An Investigation into the Potential Impacts of Watershed Restoration and Wildfire on Water Yields and Water Supply Resilience in the Rio Grande Water Fund Project Area

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Executive Summary

The purpose of the study was to investigate the potential changes in water yields and water supply resilience in tributary watersheds of the upper Rio Grande as a result of forest restoration and wildfires with a focus on high-elevation mixed conifer areas. This study focused on the portion of the upper Rio Grande which lies within New Mexico – henceforth referred to as the **NM-URG**. The focus watersheds included the Rio Chama, Upper Rio Grande, Santa Fe, and Jemez basins (Figure 5 and Table 2). This report contains a review of existing literature, data, and models to help guide the Middle Rio Grande Conservancy District (MRGCD) board, The Nature Conservancy (TNC), and Rio Grande Water Fund (RGWF) partners regarding the potential benefits associated with forest restoration in these high-elevation watersheds. Key findings from this study include:

1. Although there is a rich body of research on the topics of wildfire and watershed restoration affects on hydrologic process, very little research has been conducted in high-elevation southwestern forests. Research priorities include improved quantification of forest stand characteristics on snowpack dynamics and water yield and improved predictions for post-wildfire peak flows and debris flows.
2. By extrapolating research findings and practical experience from other parts of the American West, we can conclude the following with a high degree of confidence:
    a. Catastrophic (stand replacing) wildfires will continue to increase in severity, frequency, and area in the NM-URG in the absence of intervention (e.g. watershed restoration);
    b. Water supply reliability is reduced after catastrophic wildfires. The most dramatic impact of wildfires on water supply is associated with severe flooding, sediment loading, and debris flows. Further, water yields are reduced from snowpack following severe wildfires. This is of great concern in the NM-URG where water supply is largely derived from snowpack.
    c. Conversely, watershed restoration will increase water supply reliability – primarily by reducing the risk of catastrophic wildfires, with the additional benefit of a potential increase in water yields.

3. Existing databases describing hydrology, land use/land cover, and meteorology are available at large spatial scales; However, data is sparse at the local scale and especially so in high elevation headwaters – with the notable exception of the Valles Caldera.
4. Historical hydrologic data illustrate substantial annual to decadal variability in precipitation patterns (especially in snowpack) along with tremendous spatial variability across elevation bands. Strong spatial correlations are observed between elevation, precipitation, and land cover type. A remarkably strong temporal correlation was observed between seasonal snowpack conditions and downstream water supply.
5. Although mixed conifer forests cover only 17% of the NM-URG watershed, approximately 25% of the precipitation volume falls in these areas. Although insufficient data exists to quantify the percentage of water supply derived from mixed conifer forests, the figure is likely much greater than 25% due to the high water yield associated with the snowpack dominated hydrology in these regions.
6. Existing models are not capable of optimizing watershed restoration efforts with respect to source-water protection and hydrologic response. However, such tools can be developed through close collaboration between watershed partners including federal and non-federal agencies, water management organizations, non-governmental organizations, university researchers, and stakeholders. A framework for such an approach is included in Part 4 of this report including strategies for incorporating existing models.

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1 Introduction

1.1 Objectives and Key Findings

The purpose of the study is to investigate the potential changes in water yields and water supply resilience in tributary watersheds to the Rio Grande as a result of forest restoration and wildfires with a focus on high-elevation mixed conifer areas. This report contains a review of existing literature, data, and models to help guide the Middle Rio Grande Conservancy District (MRGCD) board, The Nature Conservancy (TNC), and Rio Grande Water Fund (RGWF) partners regarding the potential benefits associated with forest restoration in these high-elevation watersheds.

1.2 Background and Motivation

Global wildfire activity has risen sharply during the past few decades, and projections indicate that fire activity will continue to increase in the coming decades (Pechony & Shindell, 2010; Allen et al, 2010). In the southwestern United States, increased wildfire activity has been linked with Euro-American settlement that began in the middle to late 1880s (Covington & Moore, 1994). While forests have historically experienced frequent low-severity surface fires every 4 to 36 years (Dieterich, 1980; Swetnam & Baisan, 1996; Fule et al, 2000), activities such as fire suppression, heavy grazing and extensive logging have altered the fire regime. The marked increase in wildfire severity and destructive potential of wildfires is due to the decreased presence of large trees, overcrowding of small homogenously aged trees and increased fuel loads. Densely wooded forests are less tolerant to disease and infestations (Covington & Moore, 1994), drought (Giuggiola et al, 2013), and at increased risk for stand replacing wildfires (Dombeck et al, 2004). This condition threatens the remaining large trees through competition and fueling increasingly extensive crown fires.

For several decades, the southwestern U.S. has experienced increasing frequency of large-scale forest fires (Westerling et al, 2006). The contributing factors mentioned above, in addition to increased ground to crown connectivity, intense drought, and warm climatic conditions have resulted in increased risk of large-scale forest fires. Wildfires and flooding in their aftermath pose major challenges to water supplies from the Rio Grande watershed, which provides water for more than half of New Mexico’s population. The hydrologic implications of large-scale wildfires are vast and include: decreased infiltration, increased soil hydrophobicity, and increased risk of large magnitude flooding (Neary et al, 2011). Alternatively, thinning forests at large scales has the potential to increase surface water yield while decreasing the risk of severe wildfire (Robles et al, 2014).

In this report we present an overview of the literature on hydrologic responses to wildfire followed by that of hydrologic responses to watershed restoration. We also investigate existing watershed data and explore trends and correlations in the hydrologic record. Finally, we discuss potential modeling approaches for investigating the benefits of watershed restoration efforts including the potential to incorporate existing watershed and water operations models.

1.3 Mixed-Conifer and Ponderosa Pine Forests

This report is focused primarily on high-elevation mixed conifer, ponderosa pine, spruce-fir and aspen forests with an emphasis on mixed conifer stands. Mixed-coniferous forests in the southwestern U.S. are spatially and temporally variable and complex and can be composed of a wide range of species including blue spruce, Engelmann spruce, Southwestern white pine, white fir, Douglas fir, limber pine and ponderosa pine (Evans et al, 2011). The tree composition is determined by moisture requirements, shade tolerance, wildfire tolerance, and growing season length (Margolis et al, 2013). In some classification schemes, mixed-conifer areas are separated into relatively hot/dry zones that often occur on south-facing slopes and a cool/wet zones that are more common on north-facing aspects. In the NM-URG, there is a predictable transition between pinyon pine-juniper, ponderosa pine, mixed-conifer and aspen, and spruce-fir forest types with increasing elevation. These trends and elevation thresholds are expanded upon in section 3 of this report.

In contrast with ponderosa pine forests that historically burned with a frequency of 4 to 30 years (Margolis et al, 2013) and with low intensity, dry and wet mixed-conifer forests historically had a lower burn frequency (Margolis et al. 2007, Romme et al. 2009) and included low, mixed, and occasionally high severity wildfires (Margolis et al, 2011). Thus, the structure and composition of dry and wet mixed-conifer stands historically varied in space and time to a greater degree than fire-tolerant ponderosa pine forests (Romme et al, 2009). Under historical conditions, mixed and high severity fires were associated with more extreme drought conditions than low severity fires (Margolis and Malevich, 2016). Although high severity fires did occur historically in wet mixed-conifer stands, tree ring studies indicate the burn areas where typically small (<2 to 3 acres) and complete mortality was rare (Margolis and Malevich, 2016). The loss of low severity fires has resulted in an increase in stand densities across forest types over the past century and this increase is greatest for shade-tolerant and fire-intolerant species such as white fir (Heinlein et al, 2005).

2 State of the Science

2.1 Wildfire Impacts on Watershed Processes

The effects of wildfires on hydrologic processes are highly variable and complex – producing some of the most confounding hydrologic conditions that forest, land, and water managers must consider. The hydrologic response of a burned watershed is dependent on a number of factors including the wildfire severity, watershed characteristics (e.g. soil, slopes, and vegetation types), and the magnitude and timing of precipitation events following the wildfire (Debano, 2009). In this section we summarize the scientific literature on the impacts of wildfires on the hydrologic processes associated with: (1) peak flows; (2) snowpack dynamics; (3) water yields; and (4) erosion, sediment transport, and debris flows.

2.1.1 Wildfire Impacts on Rainfall-Runoff Processes

Annual and seasonal water yield, peak flood flows, base flows, and timing of flows are all affected by wildfires. Because of the potential impacts on human safety and property, peak flood flows are of great concern. Following high severity wildfires, peak flows can increase dramatically, severely affecting stream physical conditions, water quality, aquatic habitat, aquatic biota, cultural resources, and human health and safety (Neary et al, 2011).

Increases in runoff following wildfires are primarily caused by three mechanisms: (1) destruction of organic material on the soil surface; (2) reduced infiltration caused by hydrophobic soils; and (3) larger flow volumes caused by decreased canopy interception and increased bare-ground cover. The major determining factor when considering the change in peak flows is the amount of disturbance to the surface material, which is usually organic debris (i.e. duff or forest floor) that protects the underlying mineral soil. The development of hydrophobic soils is a result of the combustion of vegetative materials that create a gas that penetrates the soil profile. As the soil cools, this gas condenses and forms a waxy coating which causes the soil to repel water, which is known as hydrophobicity (Moench & Fusaro, 2012). This hydrophobic condition increases the rate of water runoff (Robichaud, 2000). Further, wildfires remove or kill vegetation within a watershed, reducing the volume of water intercepted by vegetation canopies and increasing the percentage of water available for runoff. Wildfires also decrease the water normally lost as evapotranspiration, which increases baseflows (Neary et al, 2003).

Figure 1. A student (S. Martinez) points to the high water mark on a ponderosa pine in Cochiti Canyon downstream from the Las Conchas burn scar (Photo by M. Stone).

After a wildfire, changes in peak discharges are disproportionally larger than changes in annual runoff and are therefore a more sensitive measure of hydrologic response. The change in slope of the rainfall-runoff relations suggests that, for burned watersheds, a threshold of rainfall intensity exists that implies a critical change in the behavior of the hydrologic response (Moody

& Martin, 2001). Studies have shown that following high severity fires, flood peak flows can be increased by more than 100 times from the pre flood condition (Neary et al, 2005). Table 1 provides a summary of some of the changes observed in peak flows as a result of the La Mesa and Cerro Grande fires in the Jemez Mountains.

Table 1. Examples of peak flows before and after wildfires

Fire Name	Place	Pre-Fire Peak Flow	Post-Fire Peak Flow
La Mesa (1977)	Frijoles Canyon	19 ft^3/s (1964-69)	3030 ft^3/s (1978) (Veenhuis, 2002)
Cerro Grande (2000)	Pajarito Canyon	274-840 cfs	1020 cfs (Gallaher & Koch, 2004)
Cerro Grande (2000)	Pueblo Canyon	< 250 cfs	1440 cfs (Gallaher & Koch, 2004

Another major concern for post-wildfire floods is the timing of storm flows, or response time, after wildfires (Anderson et al, 1976). Burned watersheds respond to rainfall faster and produce more flash floods. Flood warning times are reduced by flashy flow and higher flood levels can be devastating to property and human life. Another aspect of this phenomenon is the fact that recovery times may range from years to many decades (Díaz-Delgado and Pons, 2001).

2.1.2 Wildfire Impacts on Snowpack Dynamics

Snow covered forests are a critical source of water in the southwestern region, providing as much as 50% of annual water supply (Sezerette et al, 1999; Bales et al, 2006). Interception, snowpack accumulation, melt and ablation are a function of the characteristics that define the forest canopy. Natural disturbances such as insect infestations, wildfires, or increased temperatures and extended periods of drought act to (either directly or indirectly) decrease canopy density and impact snowpack processes (Westerling et al, 2003; Fauria & Johnson, 2008).

In the last two decades, removal of forest canopy due to an uptick in the occurrence of severe forest fires has likely changed snowpack dynamics in New Mexico. Burned forest canopies are more fragmented and reduce the amount of interception relative to unburned forests, increasing the amount of snow to accumulate on the ground (Burles & Boon, 2011). Increased snowpack accumulation in burned forests is offset in some instances by increased ablation, reducing peak snowpack volumes (Anderson, 1956). Burles & Boon (2011) found in a boreal forest in Canada's southern Rockies that the removal of canopy from forest fire increased melt rates and led to an earlier complete melt date as compared to a densely wooded forest. Similar research conducted following the Las Conchas fire in the Jemez mountains showed that unburned forest areas contained approximately 10% more water available for melt than the post-burn forest and losses to ablation had reduced the snowpack by nearly 50% before melt in the post-burn area (Harpold et al, 2014). The research efforts following the Las Conchas fire demonstrated the role forest canopies play in reducing snowpack sublimation and potentially increasing the water available for vegetation and runoff.

2.1.3 Wildfires Impacts on Water Yields

Generally, water yields increase when mature forests are harvested, burned, blown down, or attacked by insects (Neary et al, 2003). The amount that measured water yield increases the first year after wildfire disturbance varies greatly depending on wildfire intensity, climate, precipitation, geology, soils, watershed aspect, tree species, and proportion of the forest vegetation burned (Moody & Martin, 2001). Water yield increases from prescribed fires and wildfires in the Southwest are variable, but are generally less than 150% for prescribed fires and low-severity wildfires (Benavides-Solorio & MacDonald, 2001). Moderate-to-high severity wildfires can cause significant increases in water yield. Water yields within ponderosa-pine and dry and wet mixed coniferous forest areas in New Mexico reportedly returned to pre-fire conditions within 4 to 5 years following severe wildfires; whereas in Arizona this figure has varied from 4 to 10 years, depending on the watershed condition (Hallema et al, 2016).

In 2000, after the Cerro Grande fire, the total upstream runoff at LANL was 331 acre-ft., 3.7 times higher than the pre-fire average (Gallaher & Koch, 2004). However, by 2002 and 2003, the upstream runoff was 66 and 21 acre-ft., respectively, significantly less than the pre-fire average water yield (Gallaher & Koch, 2004). In 2000, the downstream runoff at LANL was 177 acre-ft., 2.8 times higher than the pre-fire average. In 2001 the runoff was 250 acre-ft., about 5 times higher than the pre-fire average. Whereas runoff in canyons at LANL appeared to have returned to near pre-fire conditions by 2002, the runoff in Pueblo Canyon through 2003 was still 4 times higher than pre-fire runoff (Gallaher & Koch, 2004).

2.1.4 Wildfires Impacts on Erosion, Sediment Transport, and Debris Flows

Breakdown in soil structure, reduced moisture retention and capacity, and development of water repellency are the physical impacts of wildfire on soil, all of which increase susceptibility to erosion (Neary, 2004). Thus, common geomorphic impacts of wildfires include increased soil erosion rates and debris flows, decreased water quality in areas downstream from burns, and increased sediment transport in streams and rivers. The degree of wildfire effects on soils are a function of the amount of heat released from combusting biomass into the ground and the duration of combustion (Moench and Fusaro, 2012). Figure 2 is a photograph of the Peralta Canyon watershed demonstrating a high severity burn scar following the Las Conchas Fire.

Wildfires typically result in increased sediment erosion and transport rates, which in the short term (several years) are often orders of magnitude higher than baseline conditions (Malmon et al. 2007). Sediment transport is both an episodic and steady process. Before a wildfire, sediment transport in mountain regions is typically supply-limited while after the wildfire it is transport-limited. Most of the eroded sediments come from low-order watersheds and are stored as floodplain deposits, alluvial fans, and channel fill in high order watersheds (Moody & Martin, 2001).

One of the most immediate implications of post-wildfire runoff events is an extension of the watershed rill network. Rill and gully systems can fundamentally alter the hydrology of hillslopes, greatly decreasing time to peak of runoff and significantly increasing storm discharge (Neary et al. 2010). Rills are self-organizing erosion systems characterized by numerous and randomly occurring small channels of only several centimeters in depth and centimeters to tens of meters in length. Sediment yields increase with increasing slope, rill spacing decreases as slope angle increases, rill patterns show an increased elongation on steeper slopes, and hillslope rills tend to be more evenly spaced on bare, straight slopes (Neary et al, 2010).

Figure 2. Photograph of the denuded landscape in the Peralta Canyon Watershed following the Las Conchas Fire (Photo by M. Stone).

Another important aspect of sediment delivery after fires is the transport of ash into streams, which can have major impacts on water quality and aquatic communities. Deposition of debris flows and the coarsest sediment supplied from low-order basins often occur where energy decreases on alluvial fans or close to drainage confluences. The timing of sediment delivery varies with sediment type and size. The delivery is rapid but more prolonged for fine-grained sediments, and more irregular and delayed for coarse-grained sediments (Reneau et al, 2007). Thus, most of the impacts from ash and other fine-grained sediments occur soon after a fire, whereas the pulse of coarse-grained sediment can be significantly attenuated and delayed pending flows capable of sustained bedload transport.

Debris flows are common in the aftermath of wildfires (Figure 3). Debris flows are particularly dangerous because they tend to occur with little warning and can result in dramatic damage to property. Debris flows can strip vegetation, block drainages, damage structures, and endanger human life. Generally, post-fire debris flows are triggered by one of two processes: (1) extreme surface erosion caused by rainfall-runoff (surface-driven landslides) or (2) land sliding caused by infiltration of rainfall into the ground and subsequent geotechnical instability (subsurface-driven landslides). The first category is common for short-duration, short-return interval storms that commonly occur in the monsoon season in New Mexico. In this case, large-scale debris flows can be initiated through a process of progressive sediment bulking by overland flow and rill erosion in steep upper basin slopes, followed by deep incision on lower slopes (Shakesby & Doerr, 2006). Bulking is the process of progressive accumulation of sediment in overland flows which leads to rapid sediment entrainment. Debris flows are most frequently produced from steep slopes (>20°), and are unlikely to extend beyond the mouths of basins larger than about 25 square kilometers (~10 square miles) (Bêche et al, 2005). For preliminary hazard assessment, a pair of empirical models was used to estimate the probability, volume and combined relative hazard ranking of a debris flow following flashy floods after the Track Fire in 2011 in Colfax County, northeastern New Mexico, and Las Animas County, southeastern Colorado (Tillery et al, 2011).

Figure 3. Debris jam at the mouth of Peralta Canyon following the September 13, 2013 floods. Discharge from Peralta Canyon was estimated to be over 6000 cfs (Photo by M. Stone).

2.2 Watershed Restoration Impacts on Watershed Processes

Since the 1950's, forest managers in the southwestern U.S. have progressively moved towards a more intensive phase of resource management. In water-limited states such as New Mexico, water is considered one of the most valuable resource from these lands. From this perspective, watershed management should not only consider protective functions of the watershed, but should also give important weight to other practices affecting the quantity or amount of water yield (Evens et al, 2011). In this section we summarize the impacts of watershed restoration on water yields via changes in: (1) rainfall-runoff processes, (2) soil moisture and groundwater, and (3) snowpack dynamics.

The primary forest restoration activities considered by forest resource managers are thinning and prescribed fire. Thinning refers to the cutting and removal of trees to meet treatment targets for canopy cover, basal area, and tree spacing (i.e. tree clumps and open areas) in order to meet objectives for restoration of habitat and wildfire regimes. The majority of these trees are too small to have commercial value by conventional standards (Brown, 2000). Trees that meet criteria for commercial standards and provide additional economic benefit are considered as a positive by-product of restoration activities and are not the incentive for thinning alone. Decisions about the use of thinning as an element of forest restoration must be based on local conditions and analyses that consider current and historical stand conditions, landscape context, watershed integrity, status of fish and wildlife populations, and many other variables. Nonetheless, some general principles and guidelines can be proposed, based largely on the broad categorization of forest types and fire regimes. Thinning is most effective where trees are sufficiently large or dense that attempts to kill them with fire would substantially increase the risk of killing overstory trees (Brown, 2000).

Figure 4. Thinned materials being removed from the Banco Bonito area of the Valles Caldera (Photo by M. Stone).

2.2.1 Watershed Restoration Impacts on Rainfall-Runoff Processes

Runoff from treated forested watersheds is expected to be higher for a period of time because interception and evapotranspiration losses are reduced and water is thus concentrated causing a relatively higher volume of runoff. The extent and duration of increased runoff varies with local geology, climate, and forest characteristics (pre- and post-treatment). Previous studies have predicted enhanced runoff for six years following treatment (Robles et al, 2014) and in other cases as high as four to ten years (O'Donnell, 2014; O'Donnell, 2016). Yet another study in Workman Creek, AZ showed that the increases persisted through the 21-year observation period following thinning (Gottfried and DeBano 1990). Most water-yield studies have been limited by a short-duration of the monitoring period and additional research is needed to fully understand long-term changes in water yields. The incorporation of maintenance treatments into restoration plans is likely to increase the hydrologic benefits of forest restoration (O'Donnell, 2014).

Watershed restoration practices influence rainfall-runoff processes by modifying ground cover, canopy structure, and soil characteristics. For example, a classic experiment was conducted under small diameter stands of ponderosa pine in the Manitou Experimental Forest in Colorado to determine the effect of litter removal on runoff (Dunford, 1954). For a three-year calibration period prior to removing the protective-litter cover, the runoff ratio of treated/untreated plots on the experiment averaged 0.73. And for 10 years after litter removal the average ratio was 2.3, with the individual values ranging from 6.9 in the first year to a low of 0.7 nine years after recovery (Dunford, 1954). Thus, removing vegetation cover, whether dead or alive, tends to increase runoff and subsequently streamflow, even though there is a reverse effect if the removal is not carefully designed. Excessive removal of the litter layer may expose the underlying mineral soil making it more susceptible to erosion. This would introduce the potential to increase erosion, sedimentation, and thus deteriorate downstream water quality (Tecle & Neary, 2015).

2.2.2 Watershed Restoration Impacts on Soil Moisture and Groundwater

The removal of vegetation tends to decrease the amount and rate of infiltration, resulting in reduced groundwater recharge (Castillo et al, 1997). This is because a reduction in vegetal cover enhances rapid movement of the surface runoff, and consequently lessens the opportunity for infiltration. The net effect is a lowering of the underlying water table (Castillo et al, 1997). Another important factor is climate. In the southwestern U.S. ponderosa pine zone, where freezing is common, there is a loss of recharge from rain or snowmelt during the winter months, which may cause localized water tables to fall (Williams et al, 2001). Normally, sporadic or differential freezing of the soil in the winter inhibits recharge to the groundwater, and any complete freezing of the soil prevents all recharge until the soil thaws. Thus, in such areas the effect of vegetation cover on groundwater recharge is a warm season condition.

In the southwestern U.S., the effect of vegetation manipulation on groundwater is more noticeable in aquifers underlying stream channels (Stonestorm & Harrill, 2007). In such cases, removal of vegetation tends to reduce the loss of groundwater due to evapotranspiration. Removal of riparian vegetation, on the other hand, has adverse effects on wildlife and other environmental conditions as such plants provide high quality wildlife habitat, and serve as flood control, sediment stabilizing and pollutant filtration mechanisms, and also have recreational value. For these reasons, the removal of riparian vegetation to enhance groundwater resources should be prevented in most cases.

Thinning treatments have been shown to increase soil moisture and increase vegetation growth (Covington et al, 1997). Comparisons of soil moisture in ponderosa pine stands of high and low density have shown mixed results but generally show higher soil water content in low density forests (Zou et al, 2008; Feeney et al, 1998; Stone et al, 1999; Sala et al, 2005; Gregory (unpublished data)). High-density ponderosa pine forests deplete water more quickly than low-density forests and soil water content varies to a greater degree (Zhou et al, 2008).

2.2.3 Watershed Restoration Impacts on Snowpack Dynamics

Approximately 40% of all water in the southwest falls as snow in high elevation mountains (Serreze et al, 1999). The accumulation of snow during winter months acts as a reservoir until the onset of snowmelt (Mote et al, 2005; Molotch et al, 2009; Veatch et al, 2009). Accumulation of snow in these regions is strongly influenced by climate, topography and vegetation (Carey & Woo, 1998; Pomeroy et al, 2003; Jost et al, 2007). While little can be done to mitigate the effects of climate and topography, the modification of vegetation has the potential to significantly alter the quantity of snow water equivalent that falls to the ground and the rate of ablation.

Of particular interest in semi-arid regions is the importance of winter snowpack on increasing water yield from thinned forests. Ffolliott et al (1989) suggested that the aridity of the climate in New Mexico and Arizona is such that any increase of water yield will predominantly be the result of thinning efforts that focus on increasing snow water equivalent and hence spring runoff. Veatch (2009) found that maximum SWE occurred in areas with 25-40% canopy cover and open areas located just north of tree patches contained 140% more snow than their southern counterparts during a study in the Valles Caldera, NM. A number of studies have supported Ffolliot's conclusions, suggesting that thinning has little impact on summer base flows but increases spring runoff. Wilcox et al. (2003) found that ecohydrological feedback loops in this region are complex and annually aggregated precipitation is not indicative of hydrologic conditions at any single time. Spring runoff is, however, directly related to the amount of precipitation that falls during winter months.

Snow ablation is controlled by energy fluxes including net shortwave radiation, net longwave radiation, advected sensible and latent heat, and ground heat conduction (Brooks et al, 2012; Boon, 2007). Trees reflect, absorb, and transmit solar radiation, decreasing the amount of direct solar radiation that hits the snow surface and increasing diffuse solar radiation. Additionally, canopies decrease the amount of short-wave radiation that reaches the sub-canopy floor and increase longwave radiation (Hardy et al, 2004; Sicart et al, 2004; Pomeroy et al, 2009). The largest energy flux is generally derived from shortwave energy. Simulations of net snow cover radiation in forests have shown that for northern slopes, low density canopy cover increases snow accumulations when compared to denser forests. Further, southern facing slopes perform better when moderate forest densities are present (Seyednasrollah et al, 2013). Forest cylindrical gaps of one to two times the canopy height minimize all wave radiation in contrast to gaps on the order of three to six times the canopy height, leading to increased longevity of snowpack (Lawler and Link, 2011; Golding and Swanson, 1978; Berry & Rothwell, 1992).

Forest canopies intercept snow (Hedstrom & Pomeroy, 1998) and decrease the snowpack accumulation on the forest floor. Sublimation losses from canopy and sub-canopy snowpack can be substantial in densely forested areas (Hedstrom and Pomeroy, 1998; Essery et al, 2003;

Molotch et al, 2007) and cause significant loss of water from snowpack. Sublimation losses due to interception in New Mexico were shown to account for as much as 47% of precipitation (Musselman, 2008) and open spaces were found to hold more snow than sub-canopy areas (Molotch et al, 2009). Snowmelt from intercepted snow can fall to the ground and increase the energy balance of the snowpack. Several studies have shown that reducing canopy density increases the peak snow water equivalent and reduces sublimation (Gottfried, 1991). Further, strategically thinning trees for certain spatial patterns may give water managers some control over timing and magnitude of peak discharge (Plasencia, 1988).

2.3 Watershed Restoration and Water Yield Research in the Southwest U.S.

In high-elevation forests, snow is an important source of water for much of the arid Southwest. In New Mexico less than 10% of the annual precipitation is recovered for human use. 80%-90% of the precipitation currently is not available for downstream users (Ffolliott, 2007). More precipitation could be recovered as streamflow if water yields from the high elevation watersheds were increased. The potential to increase the amount of recoverable precipitation from management of forested watershed is greater for snow than rain.

A large amount of scientific research has been conducted on forest management in the southwest especially in Arizona and Colorado, but less work has been conducted in New Mexico (O'Donnell, 2016). Increased tree densities from intensive grazing and a century of fire suppression are believed to have led to reduced water yields and herbaceous cover in Colorado (Macdonald & Stednick, 2003). Combinations of thinning and controlled burns provide the potential to increase water yields and forage while reducing wildfire danger. Research has shown that removing 15 to 30% of the basal area of a forest has led to detectible increases in water yield (Stednick, 1996). Greater reductions in basal area should yield greater amounts of runoff but at the same time it can lead to increased sediment yields; thus careful planning and implementation is needed. Research has shown that removing 15% of the basal area from the Rocky Mountain/Inland Intermountain region leads to a measurable increase in annual water yield (Madrid, 2005). The following paragraphs provide short summaries of two large-scale watershed restoration projects Arizona and New Mexico.

Four Forest Restoration Initiative: Mechanical thinning and fire treatments are planned for ponderosa pine forests within the Salt-Verde watersheds in central Arizona and the first analysis area of Four Forest Restoration Initiative (4FRI) project area (Robles et al, 2014; O'Donnell 2016). In these watersheds the ponderosa pine forests grow at elevations of 5900-8600 feet. The Beaver Creek watershed, a sub-watershed of the Salt-Verde, was used to quantify changes in runoff from thinning using a paired watershed method including control and treated watersheds. This relationship was used to predict what would have been baseline flows in the treated watershed. The difference between measured flows in the treated watershed and the predicted value were attributed to thinning effects. In the first analysis area of the 4FRI projects mechanical thinning of ponderosa pine forests increased mean annual runoff from 2,540 acre-feet in a simulated drought to 5890 acre-feet in a pluvial. From the majority of simulation scenarios, it was found that the runoff from the thinned forests was approximately 20% greater than the unthinned forests in both drought and pluvial conditions. In the Salt-Verde watersheds, mean annual runoff increased from 3860 to12,200 acre-feet over a 35-year treatment period, 5,010 to 19,000 acre-feet over 25 years and 7,480 to 34,700 acre-feet over 15 years. Similar to 4FRI scenarios the runoff in the Salt-Verde watersheds was 20-26% greater than the unthinned forests.

Rio Grande Water Fund: In New Mexico and Arizona, one of the dominant forest cover types is ponderosa pine. In the Rio Grande Water Fund Area, ponderosa pine forests make up 275,000 acres of the total project area or 46% (The Nature Conservancy, 2014). The remaining forests higher-elevation mixed conifer and aspen-mixed conifer forests.

The Nature Conservancy (TNC) has conducted an initial calculation of how much forest thinning might increase snowpack storage and the regulation of runoff and forest resiliency to drought. The estimation was limited to ponderosa pine forest and more research is needed for high elevation forest types such as dry and wet mixed conifer and aspen-mixed conifer forest.

The calculations showed that if 30,000 acres of ponderosa pine were treated annually for nine years, annual runoff would increase by 2,745 acre-feet for up to 7 years, potentially providing water to 11,000 households, and restoring some portion of historical flows to existing water right holders (Rio Grande Water Fund, 2014).

3 Existing Data Resources

A wide range of data sources can be used to improve understanding of hydrologic, geologic, and meteorological conditions in Rio Grande headwater watersheds including digital elevation models, land use/land cover maps, and weather station records. In this report we have compiled data from a variety of sources to describe watershed conditions and processes at a coarse scale. However, data is extremely sparse in most of the Rio Grande headwaters with a notable exception in the Valles Caldera National Preserve, which has hosted extensive research efforts.

3.1 Topography and Hydrology

In this report, we focus on the four sub-watersheds in the Rio Grande headwaters within New Mexico as designated by USGS 8-digit Hydrologic Unit Codes (HUC): (1) Rio Chama; (2) Upper Rio Grande; (3) Jemez; and (4) Santa Fe. The basic statistics for these basins are summarized in Table 2. The five HUCs that compose the Rio Grande headwaters within Colorado are also included in Table 2 for reference but are not investigated in any specific detail for this report.

Table 2. Summary of Rio Grande headwater hydrologic unit code (HUC) basins

Name	HUC-8	Area (acres)
Rio Chama	13020102	2,021,139
Upper Rio Grande	13020101	2,082,687
Jemez	13020202	664,923
Santa Fe	13020201	1,197,825
Alamosa-Trinchera	13010002	1,625,109
Conejos	13010005	490,952
Rio Grande Headwaters	13010001	883,590
Saguache	13010004	859,487
San Luis	13010003	1,0126,43

The locations of the 8-digit watersheds and other important regional features are included in Figure 5 on the next page. The total area of the four New Mexico watersheds is approximately 6 million acres or 9,300 square miles.

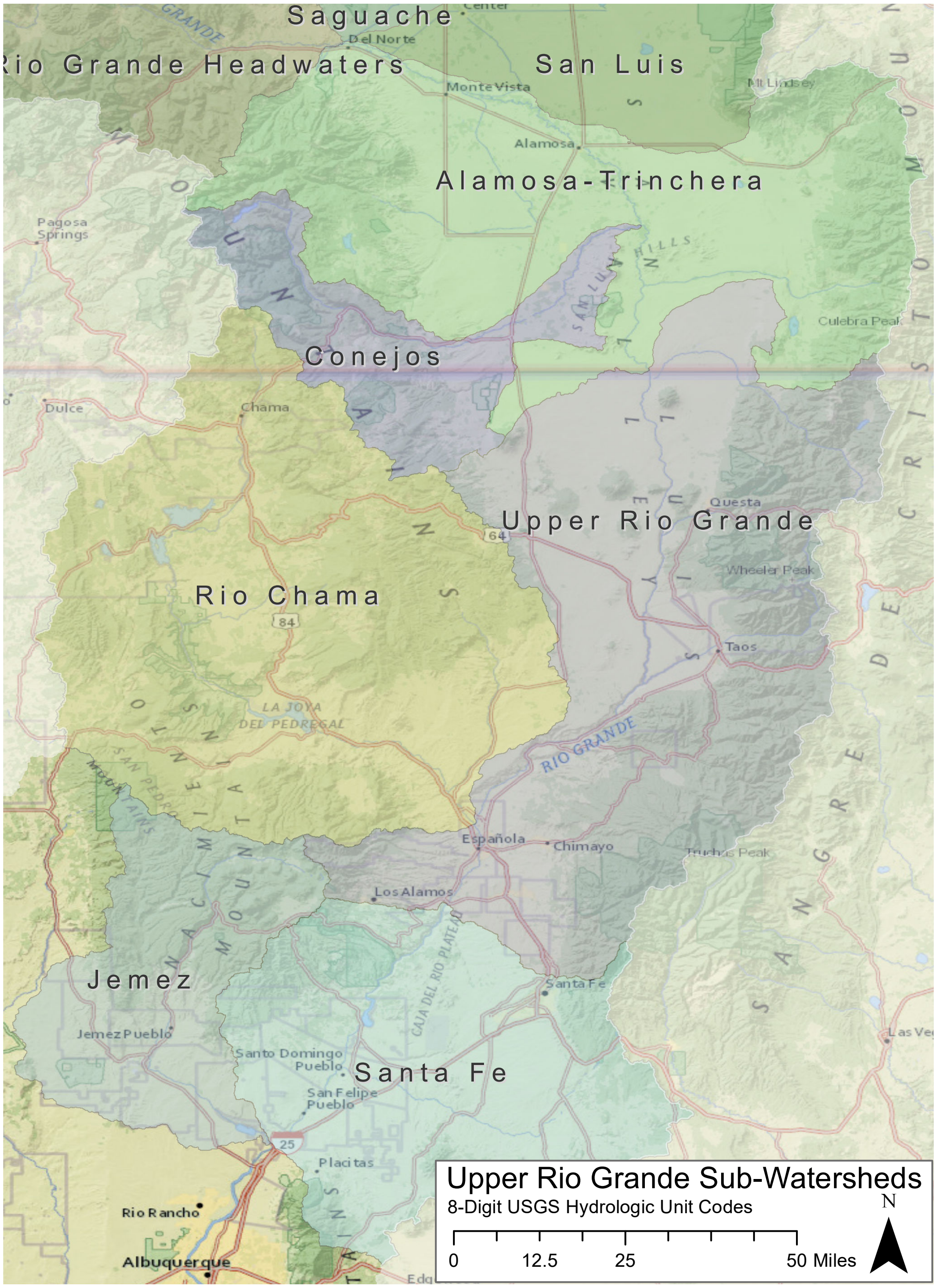

Figure 5. Map of the sub-basins that compose the headwaters of the Rio Grande within the state of New Mexico. The basin maps were obtained from the USGS data portal and the base map is from ESRI's map server.

The Rio Grande headwaters are characterized by significant topographic relief with elevations ranging from under 5000 ft as the Rio Grande enters the middle valley to over 14,000 feet in San Juan Mountains. The topography and associated drainage network of the headwater system is included in Figure 6.

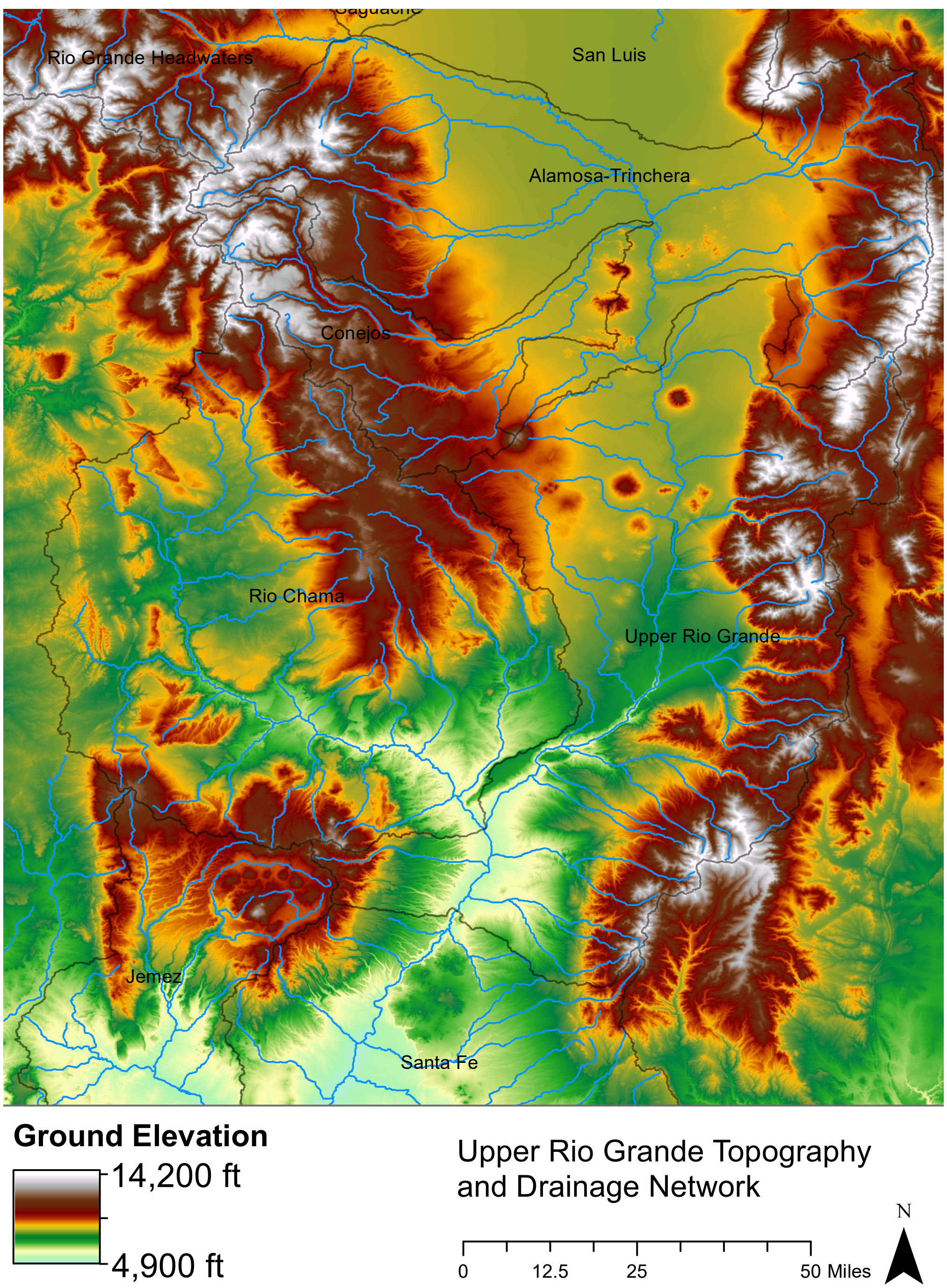

Figure 6. Upper Rio Grande topography and stream network. Basin topography was produced from 30 meter digital elevation data from the USGS Seamless Server. The stream network is from the U.S. EPA.

3.2 Land Cover / Land Use

The forested regions of the Rio Grande headwaters can be characterized through approximately five different forest types as shown in Figure 7 including: pinyon pine – juniper; ponderosa pine, mixed conifer, aspen, and spruce-fir forests.

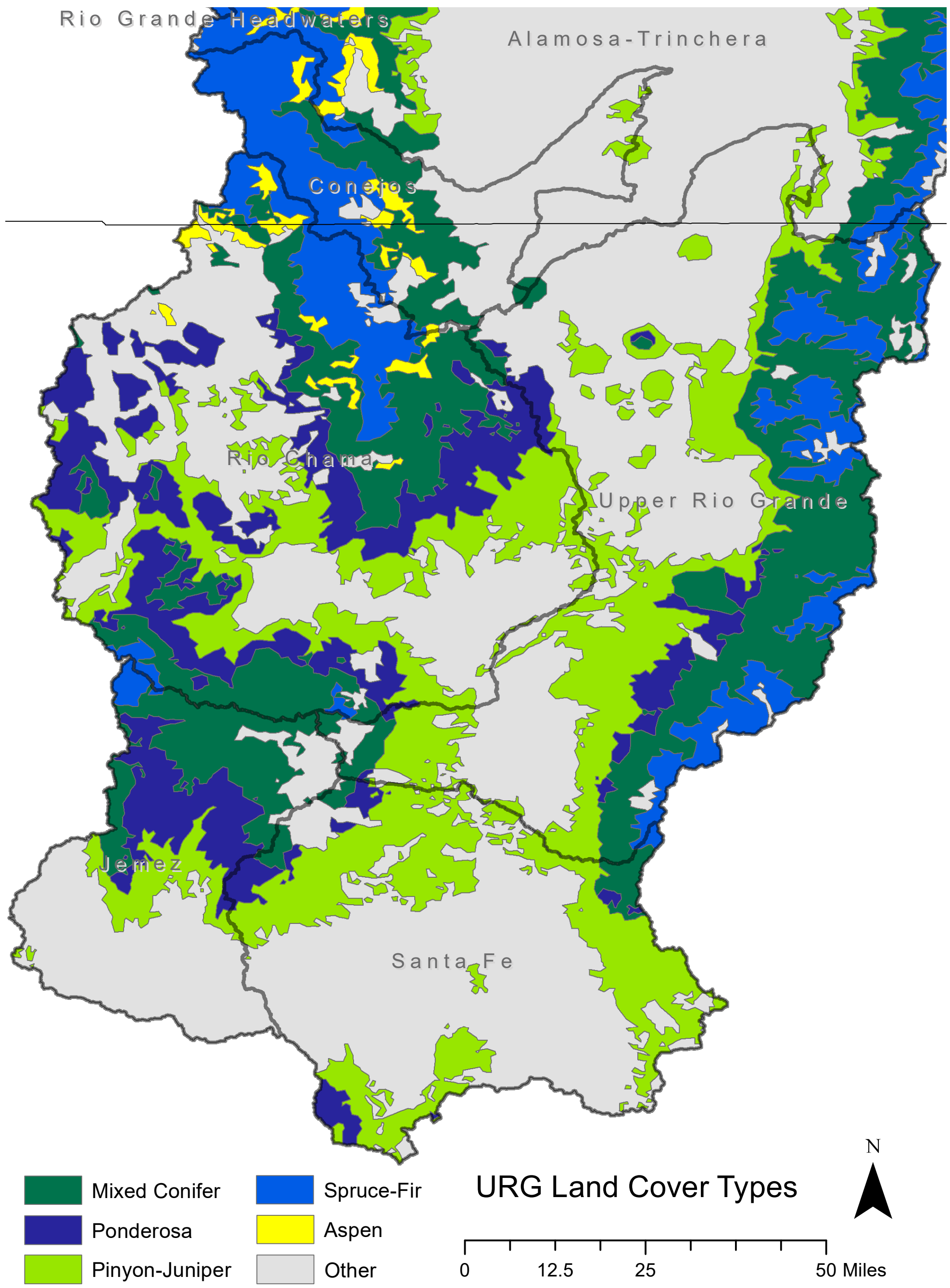

Figure 7. Land cover types in the Upper Rio Grande.
(source: https://www.landfire.gov, prepared by Steven Bassett, TNC)

Throughout the upper Rio Grande, a consistent trend from pinyon pine/juniper woodlands, to ponderosa pine forest, to mixed-conifer and aspen forests, and finally to spruce-fir forests can be observed as a function of increasing elevation. We have combined a simplified map of elevation bands and vegetation types to illustrate this relationship in Figure 8.

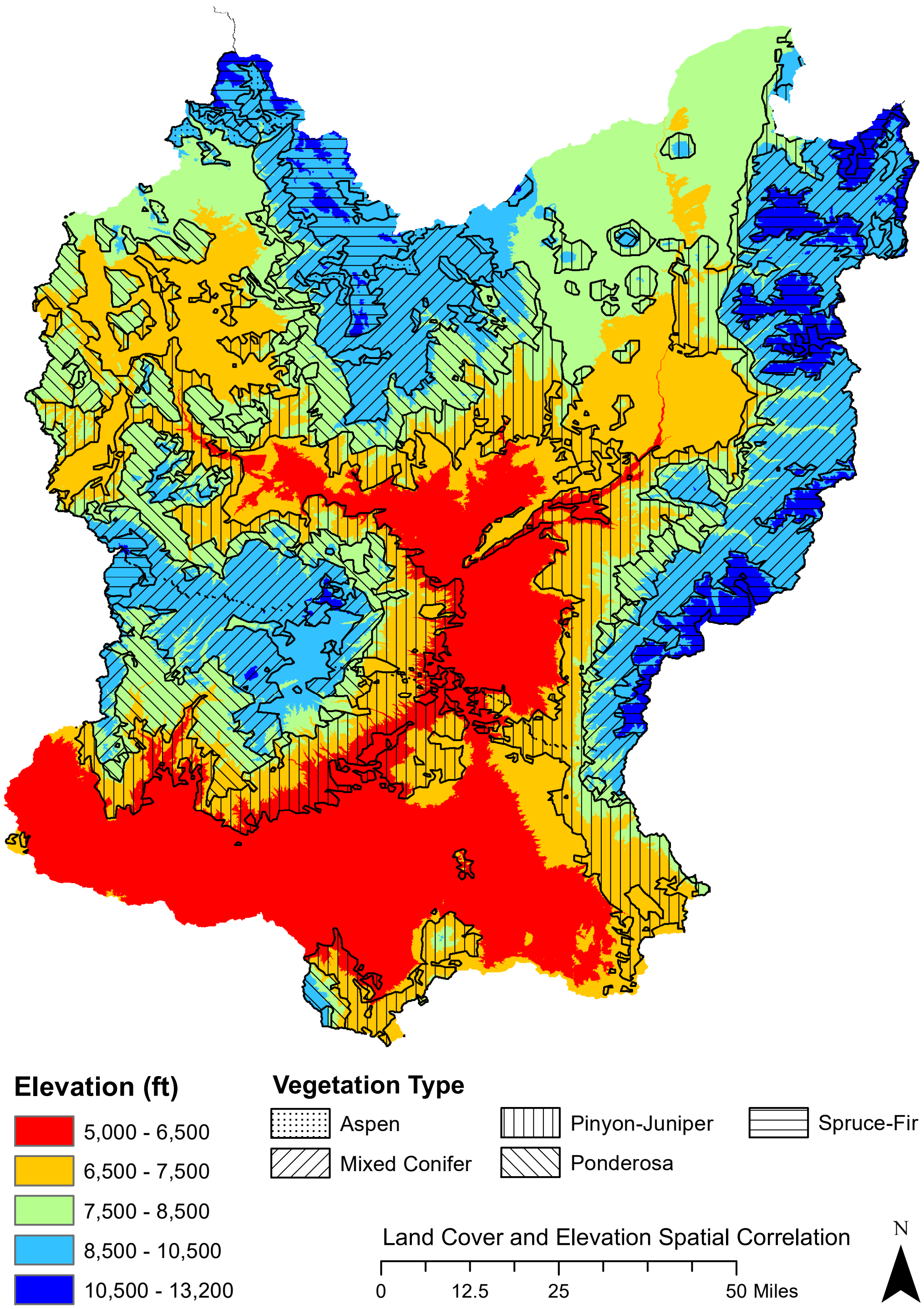

Figure 8. Forest types superimposed upon ground elevation for the upper Rio Grande.

Figure 9 includes histograms that reveal the distribution of the forest types throughout the upper Rio Grande basin as a function of elevation. The median elevations for ponderosa pine and mixed conifer forests are 8,000 ft and 9,100 ft, respectively.

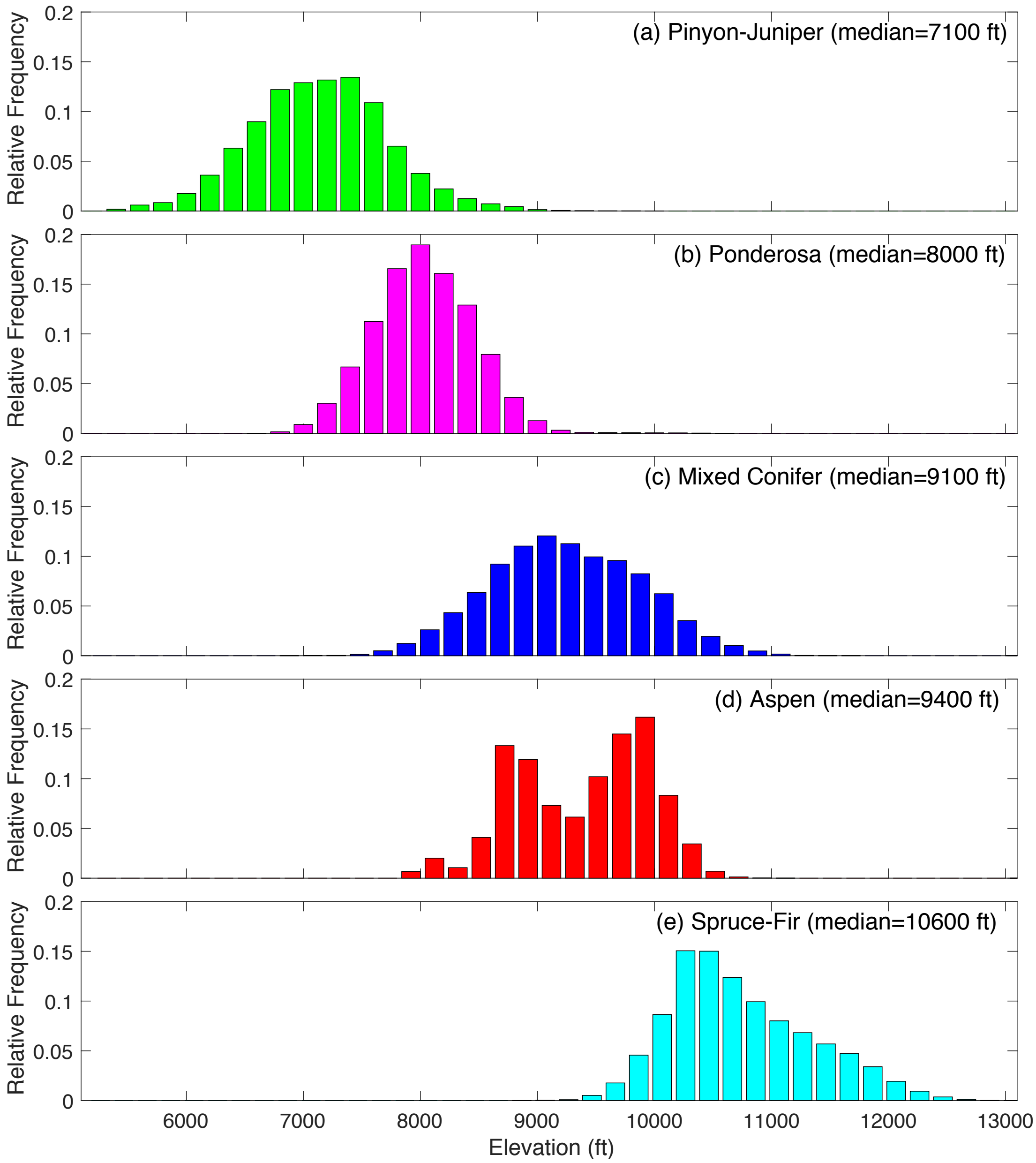

Figure 9. Elevation histograms for dominant forest types in the NM-MRG.

3.3 Meteorological Records

Several dozen meteorological stations exist or have existed throughout the NM-URG with variable periods of record, observation types, temporal resolutions, etc. Such data is maintained by a wide range of agencies including the National Weather Service, the Western

Regional Climate Center, the USDA, and others. Of primary interest to this study is the SNOTEL (Snow Telemetry) Network, which is maintained by the USDA with the primary goal of informing water supply forecasts. Eighteen stations are operated in the NM-URG as shown in Figure 10. Figure 10 also includes the mean annual precipitation across the basin as reproduced by the PRISM Climate Group at Oregon State University for the period of 1980 to 2010 (http://www.prism.oregonstate.edu).

The SNOTEL data is summarized in Figure 11 in the form of maximum annual snow water equivalent (SWE) for all 18 of the NM-URG stations. For clarity, we have separated the stations by 8-digit HUC and further divided the Upper Rio Grande basin into north and south regions (approximately at Taos). Also included in Figure 11 is the mean peak SWE averaged across all stations and years for each watershed (green dashed lines).

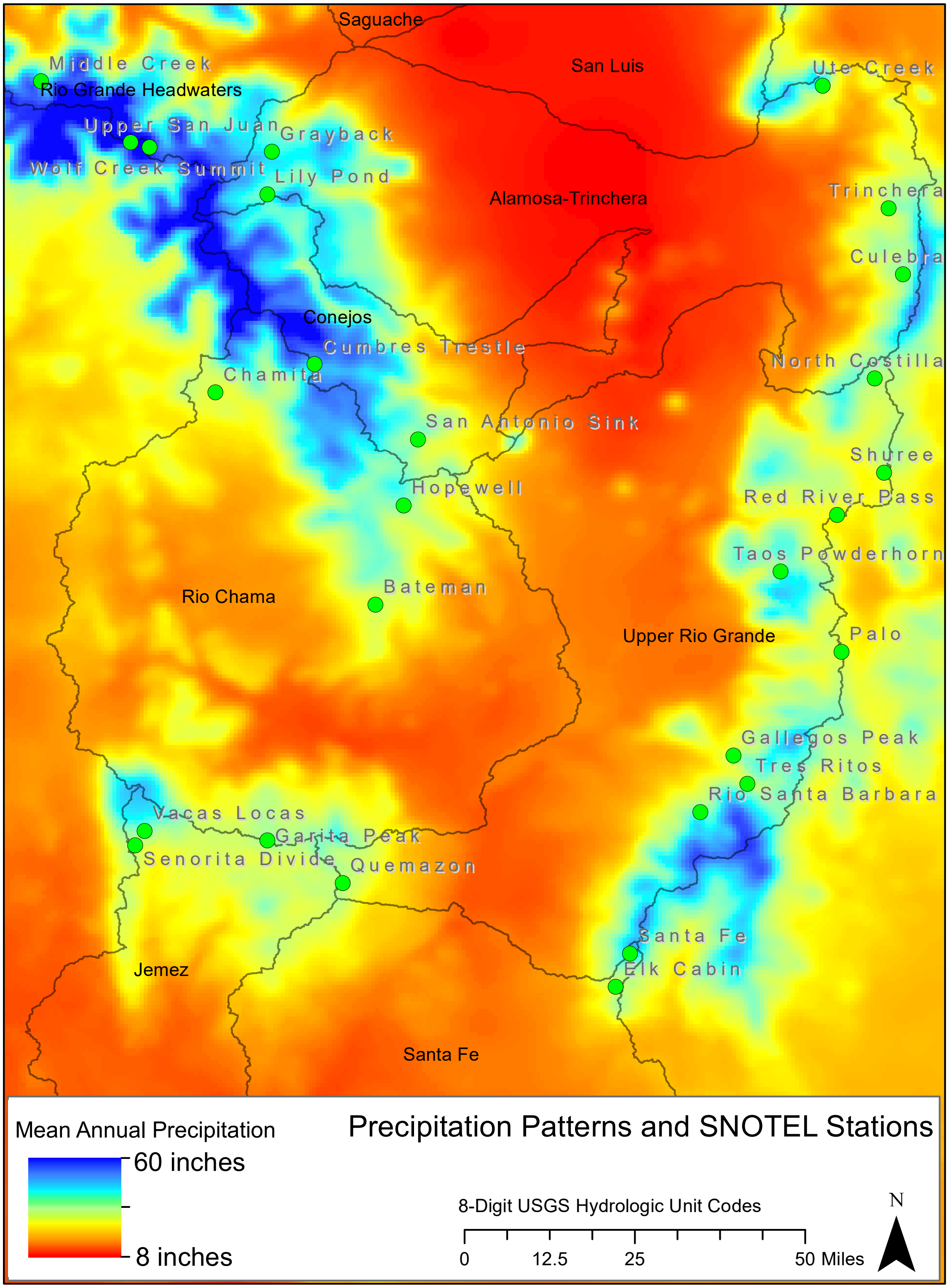

Figure 10. USDA operated SNOTEL stations combined with mean annual precipitation from the PRISM Climate Group.

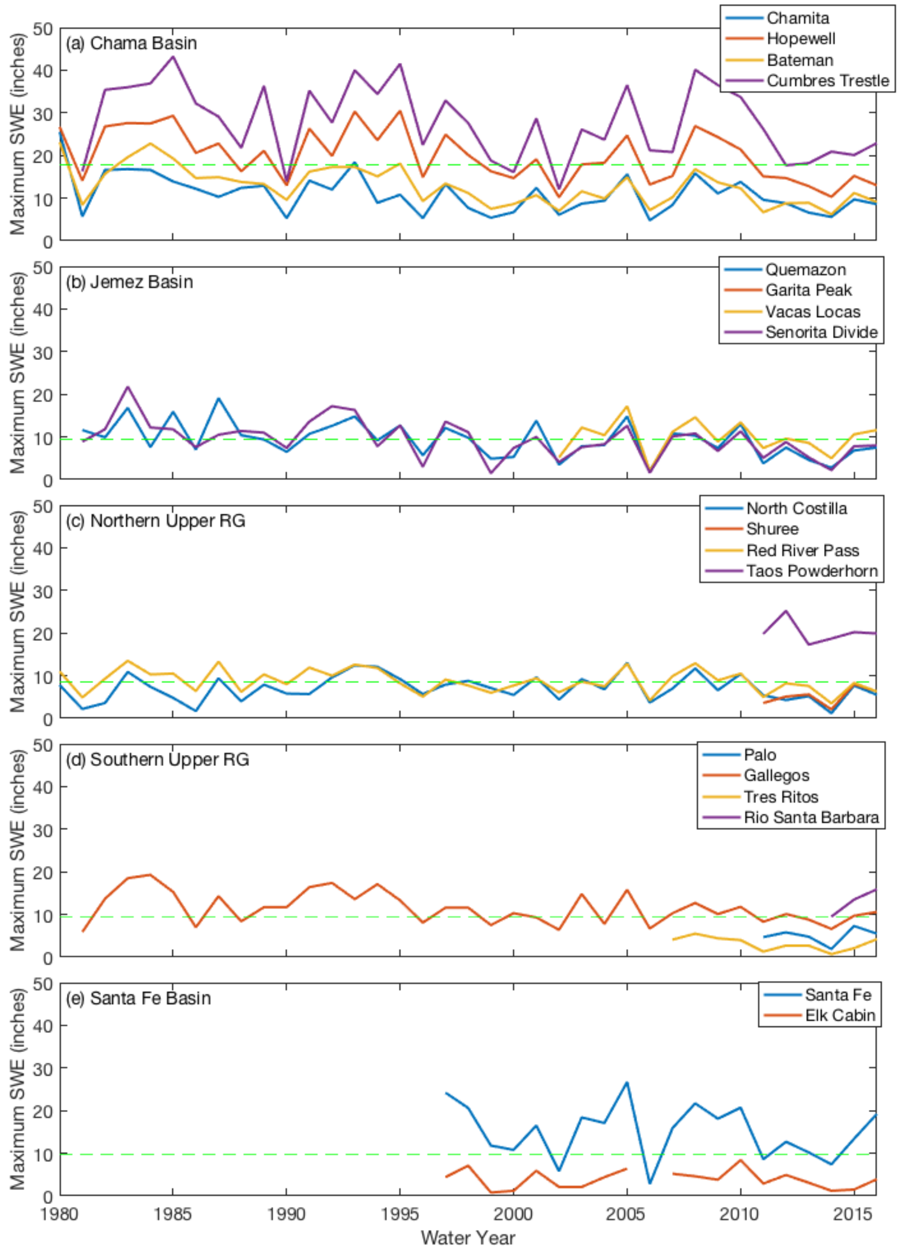

Figure 11. Annual peak snow water equivalent derived from each SNOTEL station in the NM-URG. The green dashed line represents the mean maximum SWE for each watershed over the entire observation period.

Figure 11 reveals the high degree of annual variability in peak SWE and this feature is investigated further for the Chama Basin in Figure 12 which includes the maximum SWE when averaged across all four SNOTEL stations in the basin. Figure 12 also includes the mean annual discharge for the Rio Chama as measured at the La Puente stream gage. Blue bars represent years where the maximum SWE or mean discharge was above the long-term mean (dashed green line) and the red bars represent years below the mean. As expected, a high degree of correlation is observed between the SWE and discharge data with almost perfect agreement between above and below average years; 35 out of 37 years experienced the same pattern of being below or above mean conditions in both maximum SWE and mean discharge. This correlation was further investigated in a correlation analysis between peak SWE and mean discharge in Figure 13(c). Remarkably, the R^2 coefficient was 0.8, which is extremely high for a natural system and two simple representations of complex hydrologic processes. We can conclude that water supply in the Rio Chama is heavily dependent on snowpack.

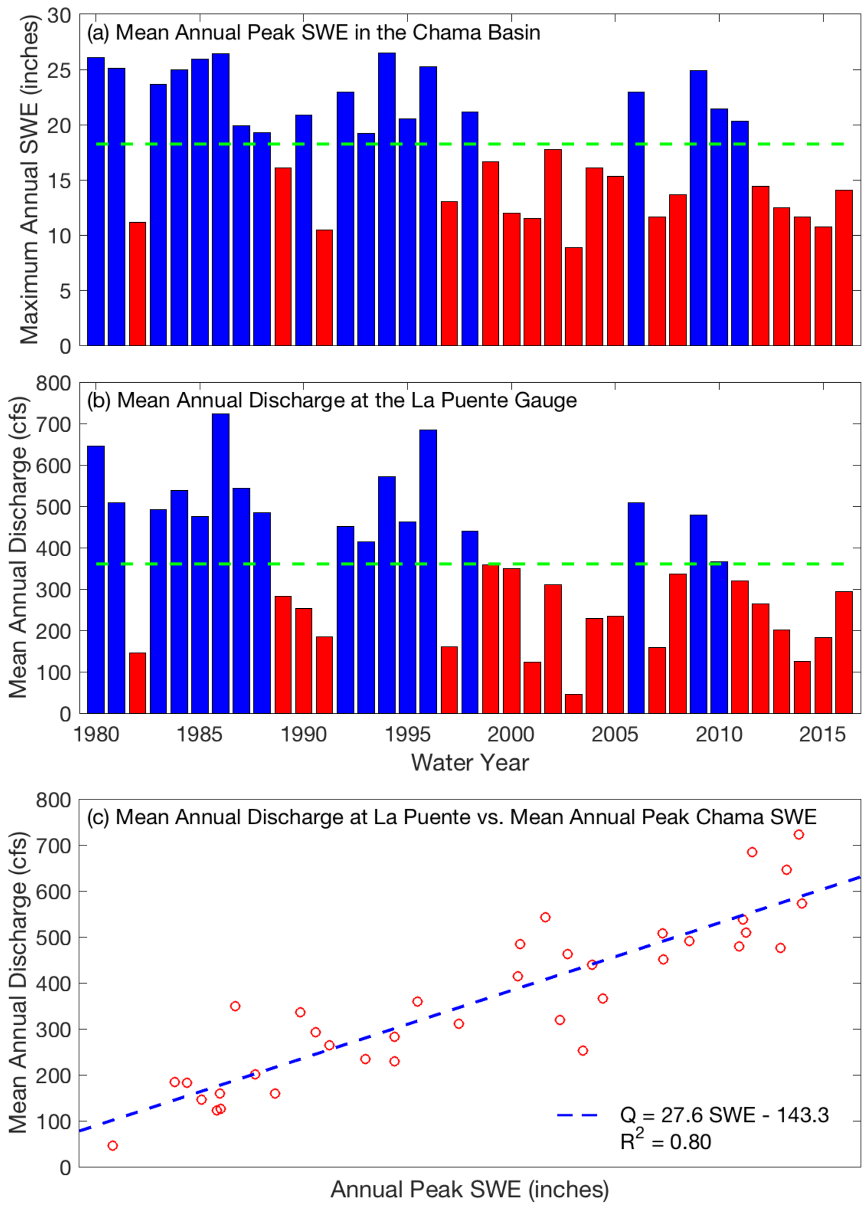

Figure 8. (a) Annual peak snow water equivalent averaged for all four SNOTEL stations on the Chama watershed, (b) mean annual discharge for the Rio Chama at the La Puente gage, and (c) A correlation analysis between peak SWE for the Chama basin and mean annual streamflow in the Rio Chama.

From Figures 8 and 10 it is clear that the high elevation mixed conifer and spruce-fir forests receive a disproportionally high amount of precipitation as compared to other parts of the basin. Figure 13 summarizes the forest composition and associated precipitation for each of the NM-URG watersheds and as a total for all four watersheds combined.

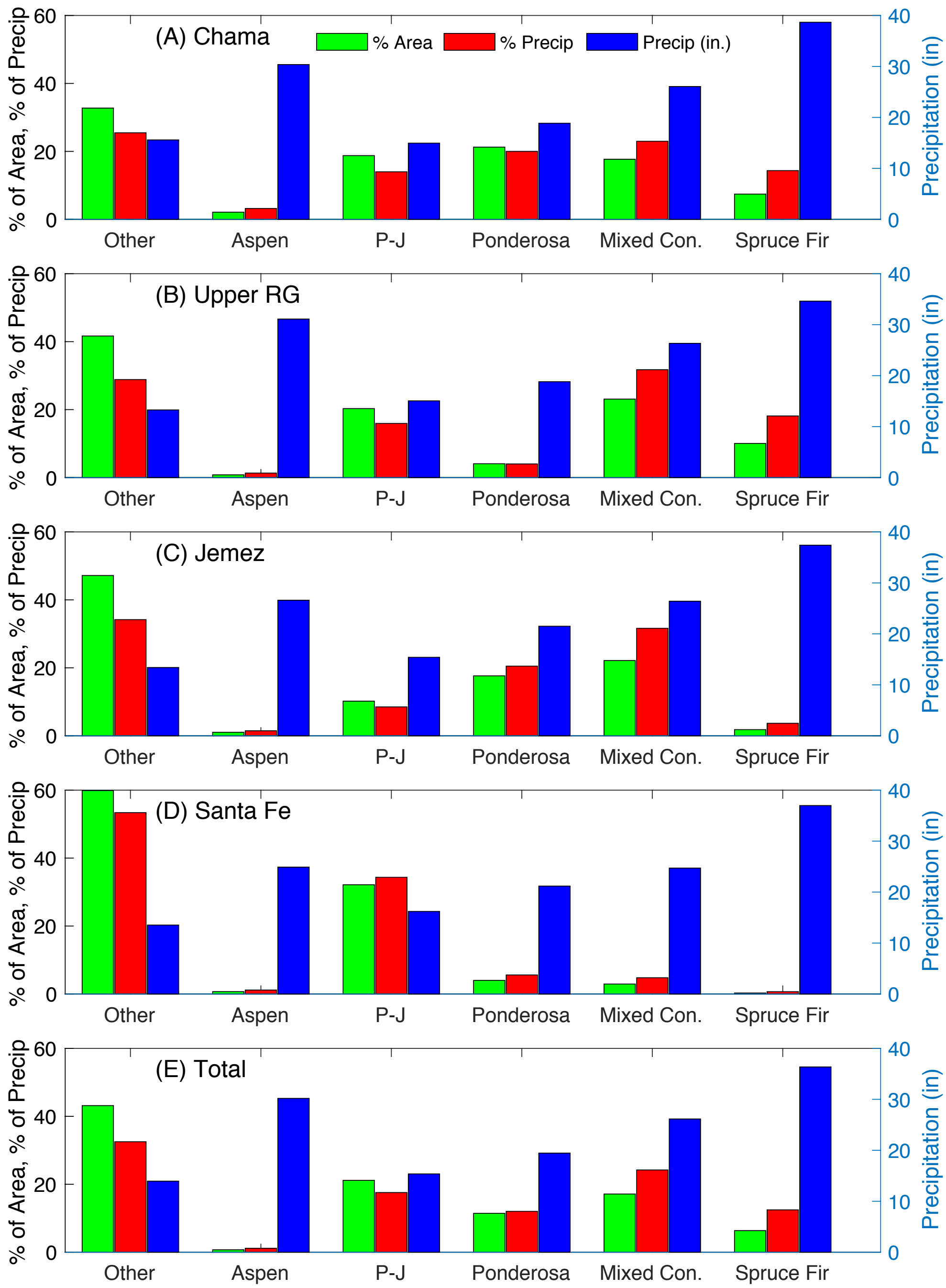

Figure 13. Area of land cover (blue) compared with precipitation volume (red) for the ponderosa and mixed conifer forest types.

In Figure 13, we see that 17% of the land area in the NM-URG watershed is covered by mixed-conifer forests but that 25% of the precipitation volume falls upon that same land use type. Consistently across all four watersheds, the precipitation volume that falls upon the mixed conifer forest type is approximately 50% larger than the associated area. A similar pattern is true for aspen forests, albeit over a much smaller area. For spruce-fir forest types, the precipitation volume is approximately twice as large as the associated area. Over the total NM-URG, the land area covered by spruce-fir forests represents approximately 6% of the area but approximately 12% of the watersheds precipitation falls upon spruce-fir forests. Precipitation associated with ponderosa pine forests is roughly equivalent with the associated area of land coverage; or in other words, this land cover type exists within an elevation band that receives an average amount of precipitation as compared to the overall watershed. Pinyon pine-juniper regions represent approximately 21% of the NM-URG area but only receive around 18% of the basins total precipitation. When combined with the analysis shown in Figure 12(c) that suggests a very strong influence of snowfall on streamflow in the NM-URG, we can conclude that water supply derived from mixed-conifer, spruce-fir, aspen, and ponderosa pine forests is of critical importance to the NM-URG water supply. A more detailed analysis, likely including a hydrologic model, would be necessary to quantify the proportion of the basins' water supply that is derived from the various forest types.

4 Analysis of Models

A detailed description of hydrologic, hydraulic, sediment yield, and sediment transport models that can be or have been used for evaluation of wildfire impacts and/or forest restoration practices is included in Appendix A of this report. The analysis includes the intended use of each model, data sources, and limitations. To summarize our findings – due to the complexities, uncertainties, and stochastic nature of of the underlying hydrologic, ecological, and social processes, existing models are not capable of optimizing watershed restoration efforts with respect to source-water protection and hydrologic response. In this section we propose a potential path for combining existing and new models, along with expert knowledge and stakeholder input, into a modeling framework. Such an approach could adaptively inform restoration activities and lead to the gradual improvement of water supply resilience in the NM-URG.

4.1 Existing Models

A wide range of models have already been developed for the NM-URG in order to support various stakeholder needs. In many cases, these models could be used directly, indirectly, or expanded upon to support a comprehensive modeling effort for the basin. Here we highlight two important existing models that could play such a role: (1) the Upper Rio Grande Water Operations Model (URGWOM) and (2) the Variable Infiltration Capacity (VIC) model. However, dozens of other models from throughout the basin could also be incorporated as fit.

URGWOM was initiated through the Middle Rio Grande Collaborative Program to support decision making and water operations in the Middle Rio Grande. A large number of federal and non-federal partners have been engaged in the original development and continuous upkeep of the model. Based on the RiverWare software package, URGWOM is essentially a complex water accounting tool that plays a critical role in tracking water through the watershed.

The VIC model was developed through the U.S. Bureau of Reclamation's Upper Rio Grande Impact Assessment (Llewellyn & Vaddey, 2013) to advance understanding of the potential impacts of climate change in the watershed. VIC is a hydrologic model that ultimately converts meteorological data (precipitation, air temperature, relative humidity, wind speed, etc.) into estimates of streamflow at key points in the watershed. USBOR used the VIC model to project changes to water supplies under multiple future climate scenarios.

4.2 Proposed Path Forward

Although no existing models exist for translating the impacts of watershed restoration to water supply resilience, we propose here a general framework for incorporating existing models and data with future monitoring and modeling activities to inform such as effort. The details of such an approach should be developed collaboratively in cooperation between the partners in the watershed including federal and non-federal agencies, non-governmental organizations, university researchers, and other interested stakeholders. The methods proposed here are intended as a general guidance and framework.

The proposed framework is conceptualized in Figure 14. The major elements are represented using boxes and the arrows indicate the flow of impacts and information between elements as the external drivers propagate through the system. The Gaussian bell curves are meant to reflect the reality that great uncertainty exists with respect to the outside drivers as well as the intermediate processes. Rather than make major assumptions about such conditions, it is preferable to embrace this uncertainty and represent future conditions as a range of possibilities – each with varying degrees of likelihood. In some cases, a continuous function might not be possible to produce or perhaps is not necessary. For example, future watershed conditions could potentially be represented with a range of potential future discrete states. For example, we might assume a watershed has not been restored, is partially restored, or has been completely restored.

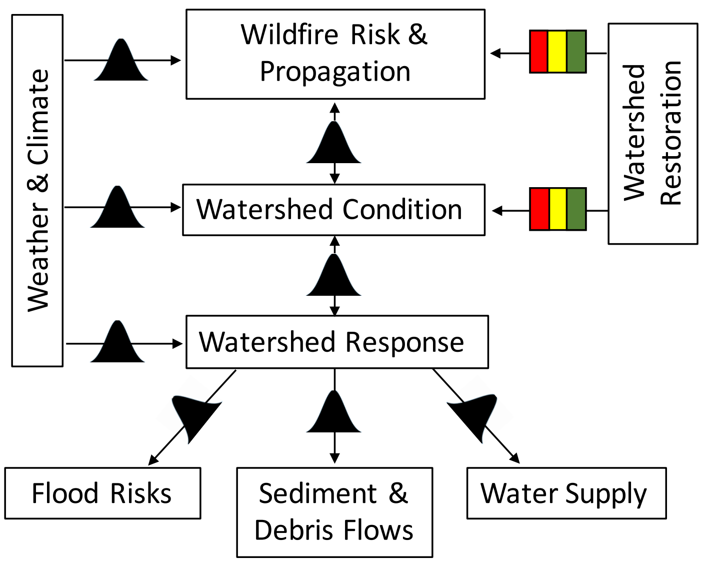

Figure 14. Conceptual representation of the proposed modeling framework for investigating the impacts of watershed restoration on water supply resilience. The bell shapes represent the probability density functions that can be produced to represent the likelihood of various outcomes. The red-yellow-green boxes provide examples of using discrete conditions (e.g. not restored, partially restored, fully restored).

Restoration activities and the climate regime will drive future wildfire risks and propagation patterns. Further, the climate and weather patterns along with restoration activities will determine the impacts of wildfires on both pre-fire and post-fire watershed conditions. Finally, the watershed condition (pre- and post-fire) and climate and weather patterns will determine how the watershed behaves with respect to flood risks, sediment and debris flows, and provisioning of a resilient water supply.

Numerical models can be used to represent aspects of this conceptual model. For example, climate models can describe the range of potential future climate conditions and fire propagation models can be used to investigate wildfire behavior. The existing VIC model can be adjusted to investigate watershed response to restoration and wildfire. Further, URGWOM can be used to test how changes in the water supply are likely to influence water deliveries.

5 Summary and Recommendations

The purpose of the study was to investigate the potential changes in water yields and water supply resilience in tributary watersheds to the Rio Grande as a result of forest restoration and wildfires with a focus on high-elevation forested areas. The review of existing literature, data, and models provided insights into current knowledge and limitations to our knowledge in the NM-URG. Although much can be learned from other basins with similar conditions and processes, there is a severe shortage of research on the hydrology of high-elevation portions of the NM-URG. Nearly all field research at high-elevations in New Mexico has been conducted in the Jemez Mountains. Thus, additional fundamental and applied research is needed in high-elevations regions such as the Chama and Upper Rio Grande watersheds.

An initial investigation into existing datasets in the NM-URG reveals strong spatial and temporal correlations between elevation, water availability, vegetation types, and water yields. The preliminary analyses underscored the important role of high-elevation wet mixed-conifer forested areas for generating water supplies. Although these areas represent only 19% of the area, 30% of the watershed precipitation volume falls on wet mixed-conifer forest stands. These results underscore the need for additional data collection and a justification for watershed protection in these areas.

The processes of interest in this work are complex, dynamic, spatially variable, stochastic, and highly non-linear. In other words, it is exceptionally difficult to produce meaningful models to inform and attempt to optimize watershed restoration to enhance water supply resilience. However, a modeling framework has been proposed that embraces these complexities and uncertainties. Such an approach would require broad cooperation across all stakeholder groups in order to build upon existing knowledge and models.

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Appendix A. Summary of Models

Models Used in Wildfire and Watershed Restoration Studies

Predictive models of hydro-geomorphic processes are used by land managers to assess risks, quantify rehabilitation effectiveness, prioritize resources, and evaluate trade-offs between management strategies. Predictions can be difficult to make, however, because of heterogeneous landscapes, stochastic rainfall, and the transient and variable fire effects (Nyman et al, 2013).

Few studies attempt to model the range of possible post-fire hydrologic and geomorphic hazards because of the sparseness of data and the coupled, nonlinear, spatial, and temporal relationships among landscape variables. It is difficult to state that how many post wildfire models are available. Here we have provided an overview of 12 models that are commonly used to evaluate modified hydrologic and geomorphic conditions in post-wildfire environments. All these models have used mostly in the southwest region after a wildfire event. Not all the models focus on the same area. The focus area varies according to the post wildfire condition such as soil loss or changed soil properties, post-fire flash floods, changed runoff, peak flow, peak discharge, vegetation loss, debris flow etc. There are tradeoffs associated with each model. Thus, the overviews include descriptions of the limitations to each model. All models represent a simplification of real world conditions, and in the case of post-wildfire modeling, the uncertainty associated with model use will almost always be very high.

1. The Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) (Renard, Foster, Weesies, McCool, & Yoder, 1997) was designed to predict annual soil loss (Mg ha^{-1} y^{-1}) from hillslopes due to rain splash and runoff. It was originally developed for agricultural systems but its use is now widespread across different land uses and natural environments including burned landscapes (Larsen & MacDonald, 2007). The predictions reflect an annual average response and the model is not intended to consider the magnitude of individual events. Thus, it is unsuitable for predicting event-based impacts.

The model represents basic topographic and soil information and therefore can be effective at distinguishing between areas of high and low erosion potential – despite the lack of accuracy in absolute terms. As such it can be a useful tool for prioritizing locations of and prescriptions for post-fire rehabilitation efforts (Nyman et al, 2013) and assessing the effectiveness of erosion control strategies (Rallison & Miller, 1982). RUSLE and other similar models are readily coupled with GIS and remotely sensed data on fire severity to produce landscape-scale assessments of yearly post-fire erosion potential (Rallison & Miller, 1982). This type of assessment can produce a conceptually representative measure of the relative erosion potential across burn areas.

Limitations: One of the major concerns of RUSLE is that it is not intended for application to large areas as the natural variability of vegetative cover, soil types, topography, precipitation events, and other influencing factors within that area is inherently complex. Likewise, a concern for using RUSLE is the limitations for slope length and slope steepness (Jones, 2001). Because these parameters are calculated from actual field measurement, which are labor intensive, as the user needs to gather a great deal more on the ground information to use the model effectively which may require substantially more time and expert assistance. Estimation of slope length factor and steepness factor for high quality (10m and 30 m) DEMs by the Arc/INFO AML program are resource extensive too. Because each run of a DEM for a small sub region (100 km by 100 km) for slope length and steepness factor require as long as 3 days to one week to complete on a 300-Mhz UNIX workstation (Remortel et, al. 2001). There are also practical limitations when applying the technique to large mountainous regional scale.

2. The Erosion Risk Management Tool (ERMiT)

The Erosion Risk Management Tool (ERMiT) is a distributed and event-based hydrologic model which uses the Water Erosion Prediction Project (WEPP) to model runoff and erosion response for individual storms after a fire (Robichaud et al, 2007). WEPP was initially developed in an agricultural context but has been advanced to better represent systems that are more variable in time and space (Nyman et al, 2013).

"Event sediment delivery exceedance probability" output of ERMiT can help managers decide where, when, and how to apply treatments to mitigate the impacts of post-wildfire runoff and erosion on life, property, and natural resources (Robichaud et al, 2007). With ERMiT, managers can establish a maximum acceptable event sediment yield and use ERMiT to determine the probability of "higher than acceptable" sediment yields occurring. The maximum acceptable event sediment yield will vary within a burned area. ERMiT is specifically designed to help land managers assess the risk of damaging runoff and erosion events after fire with and without mitigation treatments such as seeding, straw mulch, and erosion barriers. The model is more detailed and accurate than RUSLE in its representation of erosion processes (and fire effects), which also means that more detailed data are required for parameterization (Larsen & MacDonald, 2007). ERMiT combines the event-based WEPP response model with storm outputs from a stochastic climate generator (CLIGEN) to simulate the full range of potential post-fire erosion outcomes for a sequence of yearly post-fire increments (Robichaud et al, 2007).

Limitations: Land managers need more information and tools to determine hazard probabilities and balance the costs and potential benefits of fire treatments to reduce runoff and erosion. Another concern is that ERMiT does not provide "average annual erosion rates" rather; it provides a distribution of event erosion rates with the likelihood of their occurrence (Robichaud et al, 2007). Although more physically based than RUSLE, ERMiT is still highly dependent on several empirical formulas that have limitations when applied to highly modified landscapes (e.g. severely burned soils). There is seasonal difficulty as mostly the empirical formula set for monsoonal period and the results got changed for rainfall below threshold. The empirical formulas do not adequately represent key process such as infiltration. It does not match with the field studies and it is difficult to separate model errors from measurement errors (Larsen & MacDonald, 2007)

3. The Fire-Enhanced Runoff and Gully Initiation Model (FERGI)

The Fire-Enhanced Runoff and Gully Initiation Model (FERGI) combines a stochastic climate generator and a deterministic geomorphic model to estimate the probability of post-fire rainfall excess, peak flow, and gully initiation in catchments with and without contour felled logged barriers (Istanbulluoglu, 2004). The model is commonly used to predict peak flows, and is essentially a modified rational method based on field measurements of water repellency. The model represents hillslope processes in headwaters in order to find the upper end of channel segments, determined by threshold based channel initiation conditions. Outputs from FERGI include peak flow (m3 $s^{-1}m^{-1}$), gully length (m) and the effectiveness of log barriers in preventing gully erosion as a function of storm return periods. The model does not provide direct estimates of erosion but assumes that once a gully has been initiated the sediment transport rate is at capacity (Istanbulluoglu, 2004).

Limitations: FERGI does not provide pre-fire rainfall estimates, runoff amount, and gully initiation positions so users cannot compare pre- and post-fire changes. It also does not estimate erosion. Other major concerns are that FERGI does not consider post-fire debris flow and it requires detailed soil parameter information (Foltz et, al. 2009). The only watershed treatment that can be considered is the implementation of log barriers. Again, the underlying hydrologic calculations depend upon empirically-based equations (Rational Method), which have limitations when applied to a highly altered landscape because it considers only 24-hour storm duration so is not applicable to the regions where the damaging storm duration is much shorter such as 15 or 30 minutes. Also it is available only for forest service intranet and does not consider watershed shapes and assumes a rectangular hillslope and it only uses metric units.

4. Analytical Peak Flow Model

An analytical method was developed to predict post-wildfire peak discharge based on the natural pairs of rainfall and runoff measurements from actual burned basins (Moody, 2012). By using natural pairs of rainfall and runoff, the analytical method retains the cause and effect relation, whereas other methods, such as the curve number method, do not. The analytical method is applied to predict post-wildfire peak discharges for selected basins burned by a wildfire, and these analytical predictions are compared with numerical computer predictions for the same basins.

Application: This method was used for Buffalo Creek Fire-Spring Creek (1996) (Colorado), Cerro Grande Fire-Rendija Canyon (2000)(New Mexico), Cerro Grande Fire-Pueblo Canyon (2000)(New Mexico), Bobcat Fire-Bobcat and Jug Gulches (2000) (Colorado), Galena Fire-Bear Gulch (South Dakota), Nevada and California Fires (1988) (Moody, 2012) .

The model predicts the peak discharge per unit area Qu ($m^3s^{-1}km^{-2}$) from small upland catchments (0.25–26.8 km^2) given a 30-minute rainfall intensity (I_{30}) and a known fire severity (Nyman et al, 2013). The model accommodates different levels of detail in representation of fire impact. At the most basic level, the fire impact is given by the proportion of catchment burned, and represented through changes in a runoff coefficient, which determines the conversion of I_{30} to unit discharge. At a more complex level, the model uses the normalized burn ratio (DNBR) to incorporate information on the spatial configuration of burn severities along a hillslope (J. A.

Moody, 2012). The spatial pattern of fire severity along flow paths is parameterized through a hydraulic functional connectivity parameter. The hydraulic functional connectivity provides a more realistic representation of fire effects than the modified runoff coefficient, which assumes a uniform and spatially averaged fire impact. In the third level of complexity the effect of recovery is represented through yearly adjustments to the peak flow parameters (runoff coefficient and functional connectivity).

Limitations: Post-fire flow is difficult to predict because necessary data on soil properties are lacking, in addition to the paucity of rainfall-runoff data for burned basins (Moody, 2012). Some times it becomes difficult for large altered watershed to define the loss of vegetation because it changes rainfall interception, absorption properties.

5. Curve Number Method

The curve number (CN) approach has been used for predicting runoff in undisturbed catchments (USDA, 1986). The method relies on a curve number (CN) parameter derived from data sets of paired rainfall-runoff measurements in small upland catchments. This parameter provides an estimate of how much runoff (mm) is generated per every mm of rainfall after the catchment storage potential is depleted. Curve-number parameters have been generalized for catchments based on their soil hydraulic properties, vegetation and hydrologic condition. The depth of runoff is converted to a measure of peak discharge by incorporating a time of concentration parameter, which is influenced by surface roughness, channel configuration and topography. Fire effects on peak flows can be quantified by estimating CN for pre and post-fire conditions (Bambrick, 2012). The degree of change in CN between pre and post-fire condition is varied to reflect different fire severities and different sensitivities to fire impacts.

Limitations: The curve number approach to predicting runoff generation has been the subject of a number of critical reviews. Further work is required to clarify under what conditions the method gives satisfactory predictions (Hernandez et al, 2005). The model results are highly sensitive to modeler's estimate of the curve number, which is known to be highly uncertain and spatially variable for burned watersheds.

6. Self-Organized Map (SOM)

Self-Organized Map (SOM) is a type of unsupervised artificial neural network, which is trained using data from 540 burned basins in the western United States (Friedel, 2011). In Friedel's study (2011), the sparsely populated data set includes variables from independent numerical landscape categories (climate, land surface form, geologic texture, and post-fire condition), independent landscape classes (bedrock geology and state), and dependent initiation processes (runoff, landslide, and runoff and landslide combination) and responses (debris flows, floods, and no events).

The SOM technique is a type of unsupervised neural network that learns to project, in a nonlinear manner, from a high dimensional input layer to a low-dimensional discrete lattice of neurons called the output layer (Friedel, 2011). The learning process occurs in two phases: an ordering phase (when large changes are made to the neurons) and tuning phase (when smaller changes are made to units immediately adjacent to the winning neuron). Ultimately, this training process results in an organized map, where the asymptotic local multivariate density of the weights approach that of the training set (Martinetz & Schulten, 1994).

It is possible to identify relations among variables in post-fire landscape system elements (climate, susceptibility and initiation processes, and responses) at the western U.S. scale (Friedel, 2011). Many variables in certain categories are highly correlated indicating an unnecessary redundancy in describing system contributions.

The SOM is able to forecast the simultaneous effects of changing climate on multiple post-fire hydrologic and geomorphic responses. The fact that 60 independent basin forecasts of initiation process and response variables sum to one suggests that relations in the underlying multivariate density provide a reasonable constraint at this scale of study (Friedel, 2011). Further support for this assertion is the post-fire landscape trend in which these basins indicate a decrease in the number of debris flows, flooding, and runoff events under dry conditions. Whereas the decreasing trend in the forecasted number of events is intuitively anticipated under a drier climate scenario, its ability to simultaneously forecast the individual basin effects is considered more important from a hazards perspective. Forecasting the annual climate effects can be profitable for planning and management of basin resources, particularly because of the long-term basin recovery process and future climate change projections. Likewise, implementation of a SOM-based approach affords the possibility for real time forecasting of regional post-fire hazards (Friedel, 2011).

Limitations: One major problem with SOM is getting the correct data. Unfortunately the researchers need a value for each dimension of each member of samples in order to generate a map. Sometimes this simply is not possible and often it is very difficult to acquire all of the data. The final major problem with SOM is that it is very computationally expensive and difficult to apply for users without backgrounds in machine learning techniques (Germano, 1999).

7. **AGWA (Automated Geospatial Watershed Assessment) GIS-Based Hydrologic Modeling Tool**

AGWA provides the functionality to conduct pre-and post-fire watershed assessments for two widely used watershed hydrologic models using readily available standardized spatial datasets. The two models currently incorporated into AGWA are the Soil & Water Assessment Tool (SWAT) (Arnold et al, 2012) and the KINematic Runoff and EROSion Model (KINEROS2) (Smith, Ammann, Bartoldus, & Brinson, 1995). SWAT is a continuous-simulation model for use in large (river basin scale) watersheds. KINEROS2 is an event-driven model developed for small (<100 km^2) arid, semi-arid, and urban watersheds (Arnold et al, 2012). The AGWA tool combines these models in an intuitive interface for performing multi-scale watershed assessments (Goodrich et al, 2005)A GIS provides the framework within which spatially distributed data are collected and used to prepare model input files and evaluate model results in a spatially explicit context.

The AGWA Tools menu is designed to reflect the order of tasks necessary to conduct a watershed assessment (Goodrich et al, 2005). This process consists of five major steps: (1) watershed outlet identification and watershed delineation; (2) watershed subdivision by topographically controlled contributing areas; (3) model parameterization based on topography, land cover, and soils; (4) preparation of parameter and rainfall input files; and, (5) model execution and visualization, and comparison of results. Some of the possible output variables are evapotranspiration, infiltration, percolation, transmission loss, runoff, water yield, erosion rate, sediment yield, peak sediment discharge, and peak runoff rate.

Analysis and Application: AGWA is widely applied within the Burned Area Emergency Response (BAER) community. For example, it was applied to several watersheds on the eastern side of the Jemez Mountains following the Las Conchas Fire in 2011. The overlay of land cover and soils allows AGWA to select a parameter set appropriate for that given land cover on that soil. The addition of a burn-severity map allows further characterization of hydrologic response based on the land cover, soils classification and burn severity. A critical element in using AGWA for post-fire assessments is translating a burn severity map into relationships that can be used to alter infiltration and erosion model parameters. The burn severity map for the 2011 Las Conchas Fire illustrates a complex mosaic of low, moderate, and high severity burns. The AGWA tool offers the capability of rapid post-fire watershed assessments to more effectively target remediation efforts.

Limitations: One important limitation of using the kinematic approximation to the fully dynamic flow equation is that the kinematic wave equation assumes a free-overall downstream boundary condition. Thus, a kinematic wave description cannot predict the backwater effects of an obstruction to the flow for a surface flow event (Hernandez et al, 2005). One of the limitations is the capability of overland flow simulation between an upper sub-watershed (i.e., single-land use sub watershed, such as agricultural field) and lower sub-watershed (i.e., single-land use sub watershed, such as Vegetated Filter Strip)(Park et al, 2011). The model does not calculate sediment from upper sub watersheds to lower sub watersheds for overland flow.

8. The Distributed Hydrology Soil-Vegetation Model (DHSVM)

Removal of forest vegetation by any means will tend to alter runoff characteristics in a snow-dominated system, and the mechanism of removal affects the types of hydrologic changes that are produced (Stonesifer, 2007). Fires can create physical, chemical and biological changes in soils that affect hydrologic response in a watershed. Vegetation changes resulting from fire also differ from those due to forest harvest. Depending on the fire severity, partial to full combustion of the understory and overstory components may occur (Stonesifer, 2007).

DHSVM provides a dynamic representation of watershed processes at the spatial scale described by Digital Elevation Model (DEM) data (typically 10 - 90 m horizontal resolution) (Wigmosta, Nijssen, Storck, & Lettenmaier, 2002). DHSVM is a spatially explicit hydrologic model that accounts for the physical processes affecting the movement of water on and through the landscape with a distributed, deterministic approach (Wigmosta et al, 2002). In general, the model dynamically represents the spatial distribution of evapotranspiration, snow cover, soil moisture, and runoff across a watershed (Wigmosta et al, 2002). It is theoretically able to simulate runoff, route the movement of sediment and water through the landscape, and pinpoint specific locations prone to mass wasting failure. A GIS interface is used to automate model setup and facilitate the analysis of model output. The GIS is used to assign spatially distributed model input parameters to DEM grid cells using overlays of soils, vegetation, roads (including culvert locations), and stream channels (Wigmosta et al, 2002).

Based on the user defined date of a fire and a vegetation burn severity grid at the same resolution and extent of the other raster inputs, the DHSVM fire model edits the soil and vegetation parameters to reflect the burn severity patterns following a fire (Stonesifer, 2007). The fire model creates new soil and vegetation types characterized by the pre-fire conditions and the associated burn severity classification. In addition, the model allows soil and vegetation to recover following a fire, making yearly adjustments to the physical parameters of fire-affected pixels.

Application: The Distributed Hydrology-Soil-Vegetation Model (DHSVM) was applied to the Eightmile Creek watershed in western Montana (Stonesifer, 2007). The purpose of using the model was primarily to assess the applicability of the model as a cumulative effects assessment tool in the post-fire landscape of a forested watershed in this region.

Limitations: As DHSVM is a "research model," there is no user support beyond a web page and a user email list serve. This lack of support can be problematic for new model users for many reasons. The model code has limited translatability between computers. Finally, the cost of using DHSVM is relatively high when compared to other hydrologic models (Stonesifer, 2007).

9. A GIS-Based Flash Flood Runoff Model

The purpose of a GIS-based flash runoff model is to construct a direct unit hydrograph for excess rainfall by estimating the stream flow response at the outlet of a watershed. It uses only DEM (Digital Elevation Model), land cover, soil type, and rainfall data (Gioti, Riga, Kalogeropoulos, & Chalkias, 2013). The time-area method provides a unit hydrograph, which requires spatially constant excess rainfall data, ignoring the spatial variation of precipitation. Initially, it may be used in order to predict areas that are vulnerable to intense flood events. Consequently, such models could contribute to the economic and environmental protection of a potentially affected area (Gioti et al, 2013).

One of the most prevalent ways to assess the runoff generated by rainfall is by using a unit hydrograph. Development of GIS software has allowed rapid and accurate calculation of geometric basin parameters and improved results in hydrograph derivation methods that required spatial analysis (Li et al. 2009). This model can develop a direct hydrograph for each spatially distributed rainfall event without relying on developing a spatially lumped unit hydrograph. The sum of travel times of cells along a flow path is the travel time from each grid cell to the watershed outlet. The model is based on raster data structures. Grids such as elevation, land use, soil type, are used to describe spatially distributed soil parameters. Moreover, hydrologic features of each grid, like slope, flow accumulation, flow direction and flow length, can be calculated using standard function included in GIS (Gioti et al, 2013).

Particular geomorphological and morphological characteristics such as slope, flow direction, flow accumulation and flow length layers as well as hydrological basins and the drainage network are estimated for the study area. The most important steps in order to simulate the real rainfall event are the calculation of the travel-time layer, which indicates the time needed for the water to reach the outlet of the basin, as well as the extraction of the isochrone map which are lines of equal travel time to the outlet of basin. Subsequently, a routing model which combines all the above maps is created in a GIS environment. This model can be used after a wildfire. One of the major impacts after post-fire is flash flooding and this model can assess the post-fire runoff and develop a direct hydrograph after the event. Initially the model can be used in order to predict areas, which are vulnerable in intense flood events after a wildfire event. And consequently the model could contribute to the economic and environmental protection of the potentially affected area (Gioti et al, 2013).

<u>Limitations</u>: One severe limitation is that precipitation is assumed to be homogenous over the basin for the duration of the time step or for the entire rainfall event(Snell & Gregory, 2002). Inherent to the method is an assumption of a linear response between precipitation and runoff

volume. Also it is found that an uneven distribution of rainfall produced skewed runoff results, thereby introducing error into the flood prediction (Snell & Gregory, 2002).

10. Hydrologic Modeling System (HEC-HMS, U.S Army Corps of Engineers)

HEC-HMS is a widely accepted rainfall-runoff prediction tool that calculates stream discharge from a precipitation event. The program was developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, and is capable of quantifying changes in runoff under different watershed characteristics, including land use, soil moisture, and most importantly for this analysis, fire (Abramson et al. 2009).

HEC-HMS estimates stream discharge by converting precipitation on the land surface into runoff in the stream. Several rainfall-runoff methods are supported. The program makes separate calculations of runoff for each sub-basin in the watershed, then routes water from the sub-basins into the channel. Model parameters for each sub-basin and stream reach are estimated using ArcGIS and spatial information on land cover, soil characteristics, channel geometry, and hydrography (Abramson et al. 2009). HEC-HMS results show a range of increases in peak discharge from pre-fire to post-fire conditions for given storms. Model output has been shown to be consistent with expected results under a range of conditions. When applied to burn sites, the model has performed well when predicting discharge under burned conditions. The USACE has developed HEC-HMS for several watersheds in the Jemez Mountains in order to assess flood risks associated with the Las Conchas Fire.

Limitations: The HEC-HMS model is best suited for estimating discharge for 2- to 10-year recurrence interval storms, and uncertainty increases greatly with storms outside of a the 2- to 25-year recurrence interval range (Abramson et al. 2009). Modeled discharge predictions also work best for rainfall events in the middle or late in the rainy season. Predictions will overestimate runoff from unburned areas when little or no precipitation has occurred in the month or two prior. Estimating model parameters in post-fire conditions requires expertise from the modeler.

11. Shallow Landslide Stability Model (SHALSTAB)

This model is used to identify areas of the watershed where sediment supply from landslides could increase, enhancing the risk of debris flows. SHALSTAB was used to identify areas of the watershed where sediment is prone to mobilization by collapse events that may evolve into debris flows (Abramson et al, 2009). This mapping program calculates the instability of a hillslope based on watershed topography and soil characteristics. It is a decision support tool designed to spatially assess the potential for sediment production from unstable slopes under different watershed conditions (Dietrich et al, 1998). With SHALSTAB, the slope instability is spatially displayed under different management scenarios by changing the input parameters to the model. To deal with the sediment production land managers have concerned for spatial scale (such as offsite effects) and temporal scale (long-term and short term effects), prediction for how quickly sediment will propagate downstream and how fast it will spread. The model has been used to asses potential post burn landslides but it is a great challenge to predict magnitude, timing and duration of downstream changes in sediment transportation (Ziemer & Lisle, 1993). SHALSTAB incorporates the slope as well as the curvature of the hillside to determine areas where soil and water will converge and accumulate, creating conditions prone to land sliding.

The model also incorporates soil properties including the internal friction angle (which depends largely on soil texture), depth, bulk density, and soil/root cohesion to identify potentially unstable sites. These areas are represented by a certain value of transmissivity, or the ability of the subsurface to convey the water downhill, which can then be compared to the intensity of a rainstorm. The SHALSTAB model calculates the ratio of rainfall intensity to transmissivity, the log of which is a measure of the site's susceptibility to failure, with a larger ratio indicating a higher vulnerability to land sliding.

Limitations: SHALSTAB only identifies areas prone to shallow landslides and cannot predict whether a slide will occur or its magnitude. It is also unable to estimate the volume of sediment delivery that may be expected. Another issue is the output of SHALSTAB does not allow for prediction of the fate of the released colluvium (Abramson et al, 2009). For example, the sediment could travel as a debris flow through stream channels, causing damage and flooding to downstream communities. Alternatively, the soil could slide downslope and be contained in natural catch basins, only affecting local geomorphologic processes or individual structures.

12. Probability Model (Debris flow/Sediment Transportation)

Empirical models to estimate the probability of occurrence and volume of post wildfire debris flows can be quickly implemented in a geographic information system (GIS) to generate debris-flow hazard maps either before or immediately following wildfires. This model describes debris-flow volume as a function of the basin gradient, aerial burned extent, and storm rainfall. The result of rainfall on burned basins is often the transport and deposition of large volumes of sediment, both within and down-channel from the burned area. Methods for assessing the potential for debris flows from basins burned by wildfires over extensive areas are needed to rapidly assess hazards and to prioritize locations for pre-fire restoration efforts (Cannon et al, 2009).

Data are collected from recently burned basins to develop multivariate statistical models that can predict both the probability that a selected basin will produce debris flows and the potential volume that may issue from the basin mouth (Cannon et al, 2009).

After values of debris-flow probability are calculated for each basin, they are proportioned into classes and assigned a relative ranking to be presented in map form. After that a hazard map will show the most hazardous basins with both a high probability of occurrence of debris/sedimentation and large volume of material.

Application: Applications of a probability model and the volume model for hazard assessments are illustrated using information from the 2003 Hot Creek fire in central Idaho. The predictive strength of the approach in this setting is evaluated using information on the response of this fire to a localized thunderstorm in August 2003 (Cannon et al, 2009).

Limitations: Application of these models using conditions of a specified storm, or set of storms, immediately following a fire will provide information necessary to make effective and appropriate mitigation and planning decisions, and will guide decisions for evacuation, shelter, and escape routes in the event of forecasts of storms of similar magnitude to those evaluated. The models described here can also potentially be linked with real-time precipitation forecasts and measurements to generate dynamic maps of potential postfire debris-flow hazards as storm conditions develop (Cannon et al, 2009).

Model Parameterization Data

The required and available datasets of each model discussed in this review are shown in Tables A1 and A2. Table 1 shows the parameters required for each model. Table 2 contains the datasets that may be available for each model.

Table A1. Required datasets for each model

Models	Elevation	Meteorology	Vegetation	Soil	Slope	Area/Map	Fire
RUSLE	10-30m DEM*	Monthly precipitation, daily rainfall	Map	Annual soil loss tons/acre	Slope length up to 18%	Land use	
ERMiT	10m DEM	Historical daily precipitation, annual runoff (rainfall, snowmelt), solar radiation, wind data	Forest, range, Chaparral	Texture, rock content	Hillslope gradient , Slope length		Soil burn severity
FERGI	DEM	Daily precipitation, wind data, evaporation		Depth to water repellent layer	Slope length,	Fraction of area trenched	

Analytical Peak Flow	DEM	Peak discharge, rain intensity					Burned basin, soil burn severity
CN	DEM	Max 24 hour rain	Map (i.e. forest, grassland, meadow)	Infiltration rate, soil texture, depth		Soil map	
SOM	10-30m DEM	Average storm intensity, hourly rainfall		Clay content, soil thickness	Slope length	Basin gradient, basin area (slopes > or equal 30% and 50% relief ratio)	Burn severity, burned soil diameter skewness
DHSVM	30m DEM	Temperature, wind data, humidity, incoming shortwave, longwave	30 m resolution vegetation cover	Soil type, soil depth		Road and stream networks	

		radiation, precipitation					
Flash Flood	DEM (high resolution)	Flow direction, channel flow and overland flow velocity, monthly rainfall		Soil type	Slope length,	Soil map, land use map, basin area, flow length	
SHALSTAB	10m DEM	Rainfall, rainstorm	Vegetation cover	Soil texture, depth, bulk intensity	Slope length		
HEC-HMS	DEM	24-hour rainfall intensity, hourly precipitation, flood data		Soil types, infiltration rates		Land use, Basin area, Drainage pattern	Burn severity
AGWA	10-30 m DEM	Annual runoff, daily rainfall, daily	Vegetation Map (i.e.	Soil type, Infiltration		Land cover, Basin area,	Burn severity

		precipitation, erosion, evapotranspiration, percolation, return flow, peak sediment	forest, grassland, meadow)	rate, soil texture, depth		Burned area	
Probability Model	10-30 m DEM, relief ratio	Short duration – low recurrence rainstorms		Soil properties		Average basin gradient, percentage of basin area (slopes greater or equal to 30%, 50%), basin ruggedness	Arial burned extent

Table A2. Available datasets for each model

Models	Available Data
RUSLE	Daily precipitation data (NOAA*), DEM (State GIS data source/USGS), Vegetation map (USGS), Land cover data (Provisional) (USGS), Slope length (DEM)
ERMiT	PRISM datasets average 30 years precipitation data DEM (State GIS data source/USGS), Wind map data (Windmapper.com) (Weather station if exist), Vegetation map (USGS), Soil data (STASGO, SSURGO), 2% or less slope data (Open EI), Soil burn severity (USDA Forest Service), Slope length (DEM)
FERGI	Daily precipitation data (NOAA), DEM (State GIS data source/USGS), Slope length (DEM), 2% or less slope data (Open EI)
Analytical Peak Flow	Peak discharge and rain intensity (long-term post wildfire studies at least 3-4 years), DEM (State GIS data source/USGS), Burned basin and soil burn severity (USDA Forest Service)
CN	Daily precipitation data (NOAA), DEM (State GIS data source/USGS), Vegetation map (USGS), Soil data and soil map (STASGO, SSURGO)
SOM	Hourly rainfall data (NOAA), DEM (State GIS data source/USGS), Soil data and soil map (STASGO, SSURGO), Basin area/gradient (USGS), Slope length (DEM)
DHSVM	DEM (State GIS data source/USGS), Temperature, wind data, humidity, incoming shortwave, longwave radiation (if weather stations or towers exist), Daily precipitation data (NOAA*), Vegetation map (USGS,USDA), Road and stream network (State GIS), Soil type (STASGO, SSURGO)

NOAA*: National Oceanic and Atmospheric Administration

Flash Flood	DEM (State GIS data source/USGS), Monthly rainfall (NOAA), Land use map (state GIS),Soil map/type (STATSGO, SSURGO), Slope length (DEM), Flow direction (from DEM), Flow length (From GIS or DEM)
SHALSTAB	DEM (State GIS data source/USGS), Daily/hourly precipitation data (NOAA), Vegetation map (USGS, USDA), Soil map/type (STATSGO, SSURGO), Slope length (DEM).
HEC-HMS	DEM (State GIS data source/USGS), Daily rainfall, hourly precipitation data (NOAA), Flood data (FEMA), Soil map/type (STATSGO, SSURGO), Basin area (USGS, State GIS), Drainage pattern (State GIS), Burn severity map (USDA Forest Service, DEM)
AGWA	DEM (State GIS data source/USGS), Daily rainfall and precipitation data (NOAA), Vegetation map (USGS/USDA), Soil type (STASGO, SSURGO), Land cover, Basin area (USGS, State GIS), Burned area (USGS)
Probability Model	DEM (State GIS data source/USGS), Basin area, gradient (USGS, State GIS), Soil map/type (STATSGO, SSURGO), Burned area (USGS), Relief ratio (Basin elevation).

Data Gaps

The Rio Grande watershed is a vast area and data availability will not be easily compiled for the entire area. Parameterization of post-fire conditions can be particularly challenging. Establishment of weather stations will be one of the necessary tasks to collect necessary meteorological data, such as snow accumulation, solar radiation, wind speed, relative humidity, precipitation, evapotranspiration, percolation, and infiltration.

Information should be gathered regarding how many weather stations exist in all the watersheds, data gaps, and priorities for additional stations. The available data mentioned in Table 2 will also depend on station locations. Thus, not all of the watersheds have the available data for model parameterization. For example Valles Caldera National Preserve (VCNP) has an extensive meteorological and hydrologic dataset for the headwaters of the Jemez watershed. On the other hand, tributaries for the Chama River have a sparse meteorological network – particularly in high elevations.

For flash-flood modeling, channel flow and overland flow velocity depends on high resolution Digital Elevation Models (DEM), which might be a concern for the overall study area. Again, good datasets exist for the VCNP and for the areas impacted by the Las Conchas fire. This data is generally not available in high-resolution format for the rest of the study area.

Besides meteorological and topographic data, the models require data on fuel loads, vegetation, and soil characteristics and condition. Also a better understanding of the impacts of forest thinning and potentiality of wildfire in different sub-basins of the Rio Grande watershed are still poorly understood.

Conclusions

Wildfires can produce hydro-geomorphic events that are detrimental to water resources or infrastructure. A wide range of models has been developed to investigate post-wildfire hydrologic and geomorphic processes and conditions. These models have been designed to reduce deterministic uncertainties in catchment-specific response models while incorporating rainfall as a stochastic variable during a recovery window. New modeling approaches are needed in order to address the larger-scale implications of climate change and fire management on longer-term catchment processes (Nyman et al, 2013).

Fire regimes, rainfall regimes and landscapes vary from region to region. Developing a basis for regional comparison of catchment processes in different fire-prone systems can therefore provide useful insights into the relative importance of landscapes, fire and rainfall regimes as controls on how fire interacts over time with hydrologic and geomorphic processes. Isolating the regional differences and their effects on processes means that catchments can be compared and evaluated in terms of how fire and storm alone may act as agents (or primers) of hydrologic and geomorphic events. A large scale perspective can help reduce some of the complexity which drives fine-scale variability while allowing the key processes that drive landscape-scale differences in post-fire response patterns to emerge. Simultaneous modeling of fire and rain storms as landscape-scale processes is challenging, but th task seems increasingly feasible with new sources of data and new modeling tools for spatial-temporal representation of fire and rainfall.

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