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The Influence of Restoration Treatments on Hydrologic Output in Fire-Adapted Forests of the Southwest

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Intermountain West Frequent-Fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The Society for Ecological Restoration International defines ecological restoration as "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability….Restoration attempts to return an ecosystem to its historic trajectory" (Society for Ecological Restoration International Science and Policy Working Group 2004).

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

The Southwest Fire Science Consortium (SWFSC) is a way for managers, scientists, and policy makers to interact and share science. SWFSC's goal is to see the best available science used to make management decisions and scientists working on the questions managers need answered. The SWFSC tries to bring together localized efforts to develop scientific information and to disseminate that to practitioners on the ground through an inclusive and open process.

ERI working papers are intended to deliver applicable science to land managers and practitioners in a concise, clear, non-technical format. These papers provide guidance on management decisions surrounding ecological restoration topics. This publication would not have been possible without funding from the USDA Forest Service and the Southwest Fire Science Consortium. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as representing the opinions or policies of the United States Government. Mention of trade names or commercial products does not constitute their endorsement by the United States Government or the ERI.

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Cover photo: Projects to restore forests surrounding storage reservoirs, like C.C. Cragin in Arizona, aim to protect water quality and supplies from the debris and ash that clog streams and rivers as a result of high intensity wildfires. *Photo courtesy of Coconino National Forest, USDA Forest Service.*

Table of Contents

Introduction

Water is a vital and scarce resource in the southwestern U.S. The sustainability of water resources depends on the health of high-elevation forests that are the source of most water in southwestern streams, rivers, and aquifers (Barr et al. 1956; Flerchinger and Cooley 2000; Scanlon et al. 2006). Forests support water supplies for cities and towns, irrigated agriculture, aquatic and riparian ecosystems, recreational opportunities, and sites of historical and cultural significance.

Fire suppression, logging, and grazing beginning in the late 19th century have led to a decline in the health of southwestern forests (Covington et al. 1997). Before Euro-American settlement, frequent, low-intensity fires maintained a sparse distribution of trees in ponderosa pine and mixed-conifer forests. The exclusion of fire led to substantial increases in tree density and basal area and an increased risk of high-intensity, stand replacing wildfires (Fulé et al. 1997; Fulé et al. 2003). Forest restoration seeks to return forests to a more natural condition by thinning trees to reduce density and conducting prescribed burns in the understory or managing natural or human-caused fires to restore a low-intensity fire regime (Covington et al. 1997). The past and present structure and restoration of southwestern forests is described in detail by Friederici (2003) and in Ecological Restoration Institute working papers no. 22 for ponderosa pine and no. 28 for mixed conifer.

The immediate goal of forest restoration is to reduce wildfire risk, but improved watershed health and function is often a secondary goal. The pace and extent of forest restoration has increased since Congress established the Collaborative Forest Landscape Restoration Program in 2009, which provides funding to science-based ecosystem restoration projects. A number of forest restoration projects to protect municipal water supplies are planned or underway in fire-adapted forests in the Southwest, including the Flagstaff Watershed Protection Project, the Upper South Platte Watershed Protection and Restoration Project near Denver, and the Santa Fe Municipal Watershed Project. Forest restoration in the Southwest will expand to the landscape scale in the coming decades. The Four Forest Restoration Initiative (4FRI) plans to conduct thinning and prescribed burning on 2.4 million acres of forest in Arizona (USDA 2013). Large-scale restoration is also being planned in New Mexico through the Rio Grande Water Fund (RGWF 2014). With the increase in scale of forest restoration, it is possible that restoration treatments will affect major river basins and regional aquifers.

This working paper summarizes research relevant to understanding the effect of restoration treatments on the hydrologic cycle of southwestern forests. An overview of forest hydrology in the Southwest is presented, followed by discussions of forest restoration and wildfire effects on water quantity, water quality, and hydrologic function.

Forest Hydrology in the Southwest

The forest water cycle is essentially a balance between inputs from precipitation and outputs from evapotranspiration, runoff, and groundwater recharge (Figure 1). Differences in the timing of inputs and outputs result in water storage in snow and soil moisture. The key components of the water cycle in southwestern forests are discussed in this section.

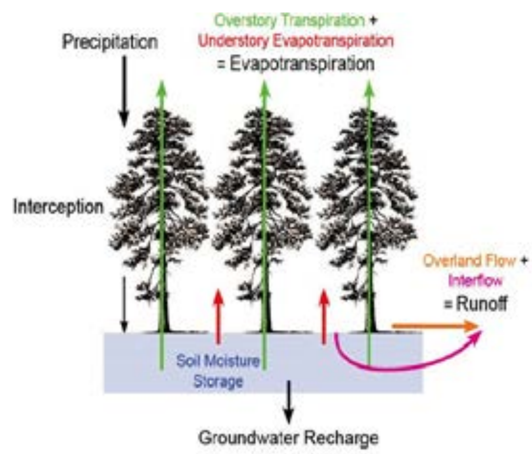

Figure 1. Diagram of the forest water cycle. Evapotranspiration is the sum of plant water use (transpiration) and direct evaporation to the atmosphere. Runoff is partitioned into overland flow, which runs off directly and interflow, which infiltrates the soil and discharges at another location.

Precipitation

Precipitation in the Southwest is characterized by wet seasons occurring in the summer and winter. Summer precipitation is driven by the North American monsoon, which draws pulses of moisture from the Gulf of California and the eastern Pacific Ocean producing localized thunderstorms. Summer precipitation accounts for 35–50 percent of annual precipitation in forested areas, with the percentage generally decreasing with increasing elevation (Vivoni et al. 2008). Winter precipitation is fed by moisture originating in the northern Pacific Ocean and transported eastward by polar and subtropical jet streams (Sheppard et al. 2002). Two large oceanic temperature cycles, the El Niño Southern Oscillation

(ENSO) and the Pacific Decadal Oscillation (PDO), have been shown to affect winter precipitation in the Southwest (Sheppard et al. 2002). The ENSO shifts between El Niño and La Niña every two to seven years. Winter precipitation tends to be higher during El Niño, when warm water is pushed eastward in the Pacific. The ENSO interacts with the PDO, another oceanic temperature cycle that switches between a warm and cool phase every 15–25 years (Mantua et al. 2002). Warm PDO phases have coincided with increased moisture in the Southwest, while cool phases in the PDO have coincided with drier conditions.

Since 1996, the forested, high-elevation regions of the Southwest have been in an extended drought (Cayan et al. 2010) associated with a cool phase of the PDO. During the 15-year period between 1997 and 2012, a 19 percent reduction in total precipitation was observed in Flagstaff, Arizona, and a 15 percent reduction was observed in Santa Fe, New Mexico, when compared to the preceding 15 years (1981–1996) (Cayan et al. 2010). Summertime precipitation has remained more or less consistent through the current drought, but winter precipitation has been far more variable and total levels of precipitation during these seasons have declined. While climate change is not expected to alter the total annual precipitation received in the Southwest, it may result in a shift toward more frequent and intense monsoon storms and less winter precipitation (Christensen et al. 2004; Diffenbaugh et al. 2008). Increases in temperature and the length and severity of heat waves are also expected with numerous potential impacts on the water cycle (Jardine et al. 2013). The implications of these shifts are discussed in the following sections.

Management Implications

- Overall, precipitation in the Southwest is highly variable in both the short-term, due to interannual variations in the North American monsoon and ENSO cycles, and long-term, due to the PDO. Therefore, scenarios considered in planning for natural resource management should draw from a multi-decadal record, if possible, to represent the full range of climate variability.

- Climate change is expected to result in a shift toward more summer precipitation and less winter precipitation as well as increased temperatures. Resources that depend on seasonal or temperature-dependent processes, such as snowmelt and evaporation, should incorporate climate projections into scenario planning.

Runoff, Infiltration, and Streamflow

Runoff is the portion of incoming precipitation that exits a watershed through a stream channel and is produced during rainfall events or snowmelt through two mechanisms, overland flow and interflow (Figure 1). Overland flow results when high-intensity precipitation or rapid snowmelt occurs on a surface with a low infiltration capacity, forcing water to runoff directly into stream channels. Interflow occurs when water infiltrates, travels through the soil and discharges into a stream channel. Vegetated surfaces, such as those found in forests, promote infiltration and a larger fraction of interflow (Moreno-de las Heras et al. 2010). Over a four-year study in a ponderosa pine forest, surface runoff was found to account for at most 18 percent of annual runoff and only trace amounts of surface runoff were measured in two of the years. Surface runoff occurred entirely during summer monsoon storms with high rainfall intensity (Wilcox et al. 1997). A high percentage of interflow is associated with good water quality and reduced flood risk (Neary et al. 2009).

Winter precipitation in high-elevation forests is the primary source of streamflow in semi-arid watersheds (Flerchinger and Cooley 2000). While ponderosa pine forests cover only 20 percent of the Salt-Verde River watershed, it is estimated that they produce 50 percent of the river flow (Barr 1956). If there is a shift toward more summer and less winter precipitation, summer monsoon storms could make a larger contribution to overall streamflow and potentially compensate for losses from winter precipitation (Hawkins et al. 2015), but could also increase overland flow.

Management Implication

Based on climate projections, managers should be prepared for higher flood peaks and erosion rates from summer monsoon storms.

Snow and Soil Moisture Storage

Of the winter precipitation occurring as snow, around 20 percent is intercepted by the forest canopy (Biederman et al. 2014, Broxton et al. 2015). The melting of ground snow pack is the primary source of infiltration to deep soil layers (Dore et al. 2012). Deep soil moisture (>12 in depth) is important to forest health because it sustains overstory trees through the spring dry season when fire risk is highest. Summer monsoon storms generally do not result in deep infiltration, but are an important source of water for understory vegetation (Simonin et al. 2007).

Evapotranspiration

The majority of precipitation that enters a semi-arid forest leaves through evapotranspiration. Evapotranspiration is the combination of evaporation of rainfall that is intercepted by vegetation, evaporation of moisture from the soil, sublimation of snow, and water use by plants (transpiration). Evapotranspiration increases under higher temperatures (Monteith 1965), and a number of studies indicate a positive relationship between evapotranspiration and vegetation density (e.g. Bosch and Hewlett 1982, Sahin and Hall 1996). Therefore, climate change and restoration treatments may affect evapotranspiration.

Total evapotranspiration can be measured or estimated through several methods. The eddy covariance method directly measures the flux of water vapor from an ecosystem and is considered the gold standard in evapotranspiration measurement. Eddy covariance measurements conducted near Flagstaff, Arizona, from 2006–2010 found that evapotranspiration losses were 80–90 percent of annual precipitation for a typical ponderosa pine forest (Dore et al. 2012). Evapotranspiration can also be determined indirectly through the water balance method in which evapotranspiration is assumed to be equal to the difference between measured precipitation inputs and runoff losses. It does not account for water lost to deep drainage, so the method is only valid for small catchments and may still overestimate evapotranspiration. Water balance methods at the Beaver Creek Experimental Watershed in the 1950s–80s estimated evapotranspiration as 72–85 percent of precipitation for ponderosa pine forests (Baker 1986). The results are likely lower than the eddy covariance measurements because deep drainage is not accounted for and fire suppression increased vegetation density and evapotranspiration. A more recent water balance evapotranspiration study in a ponderosa pine forest near Los Alamos, New Mexico, estimated evapotranspiration as 95 percent of precipitation (Brandes and Wilcox 2000). Mixed conifer experimental watersheds at Workman Creek (Rich and Gottfried 1976) and Castle Creek (Gottfried 1991) estimated evapotranspiration as 90 percent of precipitation through the water balance method. However, eddy covariance measurements along an elevational gradient in California found that evapotranspiration accounted for a higher percent of precipitation in ponderosa pine than in higher-elevation conifer forests (Goulden et al. 2012), suggesting that deep drainage plays a larger role in the water budgets of mixed conifer systems.

In the absence of measurements, evapotranspiration can be estimated from meteorological data, such as temperature, humidity, and incoming solar radiation, and vegetation characteristics using one of several equations (Dingman 2002). There are also remote sensing-based evapotranspiration estimates available that can be used in the absence of measurements (Shultz and Engman 2012). The choice of equation depends on the data available and the type of ecosystem being considered. Ha et al. (2015) compared evapotranspiration equations and evapotranspiration estimates from the MODIS satellite to eddy covariance measurements for ponderosa pine forests to determine the best estimation method. The Shuttleworth-Wallace (Shuttleworth and Wallace 1985) equation provided the best estimate, and most equations provided a more accurate estimate than the remote sensing product. However, a new evapotranspiration estimation based on the high-resolution Landsat satellite provides more accurate values for the Southwest than the MODIS estimate (Singh et al. 2013). When compared to eddy covariance measurements, even the best equations and remote sensing products can over- or underestimate annual ET by as much as 15 percent. Thus, the error in ET may be larger than runoff or recharge as a percent of precipitation, so estimating runoff or recharge by the water balance method is not feasible without a direct measurement of ET.

Management Implication

Managers needing to estimate evapotranspiration would be best served by an equation such as Shuttleworth-Wallace or the Landsat product. However, the error in these estimates is too large to provide accurate estimates of runoff or recharge using the water balance method.

Other methods exist to measure individual components of evapotranspiration. The sap flux method measures the water use rate of individual trees, and the data can be scaled up to determine the total water use of overstory trees in an ecosystem, referred to as overstory transpiration. Understory evapotranspiration, which is a combination of soil evaporation and water use by understory vegetation, can be determined by measuring changes in soil water storage in small plots where large roots have been excluded. Simonin et al. (2007) used these methods to quantify overstory transpiration and understory evapotranspiration in ponderosa pine forests. Overstory transpiration dominates evapotranspiration in the spring, when snowmelt has replenished deep soil moisture and most of annual evapotranspiration occurs. The smaller evapotranspiration rates during the summer monsoon season are dominated by understory evapotranspiration, which consumes most moisture from monsoon storms before it infiltrates to deep soil layers. Because evapotranspiration consumes most summer precipitation, winter precipitation is the main source of runoff and groundwater recharge. Thus, water resources depend on an abundance of winter precipitation.

Groundwater Recharge

The deep drainage of water below the active root zone of an ecosystem to create groundwater recharge is a complex process. It depends on both the annual balance between precipitation, runoff, and evapotranspiration and the physical characteristics of the soil and bedrock.

Projects to restore forests surrounding storage reservoirs, like C.C. Cragin in Arizona, aim to protect water quality and supplies from the debris and ash that clog streams and rivers as a result of high intensity wildfires. *Photo courtesy of Coconino National Forest, USDA Forest Service*

The morphology of watersheds and stream channels also plays a role, as drainage from ephemeral stream channels during flow events accounts for a large portion of groundwater recharge in the Southwest (Phillips et al. 2004). Groundwater recharge can be measured by tracking the isotopic composition or concentration of naturally occurring trace chemicals in precipitation and water extracted from the deep soil (Allison et al. 1994). It can also be estimated using a water balance model (Kinzelbach et al. 2002). A wide range of groundwater recharge values have been estimated for sites in forested regions of the Southwest using this method. In New Mexico ponderosa pine forests, measured groundwater recharge was 20 percent of annual precipitation for a sandy soil that drains quickly (Stephens and Knowlton et al. 1986) and less than 1 percent of annual precipitation for a forest with a deep clay soil layer that is nearly impervious to water flow (Newman et al. 2007). Analysis of long-term data has shown that groundwater recharge rates are closely tied to climate with the majority of recharge occurring during years with high precipitation (Pool 2005).

While the high variability of groundwater recharge in space and time makes it difficult to reliably estimate it at regional scales, there is strong evidence that groundwater is being pumped at higher rates than it is being recharged. Change in groundwater storage at large scales can be estimated through satellite-based measurements of the small reductions in gravity that occur when groundwater is depleted. These estimates show that the rate of groundwater depletion in the Colorado River basin exceeds the rate of depletion for large storage reservoirs such as Lake Mead and Lake Powell, indicating that groundwater is being depleted more rapidly than surface water resources in the western U.S. The sharpest decline occurred over the past four years of severe drought (Castle et al. 2014).

Management Implication

The rate of groundwater use in the western U.S. is not sustainable. As groundwater is generally used to supplement surface water, this underscores the need to maintain healthy forested watersheds.

Sediment Yield and Water Quality

The quality of water emanating from forested lands must be of sufficient quality to provide for aquatic habitat and be of use to human communities. Soil erosion within a watershed leads to suspended sediment in runoff, which alters water color and clarity, may transport contaminants that are bound to the sediment particles (Ongley et al. 1992), and settles in reservoirs and canals, reducing their capacity and function (Lane et al. 1997). The total mass of sediment leaving a watershed per unit area is referred to as the sediment yield. Sediment production is driven by overland flow, so sediment yield is minimal in undisturbed ponderosa (Brown et al. 1974; Heede 1984) and mixed-conifer (Heede and King 1990) forests. Forested is perhaps the best watershed land cover type for producing clean water, but disturbances, especially forest roads, can reduce water quality (Neary et al. 2009).

Management Implication

Maintaining healthy forested watersheds reduces the cost of water treatment and maintenance of water storage and delivery infrastructure.

Restoration Effects on the Forest Water Cycle

As restoration proceeds from small management projects to landscape-scale initiatives such as the 4FRI, it is possible that restoration treatments will affect the water cycle at the scale of large river basins and regional aquifers. Paired watershed studies to monitor the effect of landscape-scale restoration on the water cycle are planned for ponderosa pine forests near Flagstaff (Masek Lopez et al. 2013) and are underway in mixed-conifer forests near Santa Fe (Lewis 2014). Prior to the availability of new data from these studies, it is possible to predict the effect of restoration on the water cycle based on research on other types of vegetation thinning, studies of individual water cycle components in small restoration plots, modeling studies, and remote sensing-based measurements. These studies are summarized in this section.

A paired watershed study monitors streamflow to measure the effect of restoration on the water cycle.

Runoff and Streamflow

There is considerable interest in predicting how forest restoration will affect runoff, because it could result in additional water resources for downstream users. The effect of commercial forest management techniques on runoff was studied extensively in Arizona in the 1950s to 1980s using paired watershed studies, which compare runoff in treatment and control watersheds before and after treatment (Baker 1999). Forest thinning treatments applied to mixed-conifer forests in the watersheds of two of three branches of Workman Creek were found to increase runoff in a study conducted at the Sierra Ancha Experimental Forest on the Tonto National Forest (Rich and Gottfried 1976). To determine if the results from Workman Creek could be reproduced, the Forest Service's Rocky Mountain Forest and Range Experiment Station instrumented and treated three more pairs of mixed-conifer and ponderosa pine forests on the White Mountain watersheds of Castle, Willow, and Thomas Creeks on the Apache-Sitgreaves National Forest. Increased runoff was observed at all of the sites, and long-term monitoring at Workman Creek showed that the increases persisted through the 21-year observation period following thinning (Gottfried and DeBano 1990).

The most extensive series of paired watershed experiments occurred on 20 small watersheds at the Beaver Creek Experimental Watershed in ponderosa pine forest and piñon-juniper woodland on the Coconino National Forest (Brown et al. 1974; Baker 1986). The objective of the study was to evaluate the potential of clearing and silvicultural thinning techniques for increasing runoff, water quality, and rangeland productivity in the Salt-Verde River basin. The Beaver Creek studies found that both overstory removal and strip-cut thinning treatments of ponderosa pine forest that removed at least 30 percent of basal area resulted in significant increases in runoff. For comparison, ecological restoration treatments designed to restore historical structure and fire regime reduce basal area by 40–65 percent (Fulé et al. 2002; Waltz et al. 2003). In contrast to the Workman Creek Study, streamflow in thinned Beaver Creek watersheds returned to pre-treatment levels, as compared to a control watersheds, four to 10 years after treatment. The recovery is attributed to tree recovery and understory regrowth, which is discussed in the following section (titled "Evapotranpiration," page 7).

Most of the greater Phoenix area's water supply comes from winter precipitation and runoff from Arizona mountains to the north. Snow melts and drains into tributaries and is stored in reservoirs on the Salt (pictured) and Verde rivers. Forest restoration can improve watershed health and function, which has benefits for downstream ecosystems and communities. *Photo courtesy of Tonto National Forest, USDA Forest Service*

Management Implications

- Based on historical studies, restoration treatments should remove at least 30 percent of basal area to produce additional runoff and other hydrologic benefits.

  The forest thinning treatments tested in the historical paired watershed studies are not the same as restoration treatments, but the basal area reduction resulting from restoration is within the range of the forest thinning treatments tested. Robles et al. (2014) used historical paired watershed data to develop an equation that predicts the increase in runoff following thinning in ponderosa pine forest. Winter precipitation, time since thinning, and basal area reduction were the factors that significantly influenced runoff increase. Over a range of restoration and climate scenarios, runoff was predicted to increase by an average of 20 percent over the 10 years following restoration. This is the increase in flow that would be expected in a small headwater stream whose watershed is completely covered by recently restored forest. In larger river basins, it is only feasible to restore a small portion of the forested land in the watershed each year, so the increase in annual runoff is smaller. When 30-year restoration scenarios for the entire Salt-Verde basin are analyzed, the annual increase in runoff amounts to less than 2 percent of the annual Salt River flow reaching Roosevelt Reservoir near Phoenix.

- Restoration may be a useful tool for increasing flow to upland aquatic habitat and water sources, but it is unlikely to provide large and reliable increases in flow to major rivers.

  Another approach to predicting changes in runoff due to restoration is process-based modeling. These models simulate the physical processes in a watershed that influence runoff, such as evapotranspiration and snowmelt, and the parameters describing vegetation structure in the model can be adjusted to represent a restoration treatment. Kaye et al. (1999) ran the MT-CLIM (Running et al. 1987) and Forest-BGC (Running and Coughlan 1988) climate and hydrology models for two experimental restoration plots and a control site near Flagstaff. The model predicted annual runoff 32-110 percent greater in the restoration than control plots. However, data available to calibrate and test the hydrology model were limited, so the results should be interpreted with caution. Moreno et al. (2015) used the tRIBS model (Ivanov et al. 2004) to predict the effect of 4FRI treatments on flow in Tonto Creek, a major tributary in the Salt-Verde River system with a watershed that is partially forested. tRIBS is specifically designed for modeling interactions between vegetation and the water cycle and it simulated measured flow in Tonto Creek accurately. For a range of restoration scenarios, modeled flow in Tonto creek increased 1–4 percent.

  There are pros and cons to both statistical modeling approaches, such as the regression equation used by Robles et al. (2014), and the process-based modeling approaches used by Kaye et al. (1999) and Moreno et al. (2015). Statistical approaches are unable to account for differences between the conditions that existed when data was collected and the conditions under which predictions will be made. For instance, warmer temperatures due to climate change may alter the water cycle by increasing evapotranspiration and converting precipitation from snow to rain, and this would not be accounted for in a statistical model. Process-based models address this issue by directly simulating processes like evapotranspiration and precipitation. However, process-based models often require a large number of model parameters and data for calibration and testing. Uncertainty in parameter values and limited calibration data can reduce the reliability of the model. Agreement between approaches provides evidence that a prediction is reliable. The conclusion that landscape-scale restoration will result in small increases in river flow is supported by both statistical (<2 percent increase) and robust process-based (1–4 percent increase) modeling approaches.

  While restoration may benefit downstream water users by increasing flows, there is also concern that the disturbance from restoration will lead to increased flood peaks. The Beaver Creek Experimental Watershed experienced an intense precipitation event in 1970 shortly after some of the logging treatments were performed, providing evidence on how thinning affects flood peaks (Brown et al. 1974). Sites that were lightly thinned (~33 percent basal area reduction) and are most similar to restoration treatments experienced small increases in flood peak that were not statistically significant. Watersheds with more intense thinning (75 percent basal area reduction to clearcut) did experience significant flood peak increases of 88–167 percent above control levels. Data on flood peaks following a major storm are not available for watersheds thinned at levels similar to restoration treatment (40–65 percent basal area reduction). However, the data available do suggest that increases in flood peaks are possible and should be a focus of future research.

  If prescribed or managed fire is used as part of restoration, it may have additional effects on flood peaks. In ponderosa pine forest, prescribed fire temporarily reduces the capacity of the soil to infiltrate water. The effect is usually reversed by the freezing and snowpack during the first winter following burning (Zwolinski 1971). If monsoon storms occur after burning but before winter, increased overland flow is possible, which should be a consideration in flood-prone areas.

- In areas prone to high floods (e.g. steep slopes, impervious soils) or where floods could endanger lives and property, lower-intensity thinning methods (<35 percent basal area reduction) should be used and prescribed burns should be conducted in the fall to allow soils to recover before monsoon rains.

Prescribed burning, often combined with mechanical thinning of excess, small diameter trees, seeks to return forest to a more natural condition and restore a low-intensity fire regime. *Photo by ERI*

Evapotranspiration

One potential mechanism driving increased runoff in thinned forests is the reduction in evapotranspiration that occurs when vegetation is removed. Field studies of experimental restoration plots provide evidence that this is the case. The eddy covariance study of stand-level evapotranspiration in ponderosa pine forests near Flagstaff compared a restored and an unmanaged forest. Over the five years following restoration, total annual evapotranspiration was reduced by 4 percent (Dore et al. 2012). Spring evapotranspiration following snowmelt was higher in the control site, but evapotranspiration during the summer monsoon season was higher in the restored site. Measurements of individual components of evapotranspiration in restored and control plots provide evidence for why this occurs (Simonin et al. 2007). Understory evapotranspiration, which is the most important component of evapotranspiration in the summer, was higher in the restored plot because more sunlight reaches the understory. Total water use by overstory trees, which is the dominant evapotranspiration component following snowmelt, was higher in the control plot. However, water use by individual overstory trees increased as the restoration site recovered from thinning (Simonin et al. 2006). Increasing evapotranspiration due to vegetation regrowth is often cited as a reason that post-thinning runoff increases are not permanent (e.g. Baker 1986).

Management Implication

If prescribed or managed fire is used to maintain an open condition following restoration, a small increase in runoff is possible following burning due to a reduction in understory evapotranspiration. The increase will likely be smaller than that observed following thinning because water use by individual overstory trees increases after restoration.

Snow and Soil Moisture Storage

The other mechanism by which restoration may increase runoff is by decreasing canopy interception of snow, leading to deeper snowpacks and greater infiltration of snowmelt into the soil. Modeling studies predict that lower canopy densities produce greater ground snowpack (Broxton et al. 2015). However, observations of snowpack following mountain pine beetle outbreaks (Biederman et al. 2014) and high-severity wildfire (Harpold et al. 2013) demonstrate that extensive canopy removal can reduce infiltration to the soil by exposing the ground snowpack to sun and wind causing increased sublimation. Therefore, snow-water infiltration is expected to be greatest in forests with intermediate canopy density (Musselman et al. 2008; Gustafson et al. 2010). A meta-analysis of studies that measured snow accumulation before and after a change in forest cover due to a variety of drivers, such as fire, insect outbreaks, logging, and afforestation, found that reductions in forest cover were associated with an increase in snowpack (Varhola et al. 2010). While field studies focusing specifically on restoration are limited, Sankey et al. (2015) analyzed imagery from an unmanned aerial vehicle to determine that restored forests with 24 percent canopy cover had the highest fraction of ground covered by snow in the early spring. The method was not able to provide information about snow depth or water content, but it does provide preliminary evidence that forest restoration increases snowpack.

Aside from providing reliable water resources, another goal of forest restoration is to improve forest health by increasing soil moisture. Increased soil moisture reduces vegetation stress during dry periods. Studies in restored and control plots indicate that restoration increases deep (<6 in) soil moisture sourced from snowmelt. However, shallow soil moisture from monsoon storms is depleted more rapidly in the summer in restored forests due to reduced shading (Simonin et al. 2007; Dore et al. 2012). Therefore, restoration would be expected to reduce stress on

A larger patch of snowpack is retained with a large opening, or meadow, in the forest near Mountainaire, Arizona in 2010. *Photo courtesy of NAU*

overstory trees but increase stress on understory vegetation. This would support a high-frequency, low-intensity fire regime.

Groundwater Recharge

It is expected that restoration will increase groundwater recharge by increasing infiltration from snowpack and reducing losses from evapotranspiration. Wyatt et al. (2015) assumed that the increase in recharge due to restoration would be proportional to the expected increase in runoff (e.g. if runoff increases 10 percent, recharge will increase 10 percent), and used a regional groundwater flow model to analyze how the 4FRI would influence regional aquifers. The model predicted a 2.8 percent increase to major aquifers, but the increase was small relative to aquifer pumping rates. Direct measurements of the effect of forest thinning or restoration on groundwater recharge are limited to one study. Aldridge (2015) measured groundwater recharge for one year in restored and control ponderosa pine forest plots. Precipitation during the study period was anomalous with strong summer monsoon precipitation (23 percent above average). Winter snowpack was 40 percent below average, but heavy spring rains brought the winter precipitation totals to near average. Measured recharge was slightly higher in the control site, 4.8 percent of precipitation, than the restored site, 4.4 percent of precipitation, which went against the expected results. More information is needed to draw conclusions about the effect of restoration, and groundwater recharge measurements are a planned component of paired watershed monitoring studies (Masek Lopez et al. 2013; Lewis 2014).

Sediment Yield and Water Quality

Many of the historical paired watershed studies also measured sediment. Sediment yield increases following light to moderate thinning were minimal in mixed-conifer forests at Workman Creek (Rich et al. 1961) and Thomas Creek (Heede and King 1990) and in ponderosa pine at Beaver Creek (Dong 1996). Total dissolved solids, a general indicator of water quality, were also measured at Beaver Creek and showed a small increase following thinning treatments (Brown et al. 1974).

Restoration treatments that include prescribed or managed fire pose additional concerns for sediment yield and water quality. Baker (1990) provides a detailed review of prescribed burning effects on erosion and water quality. Fire can increase sediment erosion by reducing the stabilizing cover of understory vegetation and litter. In ponderosa pine, the effects of prescribed burns on sediment yield are small or undetectable. Observations over two years following a prescribed burn in a ponderosa forest in California, including slopes of up to 43 percent, found no evidence of erosion except around roads and trails (Biswell and Schultz 1957). A study in Arizona did find evidence of erosion one year after prescribed burning, but soil loss was small (less than one inch) and most was deposited a short distance downslope before reaching a stream (Cooper 1961). Many of the nutrients contained in plant matter are converted by fire to forms that are more easily dissolved and washed away, reducing water quality. Prescribed burning resulted in a statistically significant increase in nitrate and ammonium in ponderosa pine forests, but the concentrations were still very low during the year following burning (Gottfried and DeBano 1990). Post-fire nitrate concentrations were all below 0.003 parts per million, well below the EPA drinking water standard of 10 parts per million. Changes in other nutrient concentrations, including phosphorus and cations, were not detected. Kaye et al. (1999) measured nutrient concentrations in soil water in a control and two restoration plots, one that included prescribed burning and one that did not. There was no significant difference between the plots.

Management Implication

Reductions in water quality due to restoration treatments is generally low but may need to be considered if restoration is occurring near a very sensitive aquatic habitat or water source.

Wildfire Effects on Hydrology

The main goal of forest restoration is to reduce the risk of high-intensity wildfire. The potential negative impacts of restoration, increased flood peaks, sediment yield, and decreased water quality, must be weighed against the potential negative effects of a high-intensity wildfire Hydrologic studies were conducted after several of the major wildfires that occurred in Arizona and New Mexico in the 1990s and 2000s and show that these effects can be quite severe.

Flood Peaks Following Wildfire

The sites of several historical paired watershed studies were burned by large, high-intensity wildfires. Instrumentation was reinstalled after the fires to study the effects in comparison to historical pre-fire data. Neary et al. (2003) provide a detailed review of the results. After high-severity fire, the sites experienced record flood peaks, 10–100 times pre-fire levels, during summer monsoon storms.

Management Implication

The potential increase in flood peak from a high-intensity wildfire is much more severe than the potential increase from a restoration treatment.

Sediment Yield and Water Quality Following Wildfire

Erosion and sediment transport is commonly observed after high-intensity wildfire (Gottfried et al. 2003). The 2011 Las Conchas Fire burned a section of the Valles Caldera National Preserve in New Mexico, a long-term research site for which a high-resolution elevation map had been produced using airplane-based Light Detection and Ranging (LiDAR) one year before the fire. A repeat survey was performed, and erosion for any point can be calculated by taking the difference between the pre-fire and post-fire elevation maps. The analysis showed the highest erosion rates from steep slopes and areas with high burn severity (Figure 2, Pelletier and Orem 2014).

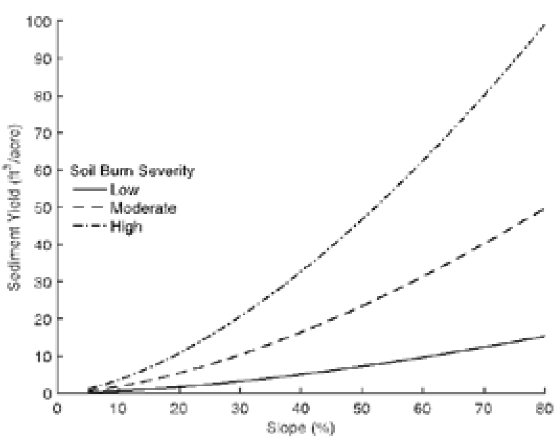

Figure 2. Relationship between slope and sediment yield for three Forest Service Burned Area Reflectance Classification (BARC) categories. Relationships are from the equation developed by Pelletier and Orem (2014) based on LiDAR-derived sediment yield data from the 2011 Las Conchas Fire. Sediment yield is expressed as ft^3 of sediment produced per $acre^2$ of contributing area in the year following the fire.

Erosion has negative consequences for water quality. Monitoring before and after the Cerro Grande Fire, which burned ponderosa pine and mixed-conifer forest in New Mexico, found that post-fire suspended sediment concentrations in ephemeral streams were more than 100 times higher than pre-fire levels (Malmon et al. 2007). Most measures of water quality, including concentrations of major ions and nutrients, turbidity, and pH, are significantly altered by wildfire for at least four months (Earl and Blinn 2003).

Severe erosion and sediment transport was observed after the 2010 Schultz Fire, which burned more than 15,000 acres of steep slopes on the San Francisco Peaks north of Flagstaff, Arizona. *Photo by ERI*

Management Implications

- From an erosion-management and water quality perspective, steep slopes should be a priority for restoration treatments.
- The water quality impacts of high-intensity wildfire are much greater than the impacts of a restoration treatment.

  The reductions in water quality associated with wildfire have a negative impact on aquatic habitat.

Leonard (2015) conducted a comprehensive review of research on high-severity wildfire effects on aquatic ecosystems in the Southwest. Native fish species have been extirpated from streams following wildfire (Rinne 1996). Wildfire also reduces the abundance and diversity of insects, which are an important link in the aquatic food web (Vieira et al. 2004). Populations recover more quickly when headwater areas of the watershed remain unburned, because the headwaters provide a source to repopulate burned areas (Vieira et al. 2011).

- Protecting headwaters from high severity fires through restoration treatment can increase the resilience of aquatic communities.

Conclusion

Forest restoration has the potential to positively affect the hydrologic cycle of fire-adapted forests in the Southwest by enhancing runoff, soil moisture storage, and snowpack. There are some potential negative effects, including increased sediment yield, reduced water quality, and increased flood peaks. Based on previous studies, the impacts on sediment and water quality will likely be minimal. More information is needed on the potential for increased flood peaks. These small negative impacts must be weighed against the catastrophic floods, erosion, and water quality reduction that has been documented following high-intensity wildfire.

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