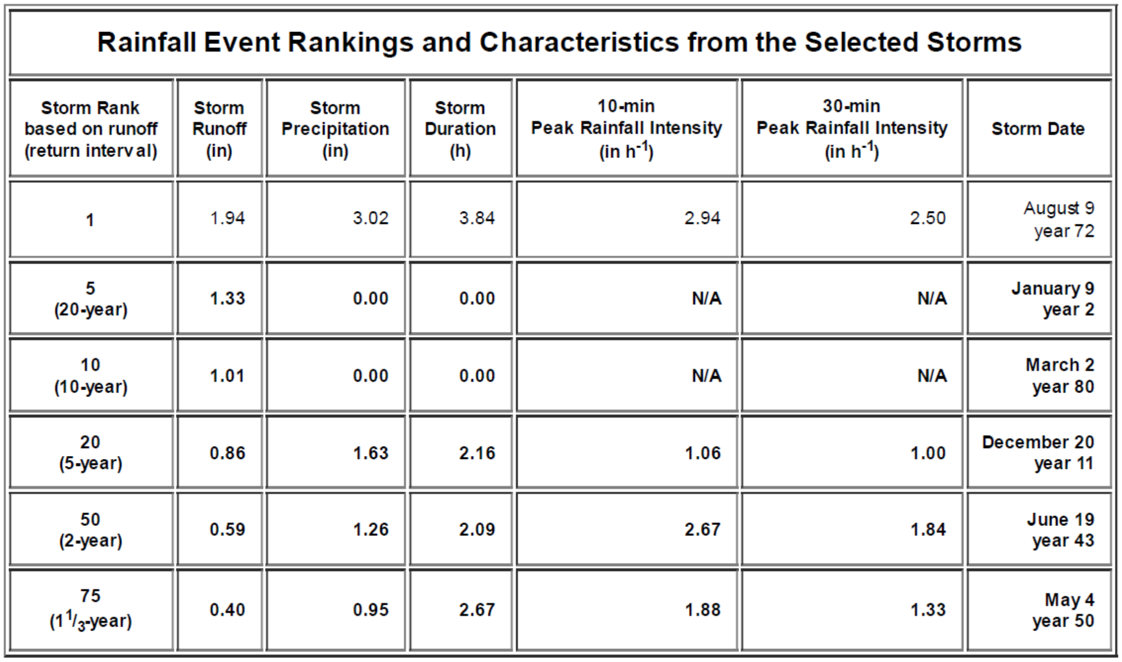


Figure 11: Landscape Burn Probability Integrated Hazard model output for Haskill Basin Watershed. Flame length, mean fireline intensity, and burn probability and severity of effects distribution collectively describe the integrated hazard model.

Storm

Using GeoWEPP, PRISM, and the Kalispell Airport RAWS, the Erosion Mitigation tool ERMiT predicts an event set of storms for 100 years at Haskill Basin. Land managers can reach consensus on what is acceptable risk within the landscape (i.e., using the 20-yr storm intensity rather than the 50-yr) in designing risk mitigation projects for the watershed. In this ERMiT output for Haskill Basin, that would entail designing for a 1.06in/hr I_{10} rather than 2.67in/hr (Table 1).

Table 1: Haskill Basin storm century probability event set, by ERMiT, using the KALISPELL AB RAWS at Kalispell Airport. Local I_{10} values and storm probability are important for erosion prediction. ERMiT event rankings do not exhibit event location properties. Multiple ERMIT runs further refine predictive set quality.



Rainfall Event Rankings and Characteristics from the Selected Storms

Storm Rank based on runoff (return interval)	Storm Runoff (in)	Storm Precipitation (in)	Storm Duration (h)	10-min Peak Rainfall Intensity (in h^{-1})	30-min Peak Rainfall Intensity (in h^{-1})	Storm Date
1	1.94	3.02	3.84	2.94	2.50	August 9 year 72
5 (20-year)	1.33	0.00	0.00	N/A	N/A	January 9 year 2
10 (10-year)	1.01	0.00	0.00	N/A	N/A	March 2 year 80
20 (5-year)	0.86	1.63	2.16	1.06	1.00	December 20 year 11
50 (2-year)	0.59	1.26	2.09	2.67	1.84	June 19 year 43
75 ($1^1/_3$-year)	0.40	0.95	2.67	1.88	1.33	May 4 year 50

A major assumption is incorporated if it is assumed that rainfall intensity over the fireshed is evenly distributed. I found that this assumption is often made in the literature, especially in the case of debris flow analysis. This is an example of incorporated conservatism in the risk assessment. I created my risk characterization tool, the TRQ, to help understand the scenario when a watershed is not completely burned, nor a storm completely inundated the fireshed. An example of this more reality-based situation may be seen in Figure 12, a partially-burned Haskill Basin and partially-inundated fireshed.

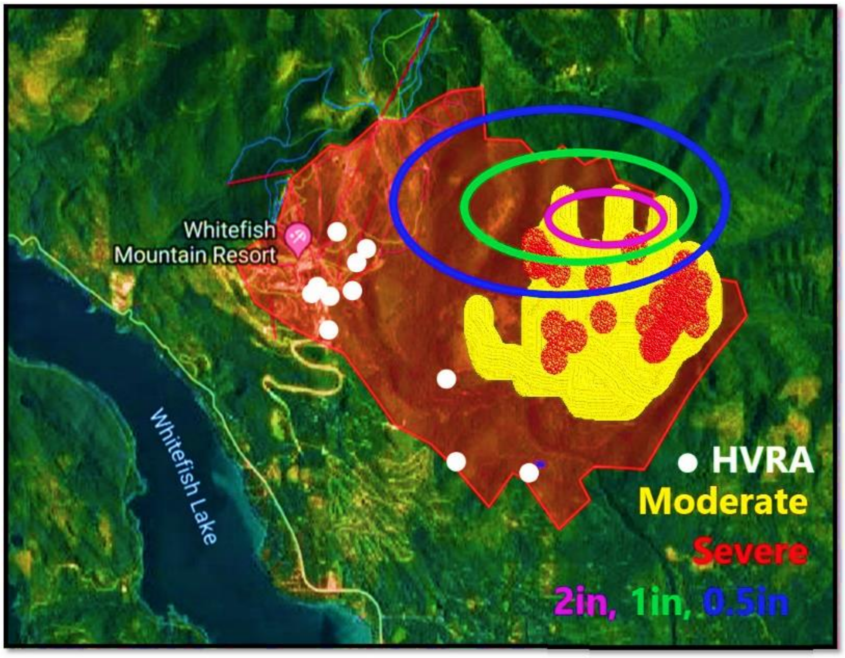


Figure 12: An example of a partially-burned Haskill Basin and partially inundated fireshed by a ca. 50-yr storm. The implications of this real-world scenario on hydrograph routing, HVRA impact, and watershed management may be resolved in the Total Risk Quotient developed in Risk Characterization.

Threshold Development and Models Summary

Using the 50-yr storm as a threshold for succession alteration and debris flow propagation in year one post-fire, a 20-yr storm for sedimentation effects, and a severe wildfire stripping over 70% of the canopy in over 30% of Haskill Basin at-risk hillslopes, hydrograph routing and sediment yield are the next modeling steps. I have assumed that water quality and ecotoxicity are not an issue in Haskill Basin. Threshold development is a good point in risk assessment procedures for land managers to assess for endangered species implications. The limiting threshold overall governs risk management.

The Landscape Burn Probability model provides an integrated risk distribution for Haskill Basin. The FlamMap6.0 model provides an analogue for soil burn severity mapping. GeoWEPP provides a geomorphic breakdown of the watershed. ERMiT provides rainfall intensity for erosion threshold development for the soil type given by GeoWEPP. The location of HVRAs, hydrograph routing by each hillslope, and sediment yield by hillslope for each hypothetical storm in the precipitation event set all contribute to the risk at each point in the watershed.

Total Risk

I define total erosion risk as the sum of background soil erosional processes, erosion effects by wildfire and weather, and the effects of management decisions for erosion. The Wildfire Management Continuum (Figure 13) represents the real-time problems facing land managers. Total risk analysis provides land managers with trigger points for management action. The Total Risk Quotient (TRQ) provides consistent units to clearly compare disparate protection and resource objectives within one currency system, satisfying EPA (1998) endpoints for risk assessment. The TRQ example is developed in the next chapter.

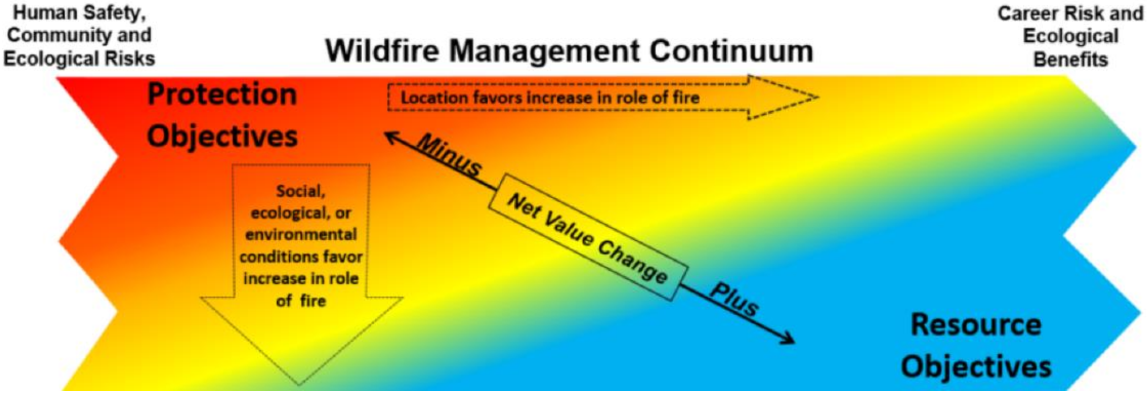
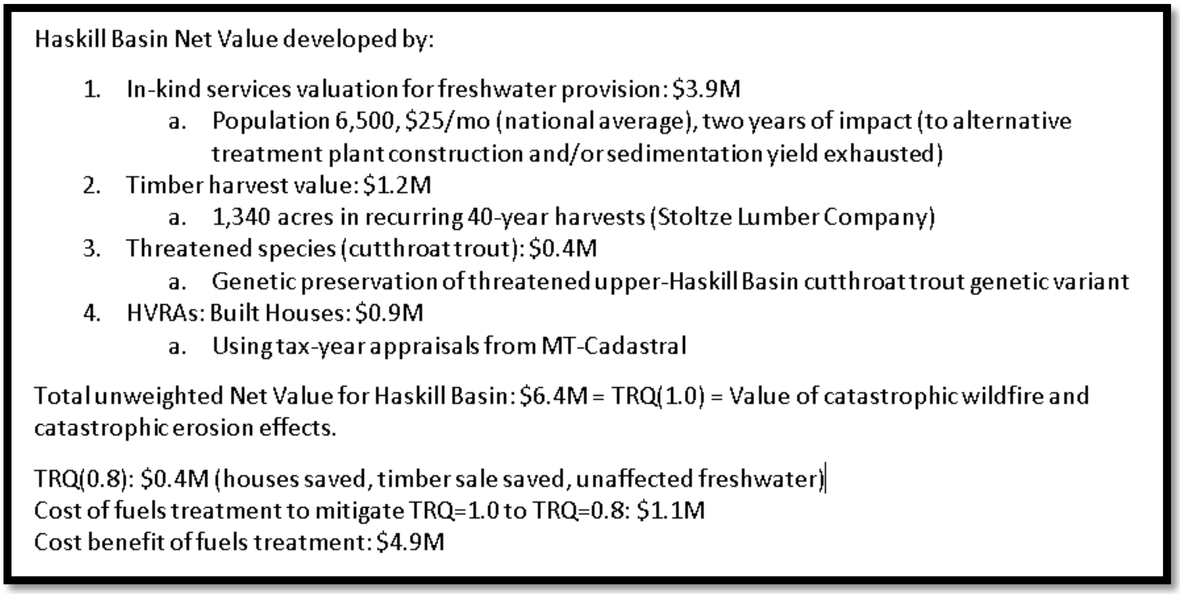


Figure13: The Wildfire Management Continuum, from Thompson (2016). The continuum enforces the give-and-take complexity of emergency decision making. Understanding this continuum allows for more proactive resource management before emergency situations occur. Additionally, risk assessment informs resource triage in the case of wildfire emergency.



Haskill Basin Net Value developed by:

1. In-kind services valuation for freshwater provision: $3.9M
    a. Population 6,500, $25/mo (national average), two years of impact (to alternative treatment plant construction and/or sedimentation yield exhausted)
2. Timber harvest value: $1.2M
    a. 1,340 acres in recurring 40-year harvests (Stoltze Lumber Company)
3. Threatened species (cutthroat trout): $0.4M
    a. Genetic preservation of threatened upper-Haskill Basin cutthroat trout genetic variant
4. HVRAs: Built Houses: $0.9M
    a. Using tax-year appraisals from MT-Cadastral

Total unweighted Net Value for Haskill Basin: $6.4M = TRQ(1.0) = Value of catastrophic wildfire and catastrophic erosion effects.

TRQ(0.8): $0.4M (houses saved, timber sale saved, unaffected freshwater)
Cost of fuels treatment to mitigate TRQ=1.0 to TRQ=0.8: $1.1M
Cost benefit of fuels treatment: $4.9M

Figure 14: Example Value Assessment and TRQ Cost-Benefit Analysis for Management of Risk within a Watershed, Haskill Basin, MT. Values determined from assessment in RDG (2007), national averages for water provision and timber markets and public tax data. Estimated fire objectives and cost ($0.4M) for resource protection are best-estimate values.

Watershed value assessment, in this case, Haskill Basin, is used to understand the economics of risk mitigation. Coupled with the Wildfire Management Continuum (Figure 13), value and value-change through time are factors the land manager must use to maximize the effect and efficiency of management decisions. Haskill Basin, a mixed-use watershed, has a total value driven from several areas: freshwater provision and timber resources provide the majority, and resource protection can be evaluated for cost benefit (Figure 14). Risk assessment provides informed risk characterization when the units of assessment are easy to understand; TRQ development in dollars is best for understanding management effects across disciplines and through time.

RISK CHARACTERIZATION

In the absence of land manager judgment on societal risk management expectations, risk characterization is accomplished by economic analysis of risk mitigation techniques. Atkinson (1999) presents the Fast-Cheap-Good (pick two) dimension of project management (Figure 1); I developed the risk triangle method presented below to understand how these dimensions relate to an ERA point.

I developed the Erosion Risk Triangle to describe the aggregate of three spatial risk variable assessments (Figure 15). For a given pixel, the Erosion Risk Triangle is comprised of A) ranked risk quotient (0-1) for burn probability and severity by RAIL analysis, B) ranked risk quotient (0-1) for soil characteristics and erosion susceptibility, and C) ranked risk quotient (0-1) for design storm and hillslope response. The log-contour plot shows Total Risk Quotient by the center of mass of the Erosion Risk

Triangle (Figure 16). Erosion Risk Triangles may be managed for two sides and still dramatically affect overall TRQ (Figure 16).The economics of hazard contribution and mitigation are understood through the Erosion Risk Triangle geometry (Figure 17).

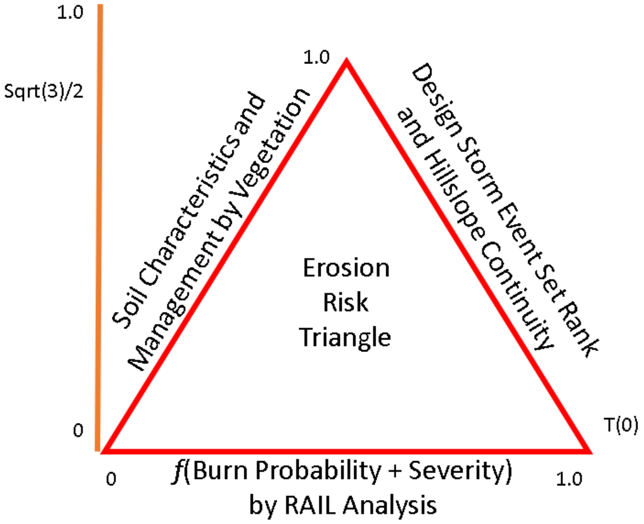


Figure 15: Erosion Risk Triangle and specific development of TRQ by the three ranked risk quotients (0-1). TRQ comes from log-contour mapping the center of mass of the Erosion Risk Triangle produced. Triangle sides are interchangeable.

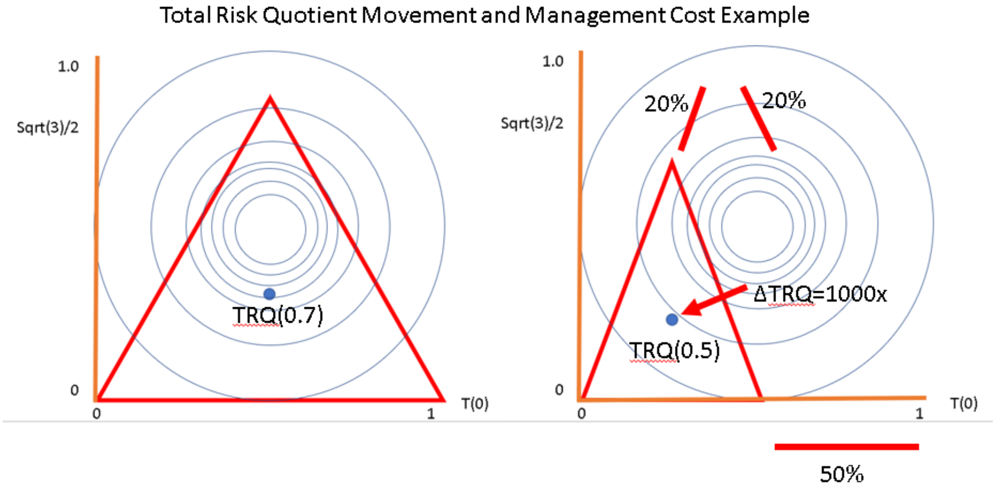


Figure 16: TRQ value, defined by the center of mass of the Erosion Risk Triangle, may be managed away from High Risk using differing strategies affecting each arm of the triangle.

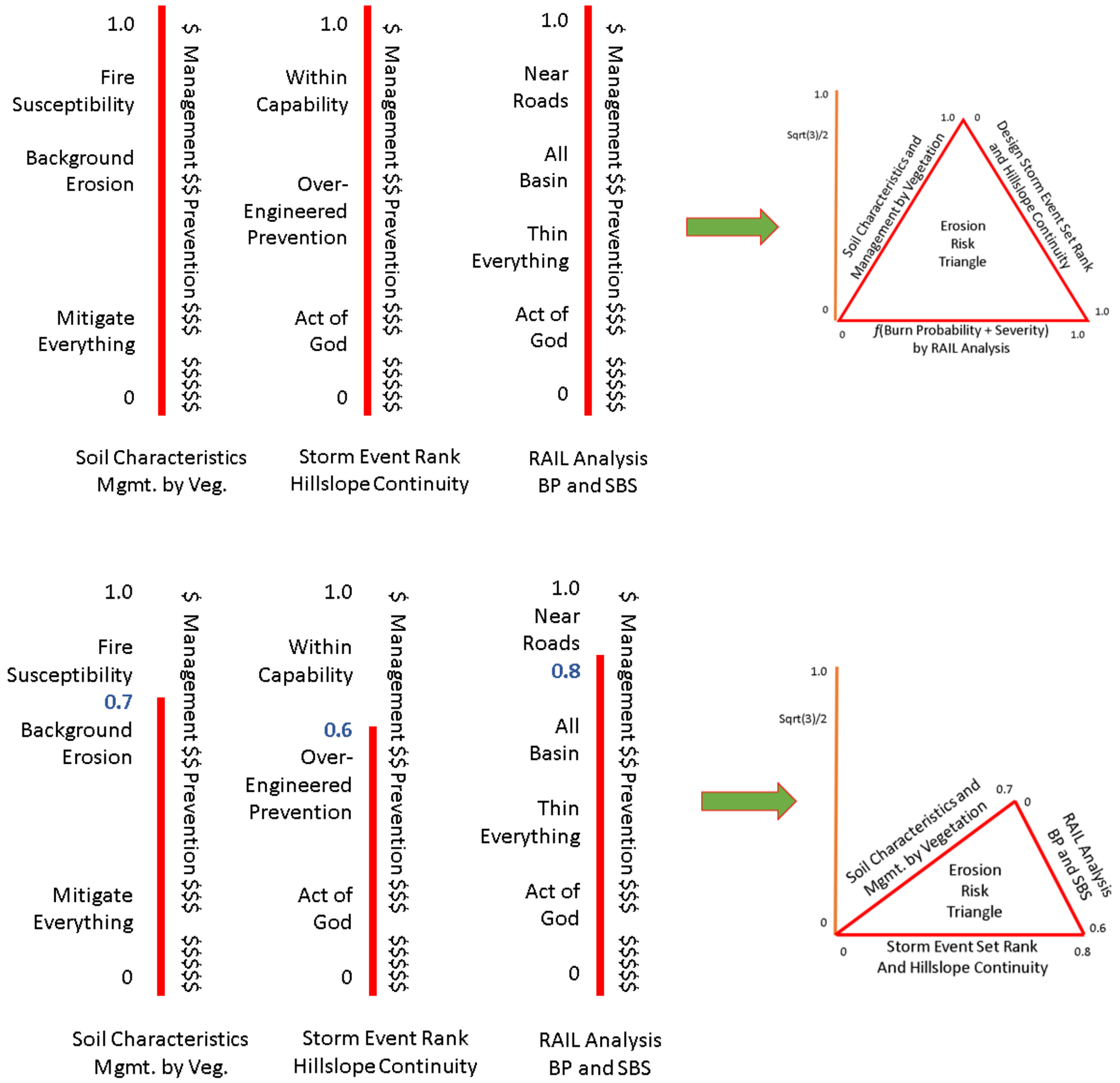


Figure 17: Erosion Risk Triangle interpretation points to the cheapest risk management options for each process affecting each arm of the triangle. The maximum movement of TRQ by the cheapest management options diminishes overall risk in the landscape by point control for risk. The triangle's area is a net risk function; a land manager must recognize the interplay of varying hazards in order to understand total risk in the landscape.

Estimation of Risk: Total Risk Quotient

What is the Total Risk Quotient? The TRQ at a point changes with time and management. Spatially explicit probability distributions, ranked by impact on total value, inform a change in net watershed value (Scott and Thompson, 2015). Erosion risk is characterized by risk to ecological value (quality and resiliency), risk to built value (real dollars), and risk to water quality (in-kind dollars). Contour plotting of risk quotients by erosion susceptibility and burn severity represents tabulated aggregate risk across the pixelated raster for the watershed and fireshed. The reduction of contour slope is the reduction of risk and represents the cost-benefit of risk-mitigating action. This total-watershed map is simplified at a point by the Erosion Risk Triangle and the Total Risk Quotient.

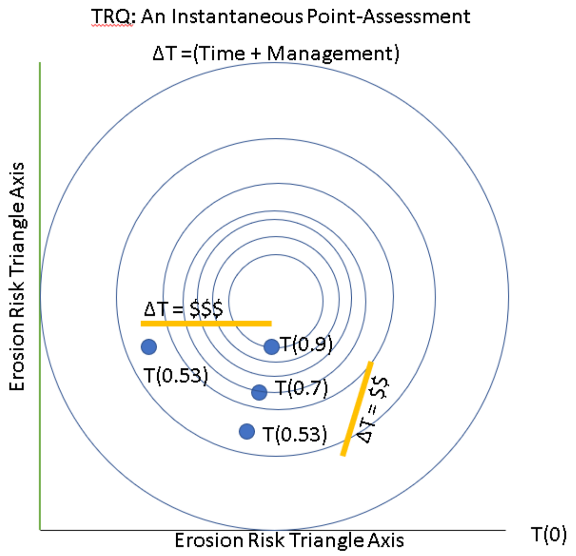


Figure 18: TRQ relationships through time. Economics of decision-making move total TRQ and discern the cost effectiveness of each change by relating total dollar value protected and dollars spent to distance TRQ moved by the Erosion Risk Triangle axis as well as net TRQ overall (log-scale).

By the log-contour plot of TRQ, a TRQ(0.7) is a 1000x decrease in risk effects from a TRQ(0.9) (Figure 18). Note that the log-contour plot does not come to a point at TRQ(1.0), but rather an area, as single-side risk quotients, especially those by ecotoxicity standards, can be larger than 1.0.

There is Extreme Risk for TRQ = 1.0, High Risk for TRQ = 0.9, Moderate Risk for TRQ = 0.8, and Low Risk for TRQ = 0.7 and below. Risk reduction management goals are set to mitigate risk quotients within the Erosion Risk Triangle to manage for TRQ. Assigning a dollar value to fire effects management by TRQ reduction is another possible currency for integrated ERA. Or, a land manager could propose a goal to reduce risk within the landscape by 0.05 TRQ units per year (Figure 19, this would be four years of management to reduce TRQ(0.7) to TRQ(0.5)).I suggest this concept of ecological risk reduction by dollar value as an important element missing from the discussion on risk management in natural systems.

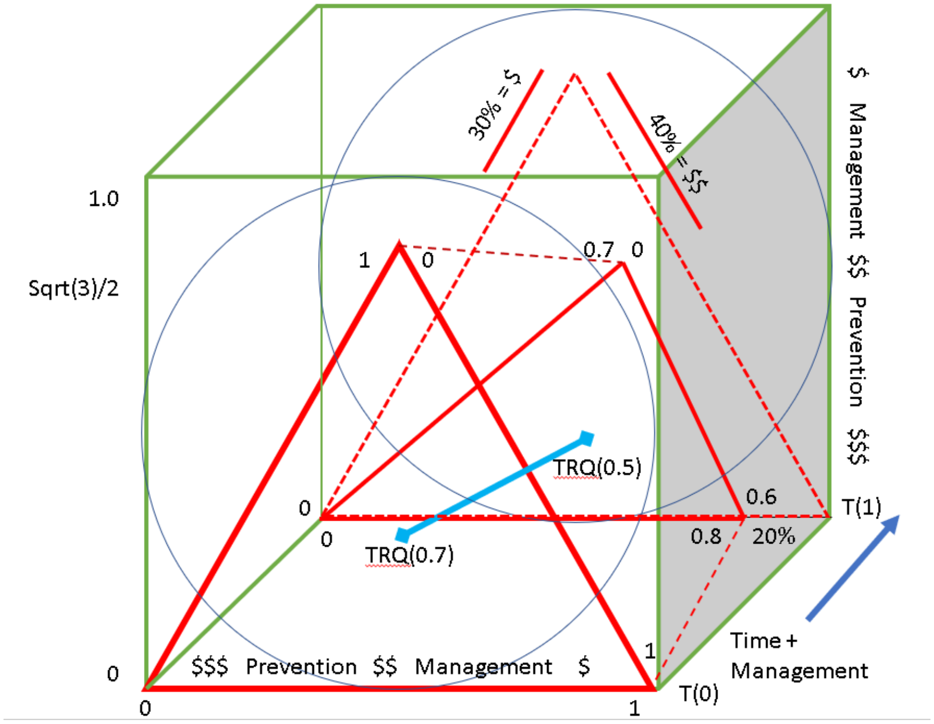


Figure 19: TRQ mitigation through time and with risk management strategy. Note that the slope of Erosion Risk Triangle vertex change represents the (dollar) value of management or "Do Nothing" effects and may not be linear through time. However, relating vertex change line slope for each vertex informs the cheapest option for risk management.

Uncertainty and Variability

A watershed scale raster increases the variance in distribution of contributing and buffering elements for a single quality metric and related risk probability. Major variation is found in four areas: SBS, soil characteristics, weather, and fuels condition. These independent probability distributions each carry inherent uncertainty.

I found the limits to risk development is in assessment of project outcomes. The optimal case is that all assessment variables are objectively quantitative and TRQ development is consistent and comparable. ANOVA for model input variables may assess governing variables to refine pre-fire ERA for hillslope erosion. Consequently, I argue for using ANOVA for post-fire assessment variables as the best technique to refine pre-fire ERA.

Tier Development

Tiers reduce uncertainty (EPA, 1998). A predicted fire tier is important because burn probability and maximum fire behavior are highly dependent on ignition location. A storm tier is important because the hillslope erosion risk assessment can be accomplished for any fire and the storm occurrence is an independent event.

Number of Variables

Ecological health parameters must be comparable to reference sites (EPA, 1998). Relative risk assessments and TRQ development may only be accomplished if sites are described by the same number of explanatory variables (Phelan et al, 2015).

Error and Sensitivity Analysis

Sensitivity analysis is accomplished by referencing changes in boundary conditions for models (Thompson et al, 2012; Scott and Thompson, 2015). Where known limits exist, such as water quality thresholds or seasonal flow averages, the necessity of extra parameters should be examined (EPA, 1998). Social expectation drives risk management; cultural value allocation drives economical decision making (EPA, 1998; Finney, 2005; Scott et al, 2013).

RECOMMENDATIONS AND CONCLUSION

This assessment of hillslope erosion risk from wildfire provides the inputs for a risk characterization tool for understanding risk. I believe this tool is needed to consolidate current prediction models and risk threshold assessments into one universal projection, otherwise the risk characterization doesn't have implied value. Is this the most objective assessment of hillslope erosion risk from wildfire that we can make? No. Bias still exists and natural systems are too dynamic to understand three layers of disturbance probability and outcome. My TRQ concept of risk analysis is important and may help land managers discern between various event thresholds affecting their respective landscapes. I recommend developing a landscape raster and incorporating aggregate risk by event set for fire effects, geomorphic characteristics, and storm effects.

The instantaneous TRQ developed in Risk Characterization does not reflect projected management decision effects. However, the slope of TRQ trajectory by vertex alteration of the Erosion Risk Triangle is a dollar-value savings through time. This measure of future cost savings is a potential bargaining unit for management advocacy; I suggest my TRQ method to discern the potentially negative cost of the “Do Nothing” alternative to risk mitigation in ecosystems

Hillslope Erosion Impact from Wildfire

Strict consideration of solely geophysical properties of watersheds does not sufficiently encompass the variance in ecosystem function that contributes to the occurrence of disturbance events (such as wildfire) and the variation in fire effects (such as erosion potential). The post-fire distribution of erosion potential by fire effects is considered a Tier III Advanced-Quantitative ERA; the prediction of hillslope erosion from wildfire by a storm requires dilution of confidence to a Tier II Semi-Quantitative ERA (EPA, 1998). A fuels assessment without fire behavior modeling or weather inputs is considered a Tier I Qualitative Screening ERA. In light of natural disturbance scope and consequence, as well as the human value systems and perceptions of disturbance as “disaster,” I argue that a more conservative risk assessment declaration is appropriate.

Without calibration, the models suggest limited understanding of conditions governing fire ignition and behavior. For erosion prediction, the expected correlation between pre-fire fuel loading on at-risk hillslopes and modeled effects is driven primarily by fire ignition location and number of burn periods modeled. Fundamental erosion principles and geomorphic prediction are secondary factors to fire effects modeling for hillslope erosion prediction.

Erosion production is still a major focus of this assessment technique. Sediment traps and buffering capabilities are within the capacity of management techniques; in-channel buffering of the sediment produced can effectively limit water quality impacts of post-fire runoff. My assessment technique points to economical risk management decision-making for in-channel erosion mitigation and the cost of total control.

Moving Forward

Land managers can use this synthesis and provided TRQ mapping tool to make proactive, better informed, and more economical decisions. The economics of natural resources and valuation of ecosystem services, coupled with the TRQ tool I suggest, has implication for potential zoning considerations or subsidization of risk mitigation action now at a much lower cost than emergency response.

How can my tool be best used? Clarification of risk identification is required: risk due to natural and human-caused wildfire, risk due to rare meteorological events, and risk considering the value of human activity for a watershed each holds a high degree of uncertainty and weight in a risk assessment. Conservatism in assigning value to undisturbed ecosystem function diminishes the integrity of model predictions: the worst-case scenario is the easiest to predict and has the highest cost, but it is economically infeasible to manage for the worst case. Climate change is another factor changing trends in ecosystem function and erosion likelihood.

Spatially explicit ERA considering more than several independent variables is not objectively feasible; bias exists in ecological assessments for vulnerability prior to natural disturbance (such as wildfire) as well as social and cultural expectations for risk management. I encourage the understanding of intrinsic watershed value in the face of external threat by objective valuation currency and comparable, quantitative assessment and risk characterization techniques.

REFERENCES CITED

Allen, C. R; Johnson, A. R; Parris, L. 2006. *A framework for spatial risk assessments: potential impacts of nonindigenous invasive species on native species*. Ecology and Society,11: 39-54. http://www.ecologyandsociety.org/vol11/iss1/art39/

Atkinson, R. Dec. 1999. *Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria*. International Journal of Project Management, 17: 337-342. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.453.1057&rep=rep1&type=pdf

Burmaster, D; Harris, R. 1993. *The magnitude of compounding conservatisms in Superfund risk assessments*. Risk Analysis, 13: 131-134. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.1993.tb01058.x

Bryan, R. 1979. *The influence of slope angle on soil entrainment by sheetwash and rainsplash*. Earth Surface Processes,4: 43-58. https://onlinelibrary.wiley.com/doi/pdf/10.1002/esp.3290040105

Byram, G. 1959.*Chapters three and four: combustion of forest fuels* in *Forest Fire: Control and Use*, by Kenneth P. Davis, 1959, McGraw-Hill Book Company, NY. https://www.frames.gov/documents/behaveplus/publications/Byram_1959_CombustionOfForestFuels.pdf

Cerda, A; Robichaud, P. 2009. *Fire effects on soil infiltration*. In: Cerda, A.; Robichaud, P. eds. *Fire effects on soils and restoration strategies*. Enfield, NH: Science Publishers: 31-103. https://www.fs.fed.us/rm/pubs_other/rmrs_2000_robichaud_p002.pdf

Cox, Jr., L A; Babayev, D; Huber, W. 2005. *Some limitations on qualitative risk rating systems*. Risk Analysis, 25: 651-662. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.2005.00615.x

Curran, M; Chapman, B; Hope, G; Scott, D. 2006. *Large-scale erosion and flooding after wildfires: understanding the soil conditions*. B.C. Tech. Re. 030. Victoria, B.C. Canada: B.C. Ministry of Forests and Range, Research Branch. 18p. https://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr030.pdf

Debano, L. March 1981. *Water repellent soils: the state-of-the-art*. USDA Forest Service Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-46. https://www.fs.fed.us/psw/publications/documents/psw_gtr046/psw_gtr046.pdf

Elliot, W; Miller, I; Glaza, B. July 2006. *Using WEPP technology to predict erosion and runoff following wildfire*. USDA Forest Service Rocky Mountain Research Station: Soil and Water Engineering Research Work Unit, American Society of Agricultural and Biological Engineers.
https://www.firescience.gov/projects/04-4-1-12/project/04-4-1-12_04_4_1_12_06_elliot_et_al_wepp_widlfire.pdf

Environmental Protection Agency (EPA). 1998. *Guidelines for ecological risk assessment*. EPA/630/R-95/002F. Washington, D.C., USA.
https://www.epa.gov/sites/production/files/2014-11/documents/framework_eco_assessment.pdf

Finney, M; McHugh, C; Grenfell, I; Riley, K; Short, K. 2011. *A simulation of probabilistic wildfire risk components for the continental United States*. Stochastic Environmental Research and Risk Assessment, 25: 973-1000.
https://www.fs.fed.us/rm/pubs_other/rmrs_2011_finney_m002.pdf

Finney, M.2005.*The challenge of quantitative risk analysis for wildland fire*. Forest Ecology and Management,(2)11: 97-108.
https://www.snap.uaf.edu/webshared/JenNorthway/AKFireModelingWorkshop/AKFireModelingWkshp/FSPro%20Analysis%20Guide%20References/Finney%202005%20Quantitative%20Risk%20Analysis.pdf

Hassenzahl, D. 2006. *Implications of excessive precision for risk comparisons: lessons from the past four decades*. Risk Analysis, 26: 265-274.
https://www.ncbi.nlm.nih.gov/pubmed/16492197.

Hohner, A; Rhoades, C; Wilkerson, P; Rosario-Ortiz, F. 2019. *Wildfires alter forest watersheds and threaten drinking water quality*. Accounts of Chemical Research, 52: 1234-1244.
https://www.fs.fed.us/rm/pubs_journals/2019/rmrs_2019_hohner_a001.pdf

Ice, G.2004. *Effects of wildfire on soils and watershed processes.* Journal of Forestry, 102(6): 16-21.
https://www.researchgate.net/publication/233499137_Effects_of_Wildfire_on_Soils_and_Watershed_Processes

Joint Fire Science Program (JFSP), Sun G; Hallema, D; Cohen, E; McNulty, S; Caldwell, P; Robinne, F-N; Norman, S; Liu, Y. April 2019. *Effects of wildfires and fuel treatment strategies on watershed water quantity across the contiguous United States: final report*. Joint Fire Science Program Project ID: 14-1-06-18.
https://www.firescience.gov/projects/14-1-06-18/project/14-1-06-18_final_report.pdf

Larsen, I; Libohova, Z; MacDonald, L; Schaffrath, K. 2009. *Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing?* Soil Science Society of American Journal, 73: 1393-1411. https://www.researchgate.net/publication/242114348_Causes_of_Post-Fire_Runoff_and_Erosion_Water_Repellency_Cover_or_Soil_Sealing

Lentile, L; Morgan, P; Hard, C; Hudak, A; Means, R; Ottmar, R; Robichaud, P; Kennedy-Sutherland, E; Szymoniak, J; Way, F; Fites-Kaufman, J; Lewis, S; Mathews, E; Shovic, H; Ryan, K. July 2007. *Value and challenges of conducting rapid response research on wildland fires*. Rocky Mountain Research Station General Technical Report RMRS-GTR-193. https://www.fs.usda.gov/treesearch/pubs/27666

Mast, M; Murphy, S; Clow, D; Penn, C; Sexstone, G. 2016. *Water quality response to high elevation wildfire in the Colorado front range*. Hydrological Processes, 30: 1811-1823. https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.10755

Matthews, K; Berg, N.1997.*Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools.* Journal of Fish Biology, 50: 50-67. https://www.fs.fed.us/psw/publications/matthews/psw_1997_matthews003.pdf

Miller, M; MacDonald, L; Robichaud, P; Elliot, W.2011. *Predicting post-fire hillslope erosion in forest lands of the western United States*. International Journal of Wildland Fire, 11: 982-999. https://www.fs.fed.us/rm/pubs_other/rmrs_2011_miller_m001.pdf

Miller, J; Frederick, R; Tracey, R. 1973. *Precipitation frequency atlas of the western United States.* National Weather Service, National Oceanic and Atmospheric Administration (NOAA) Atlas Two. https://udfcd.org/wp-content/uploads/uploads/resources/technical%20papers/NOAA_Atlas_2_Precipitation_Frequency_Vol_3_Colorado.pdf

Moench, R; Fusaro, J.2008.*Soil erosion control after wildfire*. Forestry: Natural Resources Series, 6(308). http://extension.colostate.edu/docs/pubs/natres/06308.pdf

Moody, J; Martin, D. 2009. *Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States*. International Journal of Wildland Fire, 18: 96-115.https://pubs.er.usgs.gov/publication/70032717

Moody, J; Ebel, B. 2014. *Infiltration and runoff generation processes in fire-affected soils*. Hydrological Processes, 28: 3432-3453. https://www.researchgate.net/publication/261376837

Moody, J; Kinner, D. 2006. *Spatial structures of stream and hillslope drainage networks following gully erosion after wildfire.* Earth Surface Processes and Landforms, 31: 319-337. https://pubs.er.usgs.gov/publication/70030369

Moody, J, Martin, R. 2015. *Measurements of the initiation of post-wildfire runoff during rainstorms using in situ overland flow detectors*. Earth Surface Processes and Landforms, 40: 1043-1056. https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.3704

National Research Council (NRC). 1983. *Risk assessment in the federal government: managing the process*. Washington, DC: The National Academies Press. https://doi.org/10.17226/366

NWCG Fire Environment Committee.2014. *Fire behavior field reference guide*. BLM National Wildfire Coordinating Group: Publication NWCG PMS 437. https://gacc.nifc.gov/oncc/docs/FBFRG_2014.pdf

Phelan, J; Jones, P; Matthews, K. 2015. *Montana prairie wetlands and intermittent and ephemeral streams: hydrologic needs assessment for healthy watersheds.* RTI International, Project Number 0213541.004.001.004 for the US EPA. https://www.epa.gov/sites/production/files/2015-11/documents/151016mt_final_report_july2015.pdf

Poff, L; Richter, B; Arthington, A; Bunn, S; Naiman, R; Kendy, E; Acreman, M; Apse, C; Bledsoe, B; Freeman, M; Henriksen, J; Jacobson, R; Kennen, J; Merritt, D; O'Keeffe, J; Olden, J; Rogers, K; Tharme, R; Warner, A. 2010. *The ecological limits of hydrologic alteration (ELOHA): anew framework for developing regional environmental flow standards.* Freshwater Biology, 55: 147-170. https://pubag.nal.usda.gov/catalog/380115

Pritchett, W; Fisher, R. *Properties and Management of Forest Soils.* Wiley and Sons, 512 pages. New York, NY. 1979. ISBN-13: 978-0471895725

Rhoades, C; Chow, A; Covino, T; Fegel, T; Pierson, D; Rhea, A. 2018. *The legacy of a severe wildfire on stream nitrogen and carbon in headwater catchments*. Ecosystems, 22:643-657. https://www.fs.fed.us/rm/pubs_journals/2019/rmrs_2019_rhoades_c001.pdf

River Design Group (RDG), Inc. 2007. *Haskill basin watershed characterization – final report*. Montana State Department of Environmental Quality. http://montanatmdlflathead.pbworks.com/w/file/fetch/88826789/HaskillCreekWC_2007.pdf

Robichaud, P; Elliott, W. 2006.*Protection from erosion following wildfire*. USDA Forest Service Rocky Mountain Research Station: Soil and Water Engineering Research Work Unit, presented at the proceedings of the American Society of Agricultural and Biological Engineers Conference, July 2006. https://www.fs.fed.us/rm/pubs_other/rmrs_2006_robichaud_p001.pdf

Robichaud, P; Parsons, A; Lewis, S; Napper, C; Clark, J. 2010.*Field guide for mapping post-fire soil burn severity*. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-243. https://forest.moscowfsl.wsu.edu/engr/library/Robichaud/Robichaud2010f/2010f.pdf

Rust, A. 2018.*Wildfire in the west: evaluating water quality and ecosystem impacts and their controlling factors*. Colorado School of Mines and the Joint Fire Science Program, Bureau of Land Management (Award #L14AC00165). https://mountainscholar.org/bitstream/handle/11124/172016/Rust_mines_0052E_11399.pdf?sequence=1&isAllowed=y

Rust, A; Hogue, T; Saxe, S; McCray, J. 2018.*Post-fire water-quality response in the western United States*. International Journal of Wildland Fire, 27: 203-216. https://doi.org/10.1071/WF17115

Sankey, J; McVay, J; Kreitler, J; Hawbaker, T; Vaillant, N; Lowe, S. 2016.*Predicting watershed post-fire sediment yield with the InVest sediment retention model: accuracy and uncertainties.* Department of the Interior Northwest Climate Science Center. https://acwi.gov/sos/pubs/3rdJFIC/Contents/5E-Sankey.pdf

Sankey, J; Kreitler, J; Hawbaker, T; McVay, J; Miller, M; Mueller, E; Vaillant, N; Lowe, S; Sankey, T. 2017. *Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds*. Geophysical Research Letters,44: 8884-8894. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017GL073979

Scott, J; Thompson, M. 2015. *Emerging concepts in wildfire risk assessment and management*. Rocky Mountain Research Station, USDA Forest Service Proceedings RMRS-P-73. https://www.fs.usda.gov/treesearch/pubs/49444

Scott, J; Thompson, M; Calkin, D. 2013.*A wildfire risk assessment framework for land and resource management.* General Technical Report ID: RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://www.fs.fed.us/rm/pubs/rmrs_gtr315.pdf

Shakesby, R; Moddy, J; Martin, D; Robichaud, P. 2016. *Synthesizing empirical results to improve predictions of post-wildfire runoff and erosion response*. International Journal of Wildland Fire, 25: 257-261. https://pubs.er.usgs.gov/publication/70177882

Silins, U; Stone, M; Emelko, M; Bladon, K.2009. *Sediment production following severe wildfire and post-fire salvage logging in the Rocky Mountain headwaters of Oldman River Basin, Alberta*. CATENA, 79(3): 89-197. https://www.sciencedirect.com/science/article/pii/S0341816209000885

Staley, D; Kean, J; Cannon, S; Schmidt, K; Laber, J. 2012. *Objective definition of rainfall intensity–duration thresholds for the initiation of post-fire debris flows in southern California.* Landslides, 10: 547-562. https://pubs.er.usgs.gov/publication/70045135

Staley, D; Negri, J; Kean, J; Laber, J; Tillery, A; Youberg, A. 2017. *Prediction of spatially explicit rainfall intensity–duration thresholds for post-fire debris-flow generation in the western United States.* U.S. Geological Survey Open-File Report. https://pubs.er.usgs.gov/publication/70188478

Staley, D; Kean, J. 2017. *The science and prediction of post-fire debris flows in the western United States.* StreamNotes: The Technical Newsletter of the National Stream and Aquatic Ecology Center, Fort Collins, CO. https://pubs.er.usgs.gov/publication/70198058

Tecle, A; Neary, D. 2015. *Water quality impacts of forest fires*. Journal of Pollution Effects and Control, 3: 140-152. https://www.fs.fed.us/rm/pubs_journals/2015/rmrs_2015_aregai_t001.pdf

Tedim, F; Leone, V; Amraoui, M; Bouillon, C; Coughlan, M; Delogu, G; Fernandes, P; Ferreira, C; McCaffrey, S; McGee, T; Parente, J; Paton, D; Pereira, M; Ribeiro, L; Viegas, D; Xanthopoulos, G. 2018. *Defining extreme wildfire event: difficulties, challenges and impacts*. Fire, 1: 2-28. https://www.mdpi.com/2571-6255/1/1/9

Thompson, M; Haas, J; Gilbertson-Day, J; Scott, J; Langowski, P; Bowne, E; Calkin, D.2015. *Development and application of a geospatial wildfire exposure and risk calculation tool*. Environmental Modeling and Software, 63: 61-72. https://www.fs.usda.gov/treesearch/pubs/47738

Thompson, M; Bowden, P; Brough, A; Scott, J; Gilbertson-Day, J; Taylor, A; Anderson, J; Haas, J. 2016. *Application of wildfire risk assessment results to wildfire response planning in the southern Sierra Nevada, California, USA*. Forests, 7: 64-76. https://www.mdpi.com/1999-4907/7/3/64

Thompson, M; Scott, J; Helmbrecht, D; Calkin, D. 2012. *Integrated wildfire risk assessment: framework development and application on the Lewis and Clark National Forest in Montana, USA.* Integrated Environmental Assessment and Management, 9: 329-342. https://www.fs.usda.gov/treesearch/pubs/44117

US EPA. 2018. *Ground Water and Drinking Water: National Primary Drinking Water Regulations.* Environmental Protection Agency. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

Williams, C; Pierson, F; Robichaud, P; Al-Hamdan, O; Boll, J; Strand, E. 2016. *Structural and functional connectivity as a driver of hillslope erosion following disturbance*. International Journal of Wildland Fire, 25: 306-321. https://www.fs.usda.gov/treesearch/pubs/52120

Wilson, C; Kampf, S; Wagenbreener, J; MacDonald, L. 2018.*Rainfall thresholds for post-fire runoff and sediment delivery from plot to watershed scales*. Forest Ecology and Management, 430: 346-356. https://www.sciencedirect.com/science/article/pii/S0378112717318637

Wohl, E; Bledsoe, B; Jacobson, R; Poff, N; Rathburn, S; Walters, D; Wilcox, A. 2015. *The natural sediment regime in rivers: broadening the foundation for ecosystem management*. BioScience, 65: 358-371. https://academic.oup.com/bioscience/article/65/4/358/254680

Young, T; Sanzone, S. 2002. *A framework for assessing and reporting on ecological condition*. Ecological Reporting Panel of the Ecological Processes and Effects Committee, EPA Science Advisory Board. https://yosemite.epa.gov/sab/sabproduct.nsf/7700D7673673CE83852570CA0075458A/$File/epec02009.pdf